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Effects of bed perturbation and velocity asymmetry on ripple initiation: wave-flume experiments

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Abstract

Laboratory experiments using a wave flume were designed to examine the threshold condition for ripple formation under asymmetrical oscillatory flows on an artificially roughened bed. Three types of sand beds were prepared in the experiments: they were flat, notched, and notch-mounded beds with bed roughness increasing in this order. The beds were constructed with three kinds of well-sorted sand with similar density, but different diameters. Data analyses were made using the two dimensionless parameters: the mobility number, M, a simplified form of the Shields number, and the Ursell number, U, a surrogate for asymmetry of flow field. The result confirmed that the threshold for ripple initiation is decreased with increasing bed perturbation and that as the bed perturbation increases, the dependency of this threshold on the flow asymmetry becomes less and finally null for the notch-mounded bed. This relationship is quantified by the following equations: $M=17-14.5e^{-0.03U}$ on the flat bed, $M=5.0-2.5e^{-0.1U}$ for the notched bed, and $M=2.5$ for the notch-mounded bed. A comparison between the previous field data and the present laboratory findings indicates that the threshold in the notch-mounded bed experiment, $M=2.5$, seems to provide a critical condition for rippling in the natural environment.

Keywords: Bed disturbance; Asymmetrical oscillatory flow; Wave ripple initiation

1. Introduction

An extensive literature on wave-formed ripple marks has dealt with ripples initiated from a smooth flat bed in the laboratory environment (Bagnold, 1946; Manohar, 1955; Inman and Bowen, 1963; Yalin and Russel, 1963; Carstens and Neilson, 1967; Horikawa and Watanabe, 1967; Carstens et al., 1969; Chan et al., 1972; Mogridge and Kamphuis, 1972; Dingler, 1975; Lofquist, 1978; Nielsen, 1979; Miller and Komar, 1980a; Sunamura, 1980, 1981; Southard et al., 1990; Ribberink and Al-Salem, 1994; Marsh et al., 1999). One of the problems involved in the application of the laboratory result to the field situation is the initial boundary condition introduced into the laboratory study: a flat bed. The seabed in the real world has multiple topographic disturbances prior to ripple development. Some of the previous studies (Bagnold, 1946; Carstens and Neilson, 1967; Carstens et al., 1969; Lofquist, 1978; Brebner, 1980) have attempted

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to study ripple marks generated from an artificially disturbed bed.

The nearshore environment where ripple marks are well developed is characterized by asymmetric flow field inherent in waves in the shallow-water region. The previous laboratory studies taking account of the velocity asymmetry are limited in number (e.g., Sunamura, 1980, 1981; Ribberink and Al-Salem, 1994; Marsh et al., 1999). These studies have treated ripple formation from a smooth flat bed as noted above.

Appropriate applications of laboratory studies to the field require the incorporation of two factors: (1) irregularities of sea bottom and (2) asymmetry of velocity field. With these in mind, the present wave-flume experiment was designed to examine the threshold condition for ripple formation by asymmetrical flows on an artificially roughened bed. Some comparison will be made with previous field data.

2. Laboratory experiment

The wave flume used here was 14 m long, 50 cm deep, and 25 cm wide (Fig. 1). A piston-type wave generator was equipped at the one end of the flume. At the other end, a fixed slope of 1/20 was installed, on which a layer of cobbles (several centimeters across) was placed to reduce energy of waves reflected from the down-wave side of the flume. A sand bed (3 m long, 25 cm wide, and 3 cm thick) was constructed in the horizontal portion of the flume; both ends of the bed tapered off to reduce the local perturbation of flow. Three types of sand beds with different roughness were prepared: (1) a horizontal flat bed, here referred to as "the flat bed", (2) a bed with a notch (Fig. 2a), described as "the notched bed", and (3) a bed with a notch and two mounds (Fig. 2b), called "the notch-mounded bed", with bed perturbation increasing in this order. Use of such a single notch or a notch-mounded structure, both being much simpler than disturbances on the natural bed, will enable us to examine easily the effect of the bed roughness on the ripple initiation and developmental processes.

