Research Article

MEASUREMENT AND PREDICTION OF WAVE-GENERATED RIPPLES

*Daghigh H.¹, Karami Khaniki A.² and Bidokhti A.A.³

¹Department of Marine Science and Technology, Tehran Science and Research Branch, Islamic Azad University (IAU), Tehran, Iran ²Department of Soil Conservation and Watershed Management, Research Institute (SCWMRI), Tehran, Iran ³Institute of Geophysics, University of Tehran, P.O. Box 14155-6466, Tehran, Iran *Author for Correspondence

ABSTRACT

Laboratory experiments using a wave flume were designed to examine the characteristics of ripple formed on a sandy bed. Our experiments of wave ripple were made in a flume at the Soil Conservation and Watershed Management Research Institute (SCWMRI), Iran. The flume has 20m length, 5.5m width and 2m height and the bed was constructed with 0.2mm diameter sand in a part of flume with 1m width. Water depth above the sand bed (20cm) was kept constant through each experimental run. Our experiments were carried out in the middle part of the flume (test section) with about 1m width and 10 m length. Ripples were formed on the sediment surface under a variety of surface wave conditions for different periods. Profile measurements were taken all over the flume for each wave conditions. Data collected by the sand ripple profiler after these experiments are presented, showing the sand ripple profiles under variety of wave conditions. Results showed that ripple height increased with orbital excursion for wave generated ripples. For better comparison, experimental data were compared with empirical relations of Nielsen (1981) and other previous field data. The results showed good agreement among the findings of these runs with others. Also the experimental results in this work are more in agreement with the field empirical results.

Keywords: Bed Form, Experimental Model, Ripple, Sand Beach, Waves

INTRODUCTION

Bed ripples have many impacts on the environment. Their length scales range from millimeters to meters, depending on the flow and sediment environment, affecting small-scale sediment transport to large-scale beach erosion. Even after much published research dating back as far as 1882 on ripples and the sediment transport over them, a better understanding of the dynamics of ripple development and the feedback between fluid-sediment interactions is still needed. Ripples are influential because they affect the nearbed turbulence and the boundary layer structure of the flow. The geometric properties and morphologic behaviors of sand ripples can significantly impact sediment transport, bottom friction, and the acoustical properties of the seabed.

We have setup an experimental rig for physical modeling of ripple formation in a laboratory flume. The model allows for the prediction of ripple morphology.

The model presented produces ripples similar to those seen in nature and allows for the examination of the ripple formation mechanisms. The properties that can be analyzed include the ripple height, length, and shape.

Three of the most common types of bed forms are dunes, mega ripples (or anti-dunes), and ripples. Dunes are irregular sand waves formed under the current action (i.e., in natural streams). They are generally triangular in shape with a mildly sloped upstream surface and a downstream slope approximately equal to the angle of repose. The flow over them separates at the crest and reattaches in the trough as they migrate downstream (Fredsøe and Deigaard, 1992). A mega ripple or anti-dune, is a large, round-crested, unstable ripple with a wavelength ranging from 1.0m to 10m, and a height from 0.1m to 1.0m. Their scales of evolution range from hours to days. Unlike dunes, anti-dunes can move upstream, with sand accumulating on the upstream face and eroding on the downstream slope. They form under energetic oscillatory flows and have irregular vortex shedding and unpredictable migration.

Research Article

Ripples are the most common bed forms and are the focus of this research. Ripples form in many different environments and have a variety of characteristics. The bed form type depends on the strength and nature of the flow. A steady current, tidal current, waves, or a combination of all three will influence the size, shape, and orientation of the bed forms. The nonlinear complexities of the flow present challenges in predicting ripples, and much research has been done examining bed forms under different flow regimes (e.g., Bagnolds, 1946; Sleath, 1984; Wiberg and Harris, 1994; Nielsen, 1992).

Ripples wavelengths (λ) and heights (η) vary from 0.1m to 1.0m, and 0.01m to 0.1m, respectively.

