“Hummocky” bedform and its internal structure in an oscillatory-flow circular flume experiment : effects of aggradation

Tomohiro Takagawa*

Hummocky cross-stratification (HCS) is one of the most common and widely recognized structures in ancient storm-dominated sequences. It has been thought to be formed in shallow marine environments during high-energy storm events. There is little knowledge of sedimentary processes of it because modern shelf observation during storms is limited and experimental approaches had never succeeded in forming HCS. U-shaped wave duct was commonly used in forgoing experimental studies. This is well-suited to generating oscillatory flow but not to supplying sediments because it consists of a closed duct.

New circular flume used in this study was designed for observation of sedimentary processes with sediment supply under long-period oscillatory flow as high-energy wave in storm event. This flume can generate flow by paddle movement and can keep hydraulic condition constant even in bed aggradation.

Three runs with different rates of sediment supply were conducted. Quartz sands with the mean diameter of 0.3 mm are used. Period of oscillatory flow is 15 sec and maximum near-bed velocity is 80 cm/sec. It was observed that the development of hummocky bedform was suppressed under aggrading conditions with the rate of 1–3 mm/min. This rate is not exceptional in modern shelf. In the run with temporal change of supply rate from 0 to 1 mm/min, HCS-like structure was formed. Upward flattening laminae were observed in each bed, which is common in ancient rock record of HCS. This result suggests that upward flattening laminae in HCS might be formed with increasing of sediment supply. Although further confirmation that the effect of sediment supply is not an artifact of experimental design is needed, this new criteria for sediment supply rate contributes to better reconstruction of ancient marine sedimentary processes.

Key words : aggradation, circular flume experiment, hummocky bedform, hummocky cross-stratification, oscillatory flow, sediment supply

Introduction

Hummocky cross-stratification (HCS) is a type of bedding in sedimentary rocks, and is considered to form through the sand draping around low-steepness three-dimensional bedforms due to storm waves (e.g. Harms et al., 1975). HCS has been used to reconstruct ancient palaeogeographies and marine sedimentary processes (e.g. Dott and Bourgeois, 1982 ; Cheel and Leckie, 1993). The forming condition of “hummocky” bedforms is revealed in oscillatory-flow tunnel experiments (Arnott and Southard, 1990 ; Southard et al., 1990 ; Dumas et al., 2005).

However, “real” HCS have not been produced because sediment feeding, which is necessary for aggradation and HCS formation, is difficult in the experiments using sealed tunnels. The foregoing studies “synthetically” deduced depositional structure on the assumption that the bedforms are independent of depositional rates. Therefore, “real” processes of HCS formation under the aggrading conditions are still unknown. Here I investigated effects of aggradation rates on hummocky bedforms and their depositional structures through an experiment using oscillatory-flow circular flume.
Oscillatory-flow circular flume

The Experiment was made in a newly developed circular flume (Fig. 1). This flume was designed for observation of ‘real’ aggrading processes under long-period oscillatory flow characterizing storm waves. In this flume the conduit is 14 cm wide and 45 cm deep in vertical cross section and circular in plan. The outer diameter of circular conduit is 150 cm and the average circumference is 427 cm. Both the inside and the outside walls of the flume are transparent and observations can be made and photographs can be taken from both sides.

Flow of water is caused by rotational movement of paddles extending down from radial arms. By changing speed and direction of paddle rotation, the oscillatory flow can be generated. The circular flume can easily generate long-period and high-velocity oscillatory flow like storm waves, because paddle movement is not limited by size of flume. This is the merit of circular structure.

The paddles can be moved also vertically to keep a constant distance between bed surface and the paddles; thus the hydraulic conditions were kept constant even under aggrading conditions. Bed aggradation was made by sediment supply through three hoppers placed at even intervals above the flume. The rate of supply is controlled by changing the number of holes under the hoppers.

Experimental conditions

Three experimental runs were conducted, which were different in the rate of sediment supply. The other conditions were the same in all runs. Quartz sands with the mean diameter of 0.3 mm were used as sediments. The period of flow oscillation was 15 sec and the maximum velocity of the paddles was 130 cm/sec. Average depth of water is 25 cm and average distance between the bed and the lower end of the paddles were 17 cm. All runs started from a horizontal flat bed.

