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Threshold for Ripple Formation on Artificially Roughened Beds: Wave-Flume Experiments

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ABSTRACT

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The lack of systematic studies of the influence of bottom irregularities on ripple initiation led to a series of wave-flume experiments with the purpose of exploring a general relationship. Three types of sand beds with different degrees of roughness were prepared for the experiments: flat, notched, notch-mounded beds. Three kinds of well-sorted sands with different diameters were used for the bed material: fine, medium, and coarse sands. With combinations of waves, water depth, sand, and bed roughness, 248 experimental runs were carried out. Data were analyzed considering (1) the mobility of sediment, expressed in terms of the mobility number, M, (2) the degree of bed roughness, represented by the Reynolds number, Re, and (3) the asymmetry of flow field due to nonlinearity of waves, represented by the relative water depth, kh ($= 2\pi h/L$; h = water depth and L = wavelength). The result showed that the threshold for rippling is described by $M = 2 + A \exp B$, where $A = 5.7\ (3.79/(kh + 0.65) - 1)$ and $B = -8 \times 10^{-4}\ Re$. It was found that the threshold decreases with increase in bed roughness and attains constant value with further increased bed roughness. The threshold also decreases as the flow field becomes more symmetric. Comparison between available field data and the present findings shows that the threshold on a well-roughened bed, $M = 2$, defines the critical condition for ripple formation in the natural environment.

ADDITIONAL INDEX WORDS: *Wave ripples, initiation, threshold, bed disturbance, asymmetrical oscillatory flow.*

INTRODUCTION

Wave-formed ripple marks appear on the sea floor of the contemporary nearshore environment, and ancient ripples are frequently observed in geological records. An extensive literature has dealt with multiple aspects associated with ripple marks (ALLEN, 1982, pp. 422–454). These include studies on the initiation and disappearance of ripples, modeling of mechanisms of their formation, investigations on relations of their geometries to hydraulic conditions and sediment characteristics, analyses of their internal sedimentary structures, and reconstructions of paleo-hydraulic conditions from ancient ripples. Of these research topics, ripple initiation has been intensively studied in the laboratory environment. The laboratory studies were conducted applying various experimental facilities such as: an oscillating-bed apparatus (BAGNOLD, 1946; MANOHAR, 1955; SLEATH, 1976), an oscillatory water tunnel (CARSTENS and NEILSON, 1967; CARSTENS *et al.,* 1969; LOFQUIST, 1978), a wave flume (DINGLER, 1975; MILLER and KOMAR, 1980a; SUNAMURA, 1980, 1981; FARACI and FOTI, 2001), and an oscillatory annular cell (SCHERER *et al.,* 1999; STEGNER and WESFREID, 1999). All these studies treated ripple incipience from a smooth flat bed. Theoretical studies have also been attempted by BLONDEAUX (1990) and FOTI and BLONDEAUX (1995a, 1995b). One of the problems involved in application of these results to the field situation is that the initial boundary condition for these studies was a flat bed. In contrast, the seabed in the real world usually has multiple topographic disturbances prior to ripple initiation.

Part of the laboratory studies by BAGNOLD (1946), CARSTENS *et al.* (1969), LOFQUIST (1978), NIELSEN (1979), BREBNER (1980) and SLEATH (1984) dealt with ripple generation from a roughened bed. Bed irregularities set up in these studies were created as a small mound of sand (BAGNOLD, 1946; NIELSEN, 1979; BREBNER, 1980), relict ripples (LOFQUIST, 1978), and foreign objects such as a half-round bar (CARSTENS and NEILSON, 1967; CARSTENS *et al.,* 1969) and a thin vertical wall (SLEATH, 1984).

BAGNOLD (1946), CARSTENS and NEILSON (1967), CARSTENS *et al.* (1969), KOMAR and MILLER (1975), LOFQUIST (1978), NIELSEN (1979), and ALLEN (1982, p. 442) stated that ripples can initiate from irregularities on the bed under flow conditions with velocity even below the threshold for grain movement on a smoothed-out or flat surface. SLEATH (1984) stated that ripples did not always spread from a foreign object on the bed, even if the fluid velocity was sufficient to cause general movement of the sediment. No systematic studies have been performed to address the influence of bottom irregularities on ripple initiation.