Their timescales of evolution can range from seconds to hours. Ripples can be wave- or currentgenerated, or a combination of both. Bagnold (1946) classified wave-generated ripples into two groups: rolling-grain ripples and vortex ripples. Rolling-grain ripples form first on an initially flat bed under low wave action. They are generally formed by oscillating waves creating a circular streamline path of flow. The orbital motion tends to push sediment up from a low to a high point on the bed. As the rolling-grain ripples grow, their height causes the boundary layer flow to separate behind the crest of the ripple and vortices are formed. The rolling-grain ripples are now transitioning into vortex ripples. Vortices carry sediment from the trough of the ripple up to the crest. Vortex ripples are usually two-dimensional and can be caused either by rolling-grain ripples already present or an obstruction on the sea floor such as a rock or shell. They can migrate slowly due to wave asymmetry, but not to the degree of current-generated ripples (Hanes *et al.*, 2001).

Current-generated ripples exist in rivers, estuaries, and the sea. They generally have a gentle upstream slope and a steep lee slope. The ripples migrate slowly downstream and can respond quickly to changes in the current strength and direction. They are usually three-dimensional with irregular geometries.

Ripples generated from both waves and currents have a combination of the properties mentioned above. The strength and the relative angle between the waves and current influence the ripple characteristics. If the direction of the waves and currents are parallel, the ripple pattern is mainly two-dimensional. When the wave and current directions are perpendicular or a large angle apart, the ripple pattern is primarily three-dimensional (Nielsen, 1992; Sleath, 1984).

There are two more classifications within the wave-generated ripple category: orbital and anorbital. Orbital ripples have wavelengths proportional to the near-bed wave orbital diameter and heights greater than the wave boundary layer thickness. Ripples in a more energetic wave environment can have wavelengths independent of the wave orbital diameter and instead are proportional to the grain-size diameter. These are anorbital ripples. Orbital ripples predominately form in the laboratory, whereas anorbital ripples generally found in the field (Wiberg and Harris, 1994).

The mobility number (Equation 1) is a ratio of the disturbing forces to the stabilizing forces on a sediment particle under wave's action. It is a measure of a sediment particle's tendency to move due to wave action.

$$\psi = \frac{U_0^2}{(S-1)gd_{50}} = \left[\frac{\pi A}{d_{50}}\right]^2 \chi$$

Where A is the wave orbital excursion $(A = \frac{U_0 T}{2\pi})$, ω is the radial frequency $(\omega = \frac{2\pi}{T})$, S is the specific gravity of the sediment (for quartz sand S = 2.65), d is the median grain size diameter, T is the wave period, U_0 is the maximum free-stream velocity of the flow oscillation and χ is the period parameter (

$$\chi = \frac{d_{50}}{\left(S-1\right)gT^2} \,).$$

MATERIALS AND METHODS

A series of experiments observing the interaction between surface waves and rippled bed morphology was undertaken in an experimental wave flume of the Soil Conservation and Watershed Management

Research Article

Research Institute, Iran. Experiments were designed to investigate equilibrium rippled bed under a variety of surface wave conditions. Figure 1 shows the X-Y positional table of the bed profiler used to measure the sediment-water interface.



Figure 1: The X-Y positioned table of the ripple measurement system designed and developed by this study



Figure 2: Plan (bottom) and elevation (top) views of the original wave flume setup

The wave flume has a total length of 20m and a width of 5.5m with a depth of 2m (refer to figure 2). Waves are generated via a hydraulic piston-type wave paddle with a rectangular cross section. Irregular waves were generated using a specialized wave synthesizer program known as the SW Wave Maker Wave generation control program. The wave generation software controls the movement of the wave paddle. Three surface wave frequency conditions were used in this study having peak frequencies of: 0.45, 0.55 and 0.83 Hz. A 7m long and 1m width sand bed with slope of 0.03 was installed in the flume, starting at a distance of 2m from the wave paddle. Experiments were run with a type of sand with a percentile grain size diameter (d_{50}) of 0.2 mm. The flume experiments were established with the whole of the 7m sand bed composed of this sediment type.

To measure the rippled surface under water, a specialized bed profiling system was designed and developed. The axis along the flume in the direction of wave travel was defined as the primary axis while the secondary axis was defined as the axis across the flume normal to the direction of wave travel. Bed profiler system consists of a vertical position controlled device driven by a small electric motor with a mechanical transmission actuating a rod. At the lower end of the rod there is a probe which is the bottom sensor, used for the tracking the rod point under water closely to the sediment bed. The vertical displacement of the moving elements out of water is converted into an electric signal representing depth. Bed profiler system has 0.1mm accuracy.

