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Textural Charactoristics and Transport Mode of Surface Sediments of a Tidal Sand Ridge in Gyeonggi Bay, Korea

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경기만 조류성 사퇴 표층 퇴적물의 입도 특성 및 이동 양상

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From the analyses of 16 bottom sediment samples and current data obtained during field experiments from August to September, 1987, the textural characteristics and transport mode of sand grains of a tidal sand ridge in Gyeonggi Bay are studied. The textural characteristics of the bottom sediments are diverse depending on their location on the tidal sand ridge. Sands on the crest are well sorted, near symmetric in skewness, leptokurtic in kurtosis, and are unimodal in peakedness. On the other hand, poorly sorted gravelly sands in the trough are coarse skewed in skewness and platykurtic in kurtosis. The mean values of U_{100} (velocity at one meter above bottom) and U_* (boundary shear velocity) are calculated to be 41.4 cm/sec and 2.39 cm/sec, respectively. From the analyses of characteristics of the sediments and currents in the study area, it can be concluded that almost all the sands of the tidal sand ridge (esp. on the crest) are transported as bedload (mainly as saltation).

한국 근해 경기만에 발달한 조류 기원 사퇴에서 1987년 8-9월에 획득한 16개 표층 퇴적물 및 유속 자료를 분석하여 퇴적물 조직 특성(Textural Characteristic) 및 이동양상을 연구하였다. 연구 결과 표층 퇴적물의 조직 특성은 사퇴에서의 위치에 따라 다양하게 나타났다. 즉 사퇴 정부의 퇴적물은 분급이 매우 양호하고 대칭적인 왜도 및 leptokurtic한 첨도를 보여주는 모래인 반면, 사퇴 기저부 (trough)의 퇴적물은 분급이 매우 불량하고 조립한 쪽으로 편향된 왜도 및 platykurtic한 첨도를 보여주는 모래인 것으로 나타났다. 한편, U_{100} (해저면 상부 1 m에서의 유속) 및 U_* (경계면 전단속도)의 평균값은 각각 41.4 cm/sec 와 2.39 cm/sec으로 계산되었다. 연구 지역 사퇴에서의 퇴적물 및 유속 자료를 이용하여 모래 이동 양상을 분석한 결과, 대부분의 모래가 밑짐 (주로 saltation)으로 운반되는 것으로 판명되었다.

INTRODUCTION

Gyeonggi Bay, extending from Yonpyong Do in the north to Ul Do in the south, is one of many coastal embayments developed in the western coast of Korea. Its bottom topography is very complex with numerous islands and ubiquitous tidal sand ridges trending oblique (NE-SW direction) to the coastline (Fig. 1). The water depth of the Bay is about 0~40 m.

Kim et al. (1979) have studied the internal structures (cross-bedding) of the small sand bar located in the north of Chawol Do by box coring method, and reported the path of sand transport to be SW direction. Chang et al. (1981) and Chang et al. (1982) studied the marine geological and seismic characteristics of the bottom sediments in Gyeonggi Bay. Kim et al. (1988) and Kim et al. (1989)