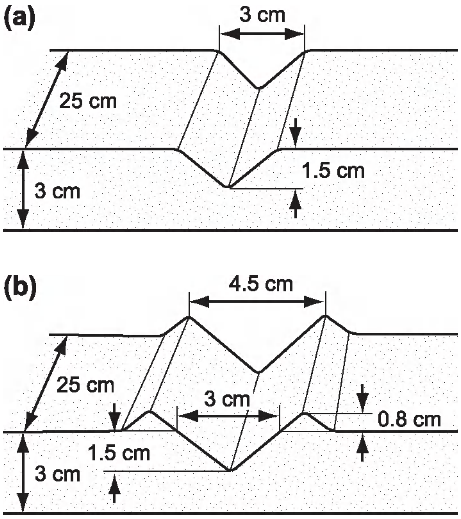


Fig. 2. Two types of disturbances in the roughened-bed experiments: a notch (a), and a notch and two mounds (b), both located in the central portion of the sand bed.

Three kinds of well-sorted quartz sand were employed for the bed material; they have similar densities, 2.6–2.7 g/cm^3, but different median grain sizes, 0.021, 0.038, and 0.054 cm. Their Trask's (1932) sorting coefficients (e.g., Sengpta, 1978) fell in the range from 1.08 to 1.12. Water depth above the horizontal portion of the sand bed (20–30 cm) was kept constant through each experiment run. Wave period ranged from 1.0 to 3.5 s, and wave height from 1.7 to 13.0 cm. By

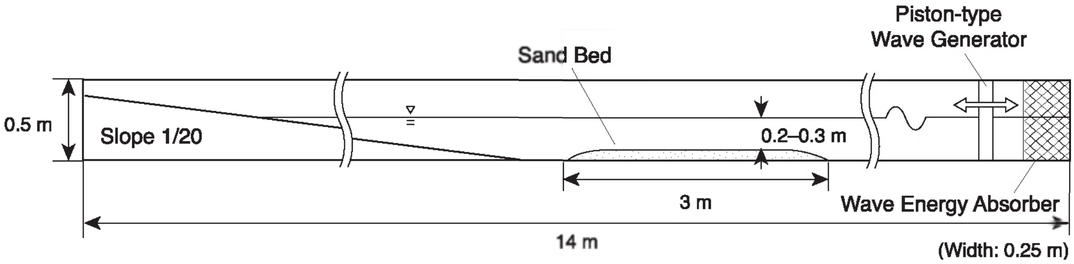


Fig. 1. Wave flume used in this study. A sand bed was constructed in the horizontal portion of the flume.