The purpose of the present laboratory study is to explore the influence of bottom irregularity on ripple formation and to present a generalized relationship for predicting the threshold of ripple formation. A series of wave-flume experiments was performed with three kinds of sand beds, each

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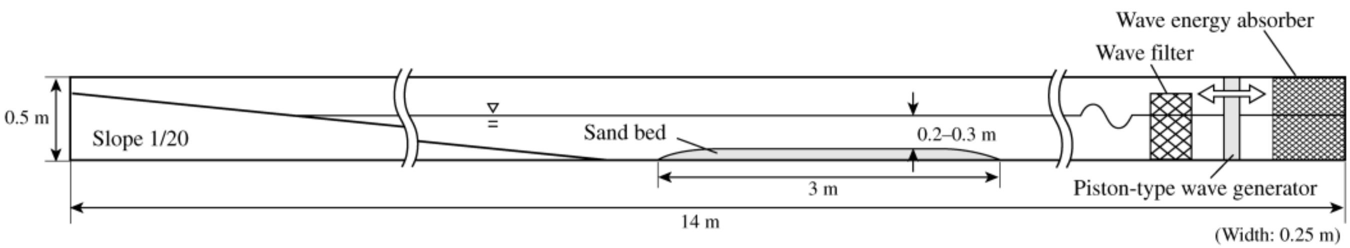

Figure 1. Wave flume used in this study. A sand bed was constructed in the horizontal portion of the flume.

having different roughness. Well-sorted fine, medium, and coarse sands were used for the bed material. Data were analyzed considering (1) the mobility of sediments, (2) the degree of bed roughness, and (3) the asymmetry of near-bottom flow velocity. The result is extended to the full-scale environment using available field data.

PHYSICAL BASIS

Linear wave theory (*e.g.,* Eagleson and Dean, 1966; Dean and Dalrymple, 1992; Komar, 1998) shows that the pattern of water particle motion alters as waves approach to the shore, which can be described with the value of the following parameter:

$$kh = 2\pi h/L \tag{1}$$

where k is wave number ($= 2\pi/L$), L is the wavelength, and h is the water depth. If $kh \geq \pi$, commonly called the "deep water" condition, a water particle moves in a circular orbit with the diameter decreasing exponentially with water depth, and no particle motion is extended to the sea bottom. If $\pi/10 \leq kh < \pi$, *i.e.,* the "intermediate-depth water" condition, a water particle moves in elliptical orbits with both the major horizontal and the minor vertical axes decreasing with water depth. The minor axis becomes zero at the bottom, but the major axis does not. If $kh < \pi/10$, *i.e.,* the "shallow water" condition, a water particle moves also in elliptical orbits with the major axis being constant from the surface to the bottom but the minor axis decreasing to zero at the bottom. It should be noted that the to-and-fro water particle motion takes place on the bottom for intermediate and shallow water waves.

In the field, the to-and-fro particle motion on the bottom is not purely oscillatory, but skewed. The asymmetry causes a larger onshore velocity of shorter duration under wave crests, and a smaller offshore velocity of longer duration under troughs. The asymmetric velocity field becomes more marked as waves enter shallower water, *i.e.,* as the value of kh decreases. Such a velocity asymmetry characterizes the shallow marine environment where ripple marks are well developed. Ripple studies, therefore, should be discussed with an appropriate parameter that can represent the asymmetric flow field.

Sunamura (1980, 1981) and Montzouris (1990) used in their ripple studies the Ursell number (Ursell, 1953) as a parameter for representing the degree of flow asymmetry. A preliminary test was conducted to examine the relationship between flow asymmetry and the speed of ripple propagation from a perturbation on a sand bed. The result indicated that the parameter kh is preferable to the Ursell number in analyzing data. The present study will employ kh.

To-and-fro water flow near the sea bottom induces a bed shear stress. The Shields number that describes the relative magnitude of shear stress to the resisting force against the motion of sand grains has been widely applied in previous studies (*e.g.,* Nielsen, 1979; Grant and Madsen, 1982; Vincent and Osborne, 1993; Hansen *et al.,* 1994; Black and Oldman, 1999; Doucette, 2000; Crawford and Hay, 2001; Hanes *et al.,* 2001). The mobility number, the simplified form of the Shields number, has also been extensively employed for many ripple studies: Carstens and Neilson (1967), Carstens *et al.* (1969), Dingler (1975), Dingler and Inman (1976), Komar and Miller (1975), Lofquist (1978), Nielsen (1979, 1981), Brebner (1980), Boyd *et al.* (1988), Blondeaux (1990), Vittori and Blondeaux (1990), Vincent and Osborne (1993), Ribberink and Al-Salem (1994), Foti and Blondeaux (1995a, 1995b), Doucette (2000), Faraci and Foti (2001), and Hanes *et al.* (2001). Although this parameter does not include frictional effects, it has an advantage of ease in calculation, so it was adopted in this study. The mobility number, $M,$ is described by:

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

where u_b is the near-bottom maximum flow velocity, D is the sediment grain size, and ρ_s and ρ are the densities of sediment grains and water, respectively, and g is the acceleration due to gravity. According to linear wave theory, u_b, is given by:

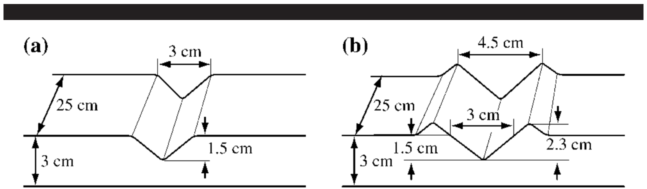

Figure 2. Two types of topographic disturbances used in the roughened-bed experiments: a notch (a), and a notch and two mounds (b), both located in the central portion of the sand bed.

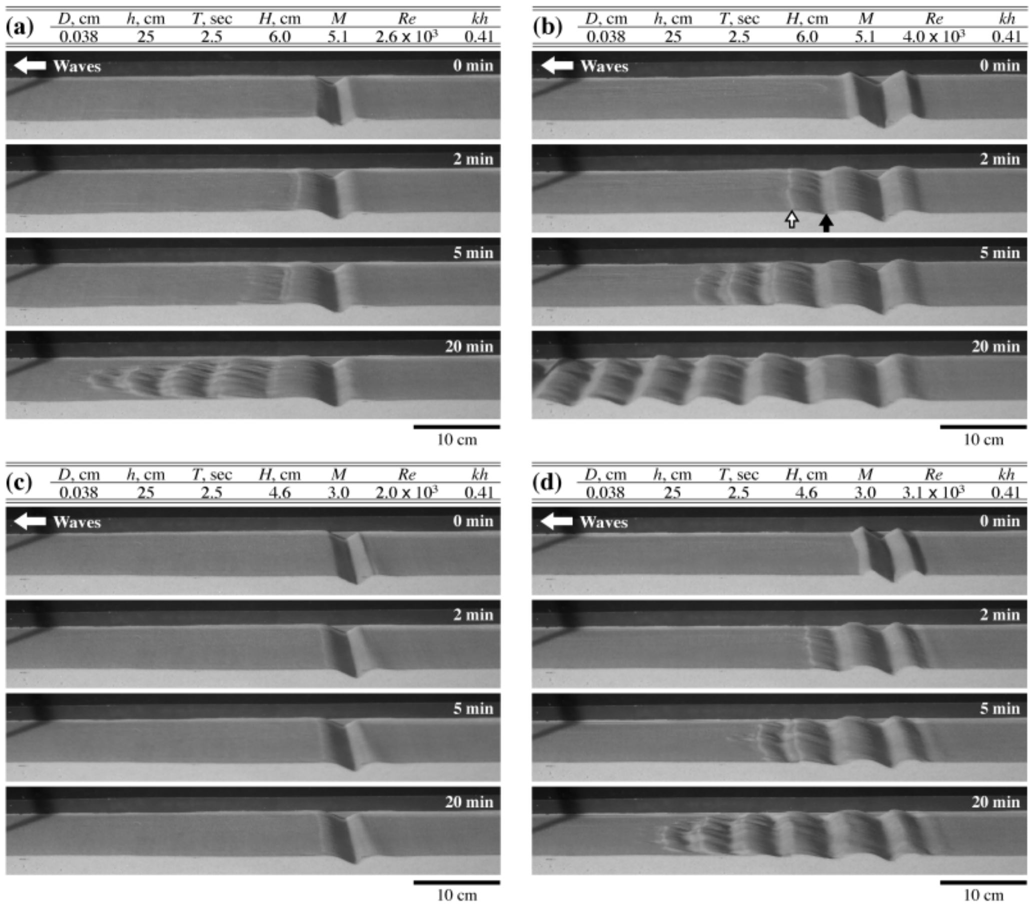

Figure 3. Photographs of the ripple formation in the notched-bed (a, c) and the notch-mounded-bed (b, d) experiments, illustrating the influence of bed roughness. Two pairs of photographs (a, b) and (c, d) respectively show the ripple development under conditions of different wave height, $H = 6.0$ cm and 4.6 cm, but of the other parameters constant. Waves propagate from right to left.

$$u_b = \pi H/(T \sinh kh) \tag{3}$$

where H is the wave height, and T is the wave period.