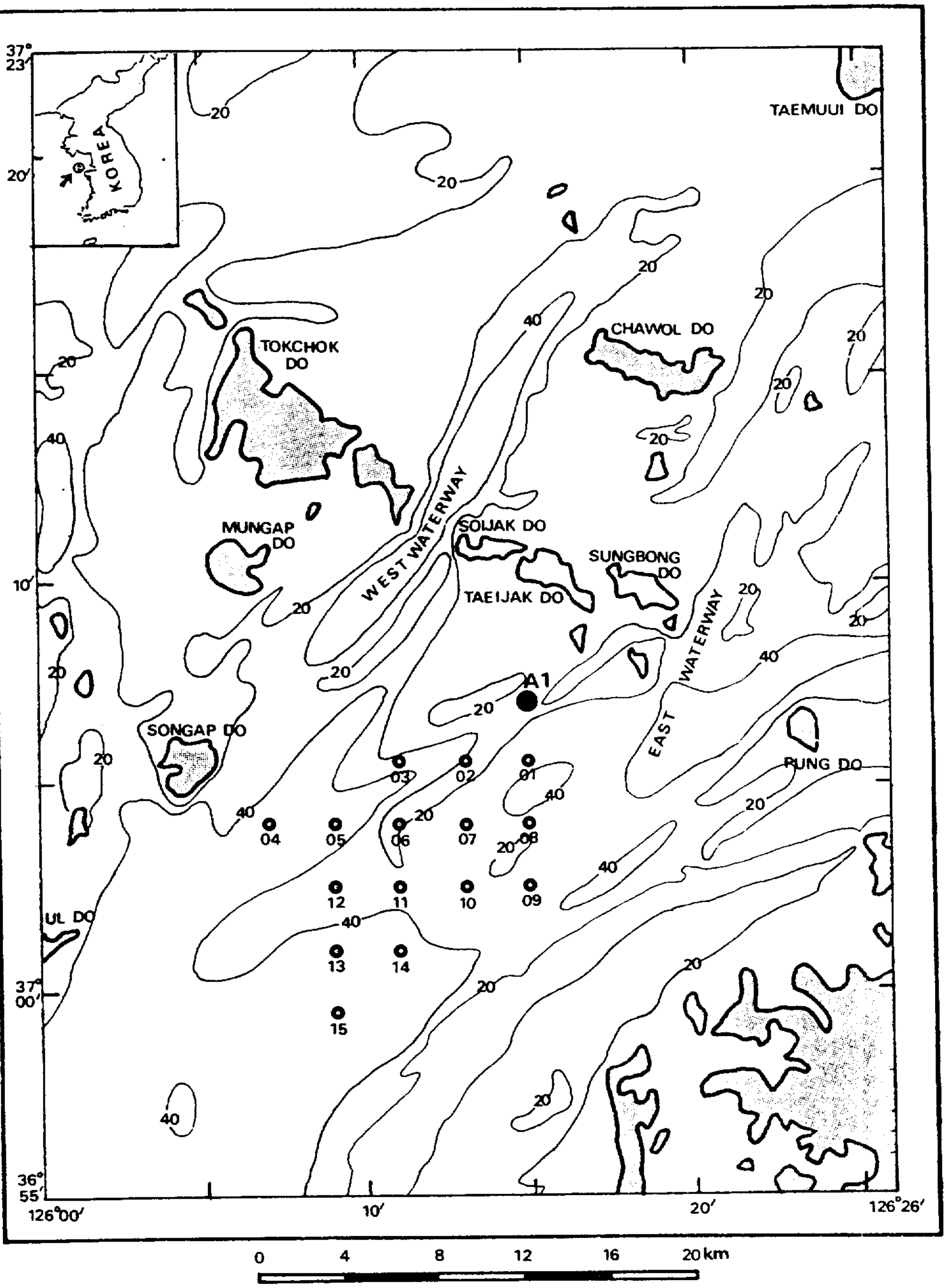

Fig. 1. Map showing the stations of surface sediment samples (small open circles) and current measurements (large filled circle).

carried out the geophysical, marine geological, and geochemical studies of the Bay, and concluded that the textural properties of the bottom sediments in the Bay are closely related to the local hydrological conditions as well as to the geology and bottom morphology.

However, there were few studies for the estimation of dominant sediment transport mode in Gyeonggi Bay. The modes of sediment transport are mainly related to the textural characteristics of sed iments and the local hydraulic conditions (Visher, 1969; Dyer, 1986; Kim et al., 1989).

The present study was carried out to estimate the major sediment transport mode in Gyeonggi Bay, especially on the tidal sand ridge. For that purpose, bottom sediments were sampled and tidal currents were measured on the tidal sand ridge, located in the southern part of Soijak Do and Taeijak Do (Fig. 1). The tidal sand ridge is located between the East and the West Waterways, and is approximately 15 km long and 2~4 km wide. The average water depth on the crest of the ridge is about 20 m. The tidal sand ridge is developed in the NE-SW direction, and the northern part of this ridge, in the vicinity of Taeijak Do, emerges during low tide.

MATERIALS AND METHODS

Bottom Sediment Samples

To know the textural characteristics of the surface sediments of the sand ridge, sixteen surface sediment samples were collected using Van Veen grab sampler on September 25, 1987. Fig. 1 shows the stations of the surface sediment samples. Nautical sextant and radar were used for fixing position during the cruise for sampling.