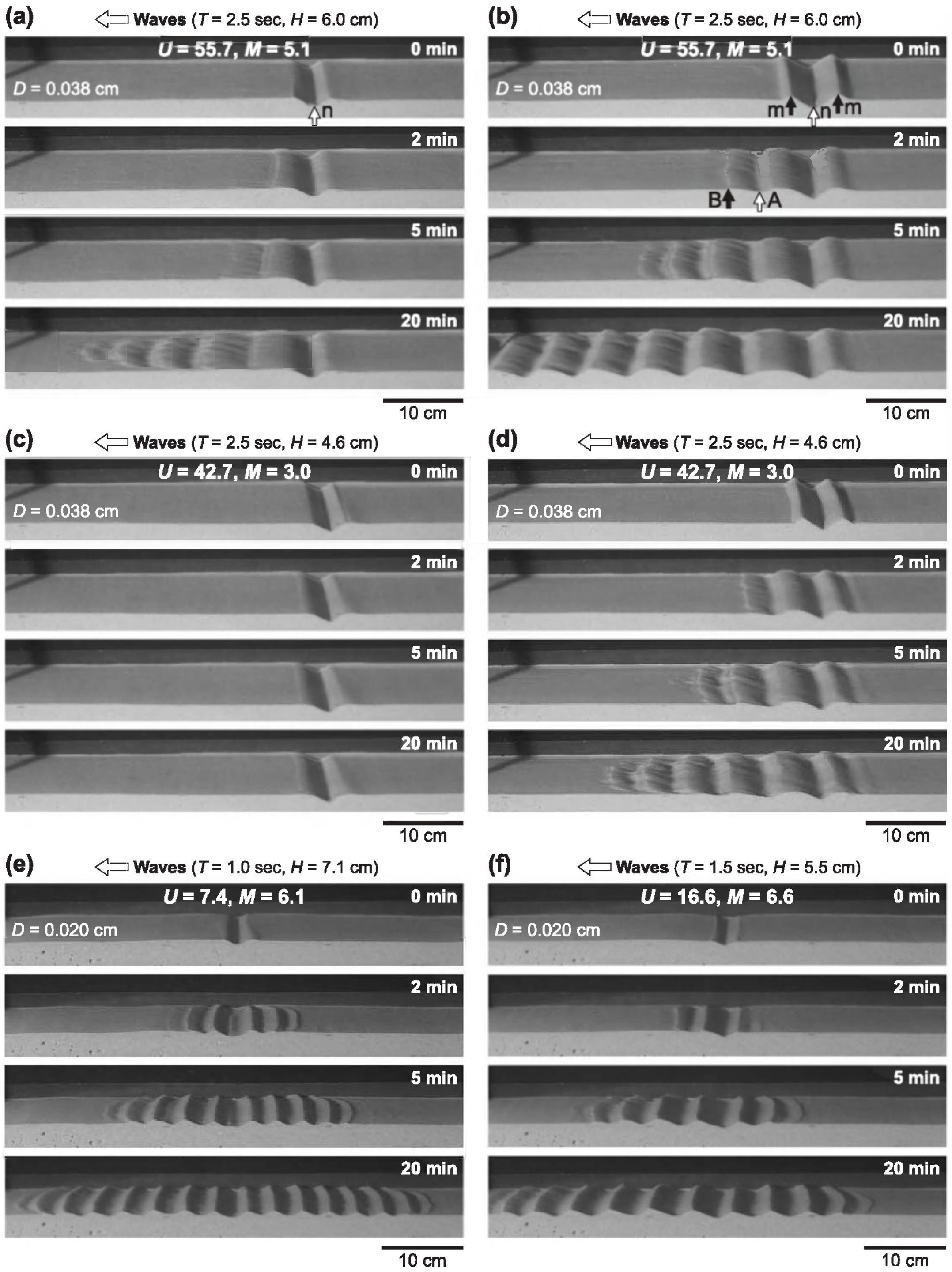


Fig. 3. Some examples of ripple formation shown by sequential photographs in the roughened-bed experiments. The symbols, “m” and “n”, denote the mounds and notch, respectively. Waves propagate from right to left. Water depth above the sand bed was 25 cm for all runs shown here.

combining these experimental parameters, approximately 250 runs were carried out. Each run had 30-min wave action. Ripple formation was recorded using a digital video camera, and photographs were taken at a certain interval of time.

3. Results

A preliminary experiment of wave reflection showed that the reflection coefficient was less than 10%. Reflection coefficients were calculated according to Wiegel (1964, p. 53). This result suggests that the influence of reflected waves on ripple initiation could be small: the influence is ignored in this study.