It is easily anticipated that turbulent flows over the sand bottom are more favorable for ripple incipience compared with laminar flows when the values of M are the same. Such flow characteristics are closely associated with the size of a topographic disturbance on the bottom surface. Studies on ripple initiation require consideration of such flow characteristics, which will be determined by the value of the Reynolds number expressed by:

$$Re = u_b h_m/\nu \tag{4}$$

where h_m is the height of disturbances on the bottom, and ν is the kinematic viscosity of water. If the bottom is flat and smooth, h_m should be replaced by D:

$$Re = u_b D/\nu \tag{5}$$

which is often called the particle Reynolds number (*e.g.,* NIELSEN, 1992, p.165). BLONDEAUX (1990), VITTORI and BLONDEAUX (1990), FOTI and BLONDEAUX (1995a, 1995b), and FARACI and FOTI (2001) have employed this type of Reynolds number to discuss conditions for ripple formation from a flat bed.

LABORATORY EXPERIMENTS

The wave flume used here was 14 m long, 25 cm wide, and 50 cm deep (Figure 1). A piston-type wave generator was equipped at one end of the flume, and a fixed slope of 1/20 was installed at the other end. A layer of cobble (several centimeters across) was placed on the slope to decrease energy of waves reflected from the slope and directed offshore. A wave filter was also set up in front of the wave generator to hinder reflected waves from reaching the generator. A sand bed (3 m long, 25 cm wide, and 3 cm deep) was constructed in a horizontal portion of the flume; both ends of the bed were tapered off to reduce the local perturbation of oscillatory flows. Three types of sand beds with different roughness were prepared: (1) a horizontal flat bed with $h_m = D$, here referred to as "the flat bed," (2) a bed with a notch with $h_m = 1.5$ cm (Figure 2a), described as "the notched bed," and (3) a bed with a notch and two mounds with $h_m = 2.3$ cm (Figure 2b), called "the notch-mounded bed," with the bed roughness increasing

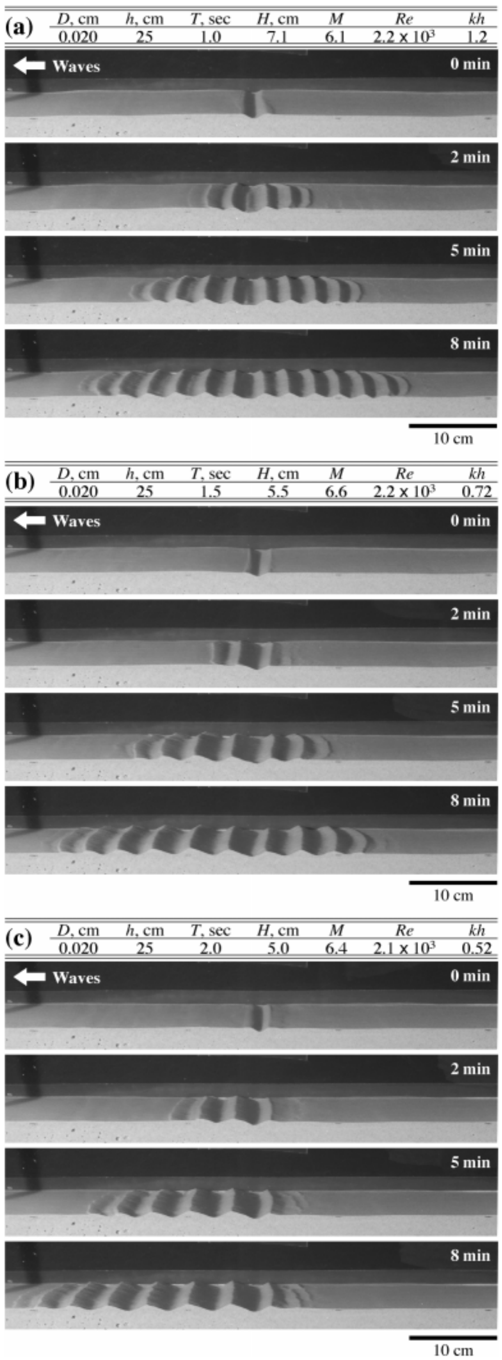

Figure 4. Modes of ripple propagation depending on the degree of flow asymmetry observed in the notched-bed experiment. Waves advance from right to left.