Approximately 50 grams of each sample was treated with 6% H_2O_2 and 10% Hcl to remove organic matter and carbonates, respectively. The samples were then wet-sieved using a 4 ϕ sieve (mesh size, 1/16 mm). The sand fractions were dried in an oven for 24 hours and dry-sieved at 0.5 ϕ intervals following the procedures of Carver (1971). Gravels were weighed at 1 ϕ intervals. Analyses of silt and clay fractions were made by pipette technique following the procedure of Folk (1968).

Current Measurements

From August 24 to September 28, 1987, the tidal current velocities were measured continously at Station A1 by mooring RCM-4 type current meters. Station A1 is located on the crest of the selected tidal sand ridge in water depth of 19.0 m (Fig. 1). The measured current data were analysed by a numerical low pass filter (Doodsen-Xo Filter) to eliminate the short term components (anomalies), and then used to draw the time variation of tidal current.

The dynamic viscosity μ and fluid density ρ are main variables to determine the shear force of fluid exerted on the sediment grains at the bottom (Middleton and Southard, 1984; Dyer, 1986). The dynamic viscosity and fluid density are primarily dependent on the temperature and salinity of the fluid. So, to evaluate more accurately the μ and ρ, temperature and sality were simultaneously measured by RCM-4 current meters with optional conductivity sensors at Station A1.

RESULTS AND DISCUSSIONS

Tidal Currents

The mean and maximum velocities of the tidal current over the entire period at Station A1 are 43.9 cm/sec and 92.5 cm/sec for flood, and 43.8 cm/sec and 95.3 cm/sec for ebb in near bottom (1.5m above bottom), respectively. And the average water temperature and salinity of seawater in near bottom at Station A1 are 21.6℃ and 29.2‰, respectively.

From the measured current data, the boundary shear velocities (U_*) and current velocities at one meter above bottom (U_{100}), which are necessary for the estimation of sediment movement, are calculated. And the kinematic viscosity (ν) and density (ρ) of sea water in near bottom are also estimated from the measured temperature and salinity. The detailed processes of current data analysis were reported in the other papers (Choi, 1990 and 1991).

Fig. 2. shows the histograms and cumulative curves of velocity distribution of U_{100} and U_* at station A1. The mean values of U_{100} and U_* are calculated to be 41.4 cm/sec and 2.39 cm/sec, respectively (Fig. 2). And the ν and ρ of sea water in near bottom are estimated to be 1.01×10^{-2} cm^2/sec and $1.02\times g/cm^3$, respectively.