Two dimensionless parameters were employed to analyze the data: one is the mobility number and the other is the Ursell number. The mobility number is a simplified form, which neglects the frictional effect, of the Shields parameter that describes the relative magnitude of bed shear stress to the resisting force against the motion of sand grains. Many ripple studies such as Carstens and Neilson (1967), Carstens et al. (1969), Dingler (1975), Komar and Miller (1975), Lofquist (1978), Nielsen (1979, 1981), Brebner (1980), Vincent and Osborne (1993), and Ribberink and Al-Salem (1994) have applied this parameter. The mobility number, M, is given by:

$$M = \frac{\rho u_b^2}{(\rho_s - \rho)gD} \tag{1}$$

where u_b is the maximum orbital velocity near the bottom, D is the sediment grain size, ρ_s and ρ are the densities of sediment grains and water, respectively, and g is the acceleration due to gravity. Using linear wave theory (e.g., Dyer, 1986, pp. 96–100; Komar, 1998, pp. 161–168), u_b can be calculated with wave height, H, and wavelength, L, at a water depth of h, and wave period, T, through the relationship:

$$U_b = \frac{\pi H}{T \sinh\left(\frac{2\pi h}{L}\right)} \tag{2}$$

In this study, H was measured over the horizontal portion of the sand bed and L was calculated from the relation:

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right) \tag{3}$$

The Ursell number, U, used here for a surrogate for representing the degree of asymmetry of the near-bottom wave orbital velocity (Sunamura, 1980, 1981; Montzouris, 1990), is given by (Ursell, 1953):