in this order. Three kinds of well-sorted quartz sands were employed for the bed material. The sands have the same density, $\rho_s = 2.65$ g/cm^3, but different diameter, $D = 0.021$, 0.038, and 0.054 cm. TRASK's (1932) sorting coefficient (*e.g.,* SENGPTA, 1978) of these materials fell in a range from 1.08 to 1.12. Water depth above a horizontal portion of the sand bed (h = 20–30 cm) was kept constant through each experimental run. Wave period T ranged from 1.0 to 3.5 sec, and wave height H (measured at the horizontal portion of the sand bed) from 1.7 to 13.0 cm. By combining these experimental parameters, approximately 248 runs were carried out. Each run had 30 min of wave action. Ripple formation was recorded using a digital video camera, and photographs were taken at a certain interval of time.

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 suggested that an influence of reflected waves on ripple initiation was small, so that this influence could be ignored in this study.

No ripple formation took place unless incipient ripples appeared in the first five minutes irrespective of the type 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 to the sporadic ripple initiation on the flat bed, ripple formation in the roughened-bed experiment started from the notched or mounded portion of the bed, as illustrated in Figures 3 and 4.

On the notch-mounded bed (Figure 3b), ripple inception took place more rapidly and, subsequently, developing ripples were more corrugated than on the notched bed (Figure 3a), when factors other than a topographic disturbance remained the same. Observations showed that the initial mound located onshore of the notch (Figure 3b) caused flow separation working as an obstacle, resulting in the generation of a marked vortex over the onshore side of the obstacle at the passage of wave crests. The vortex excavated a ditch (black arrow) and simultaneously a small hump of sand started to form (white arrow) due to the deposition of sand grains carried onshore, over the vortex in the mode of saltation from the offshore area near the initial mound. The hump grew with time to facilitate vortex generation at its onshore side and a new hump 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 (Figure 3a). Comparison of these two runs indicates that the initial topographic defect much affects the propagating speed and the shape of ripples. Another pair of examples is shown in Figures 3c and 3d: no ripple formation occurred on the notched bed (Figure 3c), whereas onshore ripple-growth took place on the notch-mounded bed (Figure 3d).

Figures 4a, 4b, and 4c show respectively the results of three runs (all, notched-bed case) with different values of *kh,* but similar values of M and Re to illustrate how the *kh*-value influences the mode of ripple propagation. If *kh* had a larger value (kh = 1.2), ripples started to symmetrically develop onshore and offshore from the disturbance (Figure 4a). At a very initial stage, a hump was simultaneously formed on each side of the notch. A vortex developed on the onshore side of the onshore hump immediately after the wave crest passed over the notch, and another vortex was generated on the off-