Run 1 and 2 were conducted under constant aggradation rates of 0 and 3 mm/min, respectively. In run 3, the aggradation rate was 0 mm/min during the first 11 minutes, and then it was changed to 1 mm/min. The choice of the imposed aggradation rate of 0–3 mm/min was based on observations of sedimentation rates during storm events on modern shelves (e.g., Morton, 1988; Cheel, 1991; Madsen et al., 1993; Dumas et al., 2005).

The height from troughs of a bedform to its crests, here after called as “bedform height,” was measured through each run. Accurate estimate of average velocity is difficult in such a paddle-drive circular flume because of centrifugal force and differences in velocity along the inner and outer wall. Turbulence generated by paddle motion is also troublesome. Therefore, results evidently must be viewed with circumspection and not taken as final proof. In this study, the paddle velocities and the near bed velocities are chosen as characteristic velocities of the flow. The near bed velocities were measured by PIV technique; the motion of neutrally buoyant markers, which was recorded by high-speed camera (Photron FASTCAM-PC1500), was analyzed by MatPIV (Sveen and Cowen, 2004) program.

Results and Discussion

Undulated “hummocky” bedform was developed in run 1. Bedform height increased gradually and saturated finally (Fig. 2). On the other hand, run 2 had minor change of bedform heights; bedform was almost flat through the run. In run 3, “hummocky” bedform was developed before the start of sediment supply, but the bed became flat gradually under the aggrading condition. These results mean that the growth of bed undulations is suppressed by sediment supply when depositional rate is larger than 1–3 mm/min.

Distinctive features of HCS were found in the deposit in run 3 (Fig. 3): for example, (1) low-angle erosional bounding surfaces, (2) internal laminae that are approximately parallel to the lower bounding surface, (3) upward flattening of internal laminae. The upward flattening laminae formed without any change in oscillatory flow as “hummocky” beds, which developed under the condition of no sediment supply, became flat due to sediment supply of 1 mm/min. These observations support the idea that flattening effect is associated with sediment concentration near bed (Bagnold, 1966, 1973; Komar and Miller, 1975; Allen and Leeder, 1980; Hallermeier, 1982), because the concentration must be higher under aggrading condition than no aggrading condition. Confirmation that the effect is not an artifact of experimental design awaits further research. Analysis of the dependency of grain size or period of oscillatory flow on threshold rate of aggradation is also needed.

The flattening effect of sediment supply may be common in the shallow marine environment because the aggradation rate of 1–3 mm/min falls in the range of the measured rates on the modern shelf as described before. Therefore, the formation of upward flattening laminae in ancient HCS can be attributed mainly to the increase in sediment supply rate, not to waning of wave intensity, although such laminae have been considered to be formed.
“Hummocky” bedform and its internal structure in an oscillatory-flow circular flume experiment: effects of aggradation

Fig. 1 Schematic diagrams of oscillatory-flow circular flume used in this study. The upper is plan view of the flume without the sand hoper and the lower is vertical cross section of total system. Oscillatory flow is generated by rotation of paddles. The paddles can move vertically to keep the distance from the bed constant even under aggrading conditions. Such conditions are generated by supplying sediments with hoppers above the flume.
by waning-storm waves or swell. The fact that wave ripples, which suggest waning of waves, rarely occur also agrees with this hypothesis.

Unidirectional component of natural combined flow in shallow water due to the anisotropy of oscillatory flow or superimposing unidirectional flow such as gravity or geostrophic flow may be the source of the sediment supply. The component must not be dominant because large anisotropy leads to form anisotropic HCS (Dumas et al., 2005). The results of this study also imply that second-order erosion surfaces (Cheel and Leckie, 1993), which divide sets of upward flattening laminae within a HCS unit, can form with the decrease in sediment supply, although the previous studies have thought these surfaces to be a sign of waxing intensity of waves. These new criteria for sediment supply rate contribute to better reconstruction of ancient marine sedimentary processes.

Acknowledgements

I would like to acknowledge valuable suggestions and discussions from Professor F. Masuda all through this research. I would also like to thank Dr. T. Sekiguchi for reviewing this manuscript and his helpful comments.

Fig. 2 Temporal change of bedform height. See text for detail of experimental conditions.

Fig. 3 HCS-like structure in run 3. The right side of the upper photo continues to the left side of the lower.
References