The tests were started with the sediment bed in a no-ripple condition by raking the bed to remove any ripples present from previous experiments. Ripples were formed on the sediment surface by running

Research Article

regular waves confirming to a standard JONSWAP spectrum along the flume for periods of 3, 30, 72 min at first run, and for a period of 30 min at the other runs. After this time the waves and rippled bed were considered to be at equilibrium. A number of three-dimensional grids were profiled at the test areas that each grid has 2cm horizontal and 2.5cm vertical spaces. This provided 13650 three-dimensional data points taken from the rippled surface.

To evaluate the effects of wave height on sediment transport in both physical and numerical models, effective parameters are taken as radial wave height parameter (H_0) and wave period (T). Table 1 shows wave programs for experimental tests.

Test no.	d ₅₀ (mm)	$H_0(m)$	T (s)	Duration	Water	Level Bed slope
	/				(m)	-
1	0.2	0.075	1.8	3 min	0.2	0.03
				30 min		
				72 min		
2	0.2	0.11	1.8	30 min	0.2	0.03
3	0.2	0.05	1.8	30 min	0.2	0.03
4	0.2	0.11	1.2	30 min	0.2	0.03
5	0.2	0.11	2.2	30 min	0.2	0.03

RESULTS AND DISCUSSION



Figure 3: Initial bathymetry of experimental flume with the studied line





Research Article

Initial bathymetry of flume with longitudinal profile used to determine ripple height and distance, presented in figure 3. Figures 4, 5 and 6 shows the rippled bed formed under regular waves with T=2.2s and H_0 =11cm after 3, 30 and 72 min, respectively. Figure 7 shows bed profile at the studied line under regular waves with T=2.2s and H_0 =11cm after 3, 30 and 72 min. Figures 8, 9, 10 and 11 shows the rippled bed formed under regular waves with different heights and periods. Figure 12 shows bed profile at studied line under under regular waves with different heights and periods.



Figure 5: Rippled bed formed under regular waves with T=2.2s, H₀=11cm after 30 min



Figure 6: Rippled bed formed under regular waves with T=2.2s, H₀=11cm after 72 min



Figure 7: The profile of the bed under regular waves with T=2.2s, H_0 =11cm after 3, 30 and 72 min

© Copyright 2014 / Centre for Info Bio Technology (CIBTech)

Research Article



Figure 8: Rippled bed formed under regular waves with T=1.8s, H₀=11cm after 30 min



Figure 9: Rippled bed formed under regular waves with T=1.8s, H₀=5cm after 30 min





© Copyright 2014 / Centre for Info Bio Technology (CIBTech)

Research Article



Figure 11: Rippled bed formed under regular waves with T=2.2s, H₀=11cm after 30 min



Figure 12: The profile of the bed under regular waves with H₀=5, 7.5 and 11cm and T=1.8s

First section of experimental runs was concluded a series of experiments that monitored the growth of rippled bed under the action of a regular wave. As can be seen in figure 7, ripples start to appear on the surface of the bed after 3min but they have changed by the time. It seems 30 min is an enough time that a rippled bed will take to reach equilibrium with the new wave conditions.

Table 2 presents the dimensions of the ripples formed in experimental flume under different wave conditions. In this table η is ripple height and λ is ripple length. Presented values were calculated from averaged values of longitudinal profile of figure 3.

Table 2: The dimensions of the ripples formed in experimental flume								
Wave	$H_0(m) = 0.075$	$H_0(m) = 0.11$	$H_0 (m) = 0.05$	$H_0(m) = 0.11$	$H_0(m) = 0.11$			
characteristics	T(s) = 1.8	T(s)=1.8	T (s)= 1.8	T(s)=1.2	T(s)=2.2			
η (cm)	0.65	0.72	0.61	0.24	1			
λ (cm)	6.92	7.77	6.54	6.8	9.13			

Table 2:	The	dimensions	of f	the r	inples	formed	in ex	perimental	flume
I UDIC #.	1 110	unnensions	U 1		ippico	101 mcu	III UA	permitte	nume