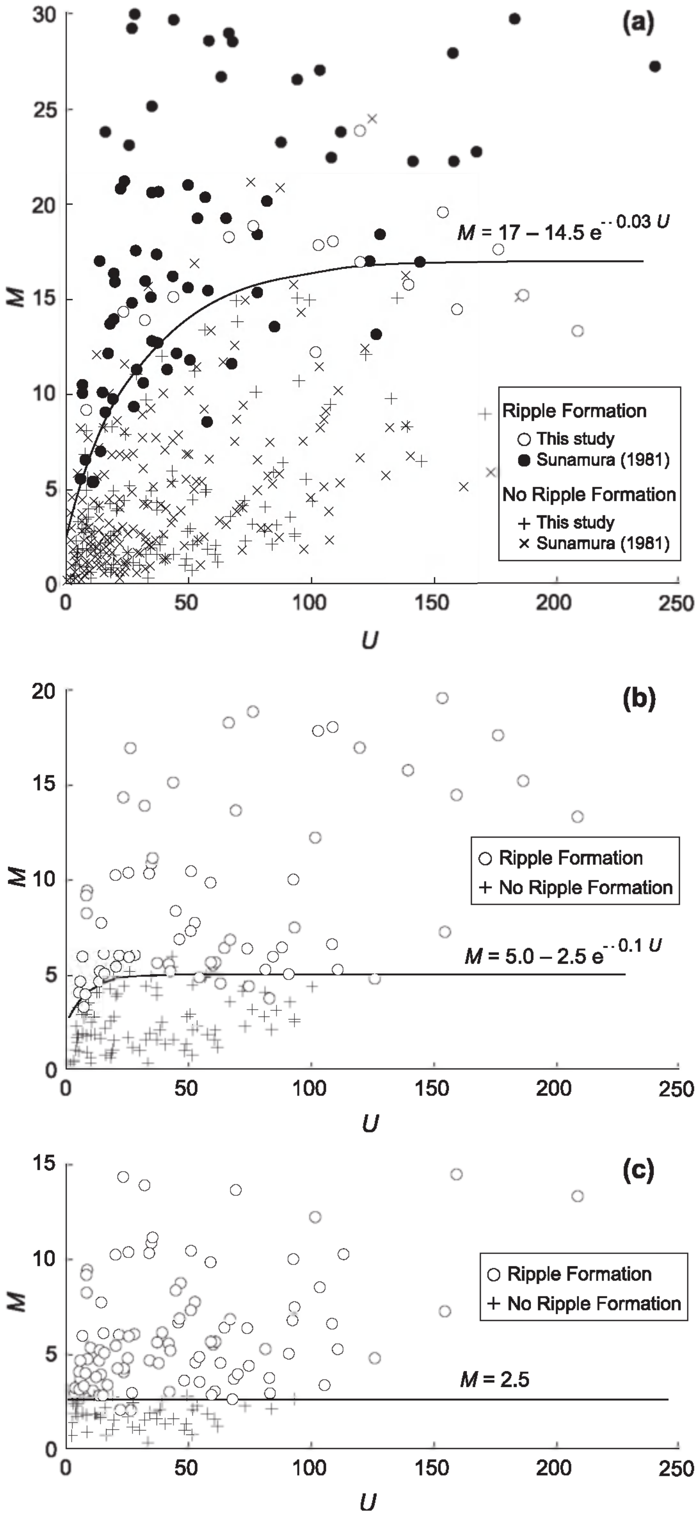
$$U = \frac{HL^2}{h^3} \tag{4}$$

With increasing U, velocity asymmetry becomes greater: a larger onshore velocity of shorter duration under wave crests and a smaller offshore velocity of longer duration under wave troughs, as compared to a purely sinusoidal orbital velocity field.

No ripple formation is recorded if incipient ripples did not appear in the first 5 min of each experimental run, irrespective of the types of sand beds. In the flat-bed experiment, incipient ripples sporadically occurred on the flat portion of the bed when bottom velocity was slightly above the threshold for rippling. In contrast, ripple formation in the roughened-bed experiment started from the notched or mounded portion of the bed.

The effects of bed perturbation and flow asymmetry on ripple initiation are illustrated by the sequential photographs in Fig. 3. These are oblique-top views of the sand bed with light illumination from the left; "m" and "n", respectively, mark the mounds and notch of the initial perturbation. On the notch-mounded bed (Fig. 3b), ripple inception took place more rapidly and subsequently developing ripples were more corrugated than on the notched bed (Fig. 3a), when factors other than topographic disturbance remained constant. This comparison of these two experimental runs indicates that the initial topographic defect greatly affected the propagation speed and the shape of ripples. The observation showed that the

Fig. 4. The relationship between the Ursell number, U, and the mobility number, M, for ripple initiation in: the flat-bed experiment (a), the notched-bed experiment (b), and the notch-mounded bed experiment (c). The solid line in each graph denotes the threshold for rippling. It is found that, with increasing topographic disturbances [(a) to (c)], the threshold value decreases and becomes independent of flow asymmetry.


(a)
M
U
0
5
10
15
20
25
30
0
50
100
150
200
250
M = 17 – 14.5 e^−0.03 U
Ripple Formation
○ This study
● Sunamura (1981)
No Ripple Formation
+ This study
× Sunamura (1981)
(b)
M
U
0
5
10
15
20
0
50
100
150
200
250
○ Ripple Formation
+ No Ripple Formation
M = 5.0 – 2.5 e^−0.1 U
(c)
M
U
0
5
10
15
0
50
100
150
200
250
○ Ripple Formation
+ No Ripple Formation
M = 2.5

initial mound located onshore of the notch (Fig. 3b) caused flow separation which resulted in the generation of a marked vortex at the passage of wave crest. The vortex excavated a ditch (arrow A) and simultaneously a small hump started to form (arrow B) due to the deposition of sand grains carried onshore, above the vortex in the mode of saltation from the offshore area near the initial mound. The hump grew with time to facilitate vortex generation on its onshore side and a second hump again started to develop further onshore; thus, successive onshore ripple-development took place. A similar process was observed in the ripple development on the notched bed (Fig. 3a).

Another pair of examples of such a topographic effect is illustrated in Fig. 3c and d. Under the same flow energy and asymmetry, no ripple formation occurred on the notched bed, while onshore ripple-growth took place on the notch-mounded bed. Fig. 3e and f shows, respectively, the results of two runs (notched-bed case) with different U-values but similar M-values.