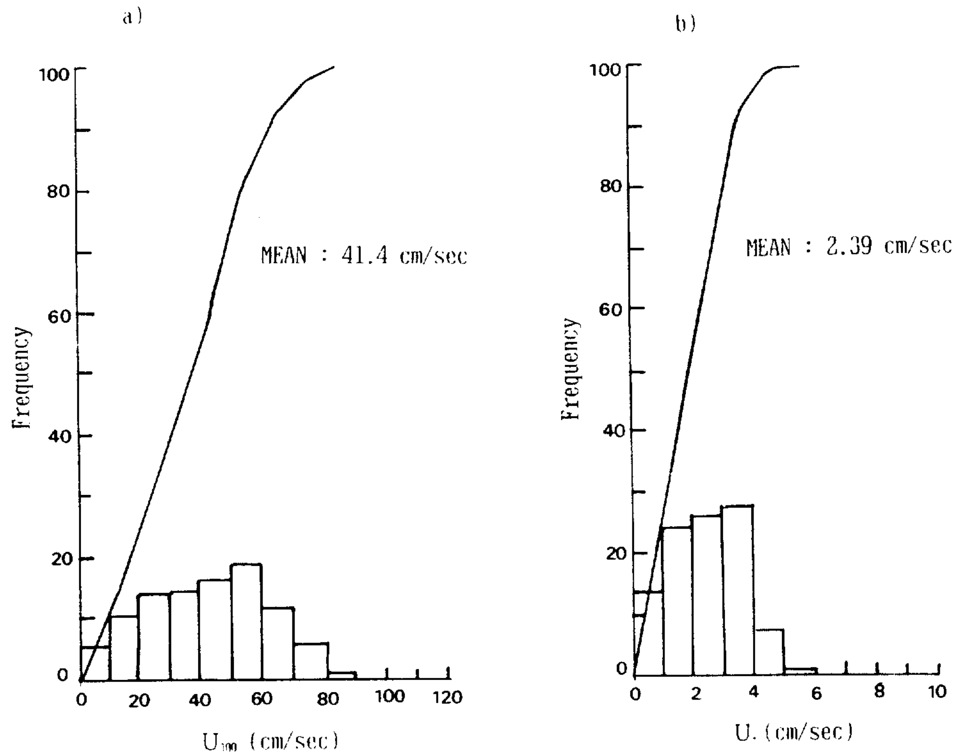

Fig. 2. Histograms and cumulative curves of velocity distribution at station A1 from 25 August to 27 September, 1987. U_{100} and U_* are calculated using logarithmic velocity profile equation (Choi, 1990 and 1991).

Table 1. Weight percentages of each granulometric size classes and textural parameters of surface sediments.

Station No.	Lat. (N)	Long. (E)	Weight% of Gravel	Sand	Mud	Mean (φ)	Median (φ)	Sorting* (φ)	Skew*	Kurt*	Textural classes+
1	37-05-30	126-15-00	34.2	65.8	0	−0.87	−0.80	0.71	−0.05	1.23	sG
2	37-05-30	126-13-00	0	100.0	0	1.57	1.60	0.42	0.05	1.01	S
3	37-05-30	126-11-00	4.8	95.0	0.2	0.86	1.05	0.80	−0.37	1.35	(g)S
4	37-04-00	126-07-00	0	99.9	0.1	1.21	1.25	0.56	−0.16	1.24	S
5	37-04-00	126-09-00	13.2	86.8	0	0.08	1.20	0.96	−0.15	1.12	gS
6	37-04-00	126-11-00	39.1	60.9	0	−0.57	0.50	1.38	−0.07	0.82	sG
7	37-04-00	126-13-00	15.2	84.8	0	0.35	0.45	1.21	−0.19	0.90	gS
8	37-04-00	126-15-00	0	100.0	0	1.23	1.25	0.42	0.02	1.19	S
9	37-02-30	126-15-00	19.4	80.6	0	0.63	1.40	1.65	−0.67	1.15	gS
10	37-02-30	126-13-00	7.7	92.3	0	0.69	0.80	0.95	−0.26	1.18	gS
11	37-02-30	126-11-00	27.7	72.1	0.2	−0.14	0.00	1.37	−0.12	0.85	gS
12	37-02-30	126-09-00	6.4	93.6	0	1.38	1.55	0.88	−0.55	2.12	gS
13	37-01-00	126-09-00	98.8	1.2	0	−3.27	−	0.16	−1.73	−0.44	G
14	37-01-00	126-11-00	0	99.8	0.2	1.56	1.55	0.43	0.19	0.94	S
15	36-59-30	126-09-00	18.7	80.0	1.3	0.27	0.40	1.41	−0.20	1.00	gS

*Nomenclature suggested by Folk (1954)
+Calculated following the method of Folk and Ward (1957)

Textures of Surface Sediments

Table 1 shows grain size parameters determined following the method of Folk and Ward (1957). Because of high contents of gravels, the range of mean grain size is relatively large from −3.27 φ

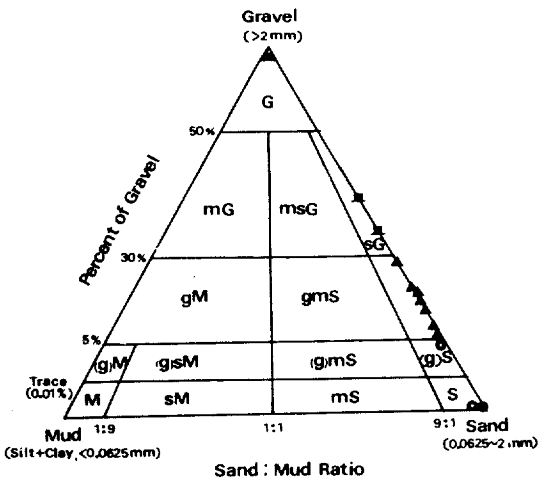

Fig. 3. Ternary diagram showing the relative amounts of three components (gravel-sand-mud) of surface sediments following the Folk's (1954) method.