Here we compare the empirical ripple prediction model of Nielsen (1981) to previous field measurements (Li and Amos, 1999; Hanes *et al.*, 2001), and to our experimental data sets. The Nielsen (1981) model for irregular waves is based on field wave-ripple data of Inman (1957) and Dingler (1974) and predicts the ripple height η and length λ of ripples using the near-bed semi excursion A and the mobility number ψ . Nondimensional ripple height is expressed as

© Copyright 2014 / Centre for Info Bio Technology (CIBTech)

Research Article



Figure 8: Dimensionless wave ripple (a) height and (b) length versus mobility number and (c) ripple steepness versus Shields parameter. Blue curves are Nielsen (1981) curves

© Copyright 2014 / Centre for Info Bio Technology (CIBTech)

Research Article

$$\frac{\eta}{A} = \begin{cases} 21\psi^{-1.85} & \psi > 10\\ 0.275 - 0.022\psi^{0.5} & \psi < 10 \end{cases}$$

And non-dimensional ripple length is expressed as:

$$\frac{\lambda}{A} = \exp\left(\frac{693 - 0.37 \ln^8 \psi}{1000 + 0.75 \ln^7 \psi}\right)$$

Nielsen (1981) independently fit curves for ripple steepness, giving:

$$\frac{\eta}{\lambda} = 0.342 - 0.34\theta^{0.25}$$

Where θ is the shields Parameter.

Some of the measured ripple heights and ripple wavelengths with their wave and current input data of the Li and Amos (1999) were chosen to compare with our data.

The Nielsen (1981) model curves for ripple height, length, and steepness are shown in figure 8 along with our measured and modeled ripple dimensions. Dimensionless wave ripple (a) height and (b) length versus mobility number and (c) ripple steepness versus Shields parameter of our experimental model, Nielsen (1981) curve, Hanes *et al.*, (2001), Li and Amos (1999) are compared in this figure.

Conclusion

Different wave conditions for ripple formation on flat bed have been examined through wave-flume experiments. Data were analyzed using the mobility number and Shields parameter. Results showed that ripple height increased with orbital excursion, as indicated by Nielsen (1992) for wave generated ripples. According to Table 2, the height of the wave ripples (0.2-1 cm), and their length of 10 cm, gives them a characteristic steepness of 0.09 to 0.2. They are therefore likely to be 'post-vortex' wave ripples, as in Bagnold's (1946) classification. Results showed that the changes in wave periods only changes the pattern of ripples formed in bed. However, the change of parameters such as bed slope and sediment size can change the ripples pattern and their dimensions. So bed parameters including bed slope, sediment size and bottom friction coefficient, depending on their significance, are considered as the important factors affecting dimensions of bed ripples. The comparison of the measured and modeled ripple dimensions with the predictions by the wave-ripple predictor of Nielsen (1981) indicates that experimental model has good agreement with Nielsen curves. On the whole the experimental results are in more agreement with the previous empirical data.

REFERENCES

Bagnold R (1946). Motion of waves in shallow water, Interaction between waves and sand bottoms. *Proceedings of the Royal Society of London A* 187 1-15.

Dingler JR (1974). Wave formed ripples in near shore sands. *Ph.D. thesis, University of California, San Diego* 133.

Fredsoe J and Deigaard R (1992). Coastal Bottom Boundary Layers and Sediment Transport. World Scientific 369.

Hanes DM, Alymov V, Chang YS and Jette C (2001). Wave-formed Sand ripples at Duck, North Carolina. *Journal of Geophysical Research* **106**(C10) 22,575–22,592.

Inman DL (1957). Wave generated ripples in near shore sands. U.S. Army Beach Erosion Board Technical Memo 100.

Li MZ and Amos CL (1998). Predicting ripple geometry and bed roughness under combined waves and currents in a continental shelf environment. *Continental Shelf Research* 18 941–970.

Nielsen P (1981). Dynamics and geometry of wave generated ripples. *Journal of Geophysical Research* 86 6467–6472.

Nielsen P (1992). *Coastal Bottom Boundary Layer and Sediment Transport* (World Scientific Publication Singapore) 4.

Research Article

Sleath JFA (1984). Sea Bed Mechanics Wiley Ocean Engineering Series New York 335. Swart DH (1974). Offshore Sediment Transport and Equilibrium Beach Profiles (Delft Hydraulics Publication) 131.

Wiberg PL and Harris CK (1994). Ripple geometry in wave dominated environments. *Journal of Geophysical Research* 99 775–789.