It is found that ripples almost symmetrically spread onshore and offshore from the disturbance when U had a smaller value (Fig. 3e), while ripples propagated asymmetrically with higher onshore speed when U was larger (Fig. 3f). For the case of much larger U-values, even if M takes on smaller values, onshore propagation dominated as shown in Fig. 3a, b, and d. The dependency of the mode of propagation on U-values was observed regardless of grain sizes and bed disturbances. It should be stated that ripple inception started simultaneously all over the bed irrespective of the presence of a topographic disturbance, when bottom velocity was considerably larger than the threshold.

The critical conditions for ripple formation on the three types of sand beds were examined using M and U (Fig. 4). Fig. 4a, with Sunamura's (1981) laboratory data being plotted to supplement data of the flat-bed experiment, shows that there is a tendency for the threshold M-value for rippling to initially increase with increasing U, and then attain a constant value for further increases in U. A similar tendency is also found in the results of the notched-bed experiment (Fig. 4b), but not in the notch-mounded-bed experiment (Fig. 4c). The curve in Fig. 4a is drawn through considerably scattered data points showing "ripple formation" or "no ripple formation" to reasonably demarcate the two domains, and may be expressed in the following equation:

$$M = 17 - 14.5e^{-0.03U} \tag{5}$$

A demarcating curve in Fig. 4b, plotted applying the same functional form as Eq. (5), is described as:

$$M = 5.0 - 2.5e^{-0.1U} \tag{6}$$

For the notch-mounded-bed experiment (Fig. 4c), the threshold seems to be independent of U. A line parallel with the x-axis would be reasonable:

$$M = 2.5 \tag{7}$$

Fig. 4a–c indicates that there is a systematic variation in the threshold, i.e., the M-value decreases with increasing bed disturbance for a given degree of wave asymmetry.

4. Discussion

Difficulties were involved in the construction of a perfectly smooth sand-bottom in the flat-bed experiment: there inevitably resided slight undulations, which may trigger the occurrence of vortices possibly leading to ripple generation in some experimental runs, or may be smoothed out by wave action leaving a flat bed without rippling in other runs. Such slight irregularities are reflected in the presence of the wide scatter of the data points in the flat-bed experiment (Fig. 4a), compared with the results of the other two tests (Fig. 4b and c).

A comparison between the curves in Fig. 4a–c indicates that the threshold values in the roughened-bed experiments (Fig. 4b and c) are much smaller than those in the flat-bed test (Fig. 4a). Such reduction in the threshold has already been stated by Bagnold (1946), Carstens and Neilson (1967), Carstens et al. (1969), Komar and Miller (1975), Lofquist (1978), and Allen (1982, p. 442), although no generalized relations have been presented in these studies. As the degree of bed perturbation increases (from Fig. 4a–c), the threshold decreases accordingly; and its dependency on the asymmetry of flow velocity becomes less notable and finally null for the notch-mounded bed. This indicates that increasing topographic disturbances tend to diminish the influence of velocity asymmetry on ripple initiation. The experiment of the notch-mounded bed that has simple two-dimensional undulations as a disturbance (Fig. 2b) exhibits the lowest threshold (Fig. 4c). A more complicated initial boundary condition, such as a fully developed ripple bed that gives a larger stress field, would bring about further lowering in the threshold value, which is possibly independent of flow asymmetry.

Data of water tunnel experiments by Carstens et al. (1969) enabled us to calculate the threshold condition on a flat bed under purely oscillatory flows; the result is $M = 11.8$. Assuming that such flow conditions can be represented by $U = 0$, $M = 2.5$ for the present flat-bed experiment from Eq. (5). The difference in M-values between the two studies may be ascribed to the difference in criteria for ripple inception: spontaneous occurrence in Carstens et al. (1969) and sporadic appearance in this study. The former requires higher velocity, resulting in larger M-values. Using another data set of Carstens et al. (1969), we calculated the threshold for their roughened-bed test in which a semi-circular rod (about 1.3 cm high) was placed on a sand bed across the flow, the result being $M = 2.2$. Brebner (1980) found $M = 3$ from his test using a roughened bed with a sand mound 1 cm high across an oscillating water tunnel. A comparison of these values with those from the present study, i.e., $M = 2.5$, shows that they are in fairly good agreement.