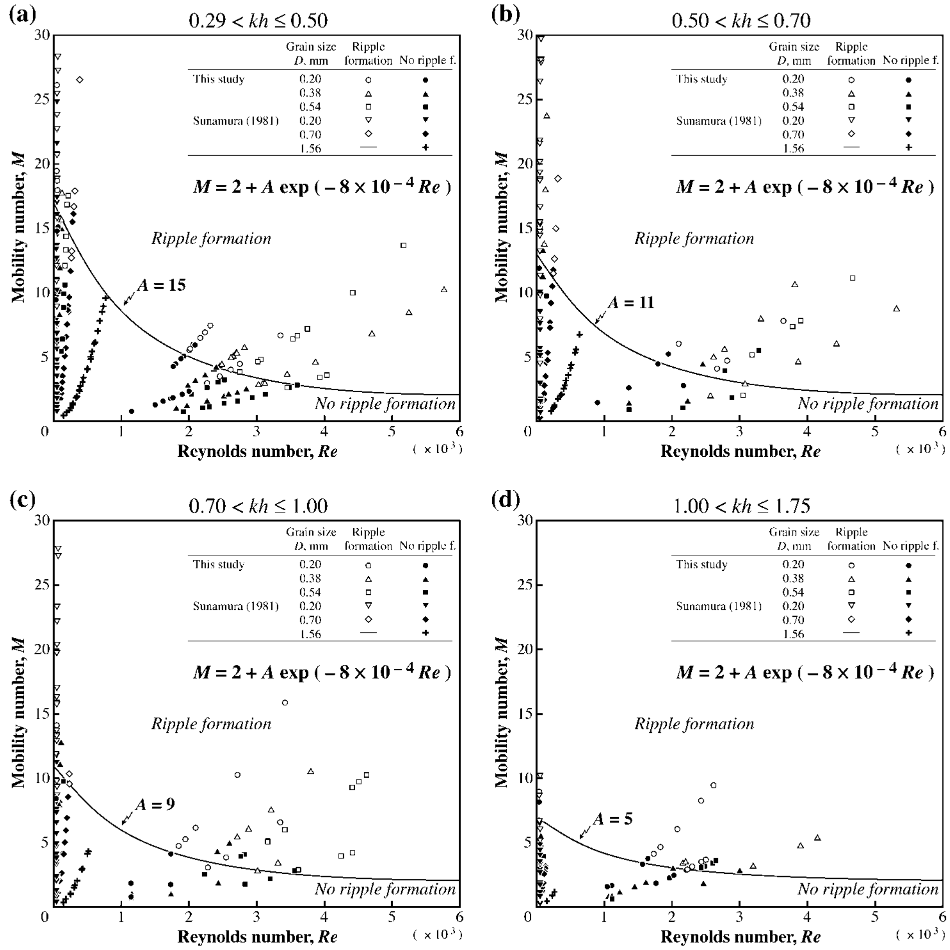

Figure 5. Relationship between the Reynolds number, *Re,* and the mobility number, *M,* for ripple initiation with different ranges of the relative water depth, *kh.* The solid curve in each graph denotes the threshold for rippling.

shore side of the offshore hump when the wave trough passed. Alternating occurrence of the two vortexes with similar intensities was closely associated with symmetry of the bottom velocity field, resulting in symmetrical propagation of ripples with an almost equivalent speed. As the value of kh decreased, $kh = 0.72$, a vortex that formed on the offshore side by offshore flows became less significant to cause the delay in offshore ripple-development (Figure 4b). For further decrease in kh-values, $kh = 0.52$, ripples developed with a much asymmetric mode as shown in Figure 4c.

Almost simultaneously, ripples started to appear all over the bed irrespective of the presence or absence of topographic disturbances, if bottom velocity was considerably larger than the threshold. Values of M for such ripple initiation were found to be larger than approximately 15 in the present experiment.

Data of ripple formation were plotted on an M–Re plane for four ranges of kh-values (Figures 5a–5d). SUNAMURA's (1981) laboratory data of ripple initiation on a flat bed were also used to supplement data with lower values of Re. The existing wave-flume data, except those of SUNAMURA (1981), were unavailable because they lacked information on the "no ripple formation" condition. Figure 5a shows that there is a tendency for the threshold M-value for rippling to decrease with increasing Re, and attains a constant value for further increase in Re, $M = 2$. A similar tendency is also found in Figures 5b–5d. In order to formulate this tendency, the following exponential decay function is employed:

$$M = 2 + A \exp(-8 \times 10^{-4} Re) \qquad (6)$$

where A is a coefficient. With A determined to reasonably demarcate two areas of "ripple formation" and "no ripple formation," a curve is drawn in Figures 5a–5d. It is found that the value of A described by the curve decreases with increasing values of kh. This relation is plotted in Figure 6. The best-fit curve by a hyperbola satisfying $A = 0$ at $kh = \pi$ to the data points gives:

$$A = 5.7\left(\frac{3.79}{kh + 0.65} - 1\right) \qquad (7)$$

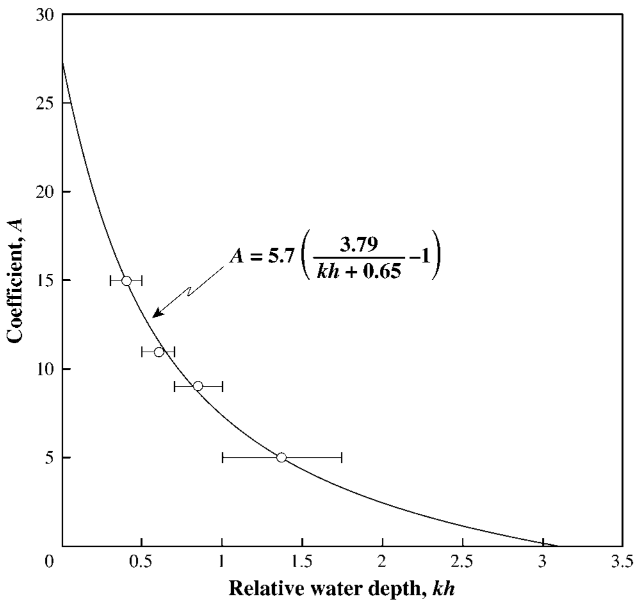

Figure 6. Relationship between coefficient, *A,* in equation (6) and relative water depth, *kh*.

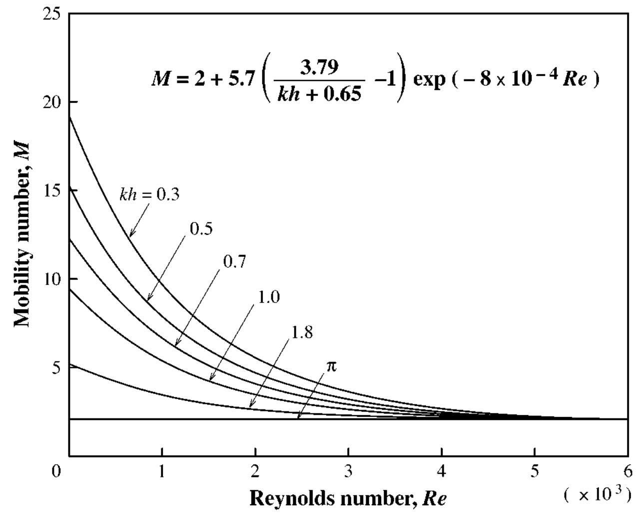

Figure 7. Threshold curves plotted in the *Re–M* plane for selected values of *kh*.

DISCUSSION

Difficulties were encountered in construction of a perfectly smooth sand-bottom in the flat-bed experiment. Slight undulations always remained, which may have triggered the formation of vortices resulting in ripple generation in some experimental runs, or may have been smoothed out by wave action leaving a flat bed without rippling in other runs. The presence of such slight irregularities is probably made apparent in the presence of a considerably intricate zone of data scatter for $0 < Re < 300$ (Figure 5).

Figure 4 well illustrates that significant onshore development of ripples takes place as *kh* decreases. This strongly suggests that the value of *kh* can represent the degree of asymmetry of a bottom velocity field: onshore stronger but offshore weaker flows become more dominant with decreasing *kh*-values. For some selected values of *kh,* the dependency of the threshold *M*-value on *Re* is plotted in Figure 7 by use of equations (6) and (7). Ripples tend to initiate with lower *M*-values as *Re*-values increase, *i.e.,* as a topographic disturbance augments. This tendency becomes less marked with increasing *kh*-values, *i.e.,* as flow field becomes more symmetric. Finally, *M* takes on a constant value, $M = 2$, independent of *Re.* This indicates that increasing bottom roughness diminishes the influence of velocity asymmetry on ripple initiation, and that the influence of bed roughness on ripple formation tends to decrease as the flow field becomes more symmetric. Using data of water tunnel experiments by 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 across purely oscillatory flows, the result being $M = 2.2$. BREBNER (1980) found $M = 3$ from data of roughened-bed experiments with a sand mound 1 cm high placed across an oscillatory water tunnel. These values are in fairly good agreement with the result of this study, $M = 2$.

Figure 8 shows the relationship between *M* and *kh,* plotted using available field data (INMAN, 1957; TANNER, 1971; DINGLER, 1975; MILLER and KOMAR, 1980b; BOYD *et al.,* 1988; DOUCETTE, 2000), plus data of a prototype-scale experiment by MARSH *et al.* (1999) using a large wave flume (100 m long, 2 m wide, and 3 m deep). Because no data employed here provided information on the initial topographic condition, cal-