Fig. 5 is plotted using available field data of Inman (1957), Tanner (1971), Dingler (1975), Miller and Komar (1980b), and Boyd et al. (1988). Data of Marsh et al. (1999) using a large wave flume (100 m long, 2 m wide, and 3 m deep) are also plotted for reference. Since any field data showing "no ripple formation" have not been available, it is reasonable to assume that the threshold condition for rippling can be represented by the lower limit of the cluster of the data points. It is found that the threshold from the present test of the notch-mounded bed, $M = 2.5$, seems to provide the critical condition when $U > 10$. The determination of the definite threshold requires data of "no ripple occurrence". When $U < 10$, some data are plotted in the area below the line of $M = 2.5$; this means that very small bottom velocities are sufficient

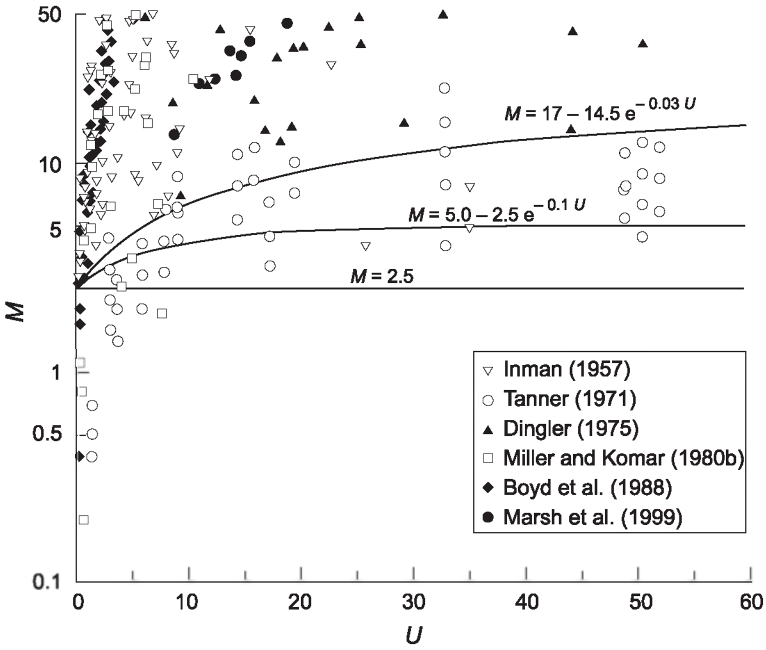


Fig. 5. The comparison between the previous ripple data in the field and the threshold conditions obtained in this study. The threshold from the test of the notch-mounded bed, $M = 2.5$, shows a reasonable agreement with the field data except for $U \leq 10$.

to produce ripples when velocity field is more symmetrical. Such ripple formation is difficult to envisage in a physical sense. A possible explanation for the presence of these field data is that the observed ripples were relicts, which were formed by earlier and larger waves, or that they were produced only by high velocity flows, occasionally occurring due to broad spectra of waves in nature (e.g., Manohar, 1955; Komar and Miller, 1975). In either case, the observed wave height, and in most cases wavelength (or period) also, would be smaller than the properties of waves that actually generated the ripples, resulting in lowering the values for M and U. Such data would tend to fall in the lower left area of Fig. 5.

5. Conclusion

The threshold conditions for ripple initiation by asymmetrical flows on roughened beds have been examined through wave-flume experiments using three types of sand beds: flat, notched, and notch-mounded beds. Data were analyzed using the mobility number and the Ursell number. The result showed that the threshold conditions on the three beds are described by Eqs. (5)–(7). It was found that bed perturbation lowers the threshold of ripple initiation and that the increase in bed perturbation also decreases the influence of velocity asymmetry on ripple initiation. A comparison between field data and the laboratory result indicates that $M = 2.5$ provides a possible critical condition for rippling in the natural environments.

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