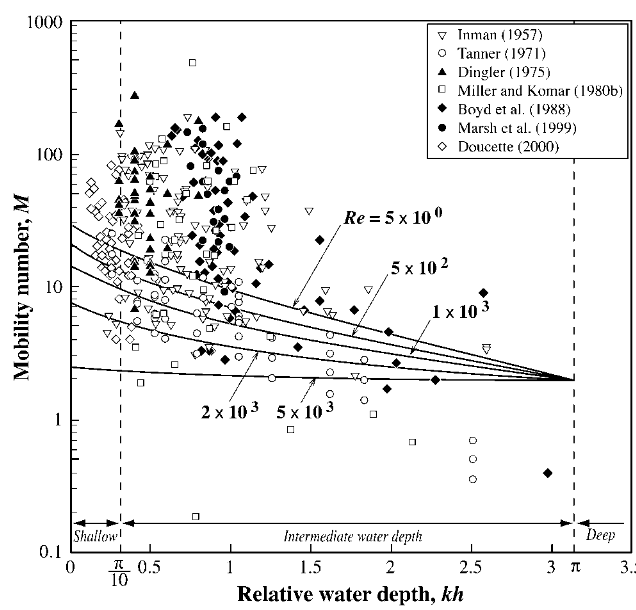

Figure 8. Comparison between the previous ripple data in the field and the threshold conditions obtained in this study.

culations of Re-values were not possible. Note that no data are available for plotting in the area of "deep water depth," or $kh \geq \pi$, where waves do not exert motion of water particles near the bottom. A family of threshold curves from the present study [equations (6) and (7)] is plotted for different values of Re ($5 \leq Re \leq 5{,}000$). The minimum value, $Re = 5$, is obtained based on INMAN's (1957) data with $u_b = 6.1$ cm/sec and $D = 0.008$ cm, assuming that ripples had formed from a flat bed, and the maximum, $Re = 5{,}000$, gives a critical value beyond which the threshold M-value becomes constant, $M = 2$. The two curves of $Re = 5$ and $Re = 5{,}000$, respectively, demarcate the M–kh diagram into three areas: (1) the area above the curve of $Re = 5$ indicates that ripples are always formed regardless of the degree of bed roughness, (2) the area below the curve of $Re = 5{,}000$ shows that no ripples are formed, and (3) the area between the two curves implies that ripple development is associated with irregularities of the bottom surface.

Major factors that are thought to influence the threshold for rippling in the natural environment are not only the irregularity of the bed but also high velocity flows, occasionally occurring due to broad spectra of waves (MANOHAR, 1955; KOMAR and MILLER, 1975) and heterogeneous sediment texture with different diameters (MANOHAR, 1955; FOTI and BLONDEAUX, 1995b). Initiation of active ripples observed in the field would probably associated with one of these factors or a mixture of them. Relict ripples are occasionally present, which were formed by earlier and larger waves (KOMAR and MILLER, 1975; LOFQUIST, 1978). Some of the previous field data must have included relict ripples and/or ripples formed by episodically occurring high waves. Such data lead to underestimated M-values compared with those obtained when ripples were actually formed, so that plots of the data tend to shift to the lower part of Figure 8. In spite of the presence of such a tendency, it is interesting to find in this figure that most of data points fall in the area above the line of $Re = 5{,}000$, *i.e.,* $M = 2$, the smallest of threshold values for ripple incipience. A considerable amount of data lie in the area above the curve of $Re = 5$. This means that most of the existing field data were collected from the environment in which flow velocity had been so high that ripples were formed irrespective of topographic disturbances on the sea bottom.

CONCLUSIONS

Threshold conditions for ripple formation on roughened beds were examined through a wave-flume experiment using three types of a sand bed with different degrees of roughness: flat, notched, and notch-mounded beds. Data were analyzed considering the mobility of sediments, the degree of bed roughness and the asymmetry of near-bed flow velocity. The result showed that the threshold for rippling is described by equations (6) and (7). The threshold decreases not only with the increase in roughness of the bed, but also with the decrease in asymmetry of flow velocity. For further increase in bed roughness and/or decrease in flow asymmetry, the threshold becomes constant, $M = 2$. It was also found that the increase in bed roughness tends to reduce the influence of velocity asymmetry on ripple initiation, and that the influence of bed roughness on ripple generation becomes less notable as the flow field becomes more symmetric. Comparison between the present laboratory results and available field data indicates that (1) $M = 2$ provides a possible critical condition for rippling in the natural environment, and (2) much of the field data was obtained from the nearshore environment where flow velocity had been sufficient for ripple formation regardless of the existence of bottom irregularities.

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