to 1.57 ϕ (Table 1). The sorting value ranges from 0.16 ϕ (well sorted) to 1.65 ϕ (poorly sorted). The sediment of sand (S) or gravel (G) group shows a good sorting value, while the mixture (sG, gS, etc.) shows a poor one (Table1). The skewness is generally coarse-skewed or nearly symmetric, indicating a high energy environment in which most of the fine-grained sediments have been winnowed. The kurtosis which is the quantitative measure used to describe the departure from normal distribution is meso-kurtic or lepto-kurtic, indicating that the modality of the sediment is good and nearly unimodal (Table 1).

Based on the nomenclatures suggested by Folk (1954), sediment types of the sand ridge can be classified into 5 groups : gravel, sandy gravel, gravelly sand, slightly gravelly sand, and sand (Fig. 3). The proportion of gravel content is in part a function of the highest current velocity at the time of deposition, together with the maximum grain size of the sediment particle that is available (Folk, 1968). On the whole, sandy sediments are prevalent in shallow regions (crest of sand ridges), and gravelly sediments in deeper regions (channels).

Textural characteristics of surface sediments are diverse depending on the locations on the tidal sand ridge. Fig. 4 shows the histograms of grain size frequency distribution (in phi scale) of the

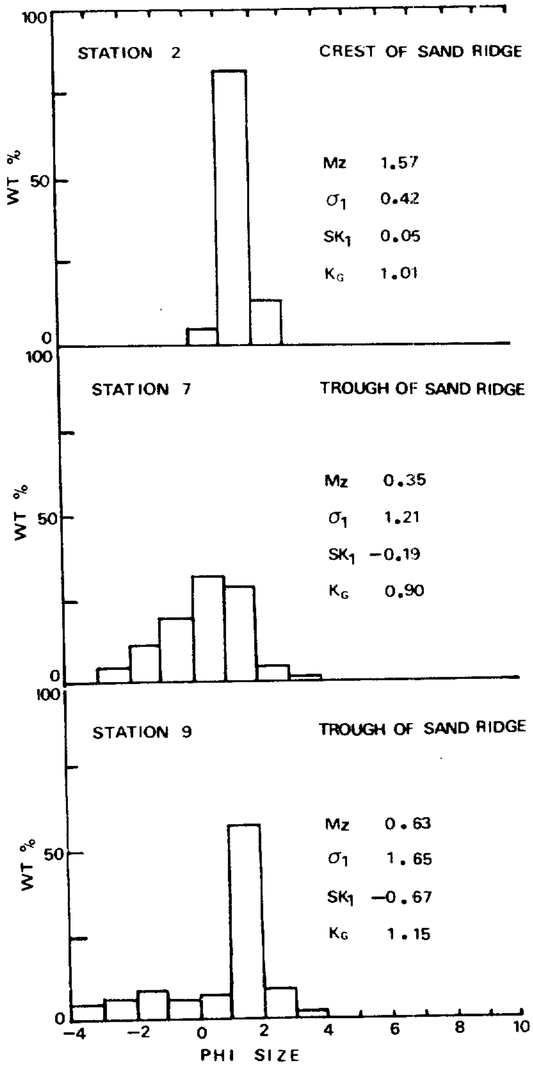

Fig. 4. Histograms of grain size frequency distributions of the surface sediments of station 2, 7, and 9 (for positions, refer Fig. 1). Textural characteristics are diverse depending on the locations on tidal sand ridge.

surface sediments of Stations 2, 7, and 9. Each station is located on the eastern flank across the sand ridge (Fig. 1). Station 2 is on the crest, and Station 9 is in the trough (Fig. 1). Well sorted sands on the crest (Station 2) are lepto-kurtic in kurtosis and near symmetric in skewness, so that almost all the sands are unimodal and can be represented as a mean grain size of 1.57 ϕ. The median diameter (1.60 ϕ) of sands at Station 2 is almost the same as the graphic mean grain size

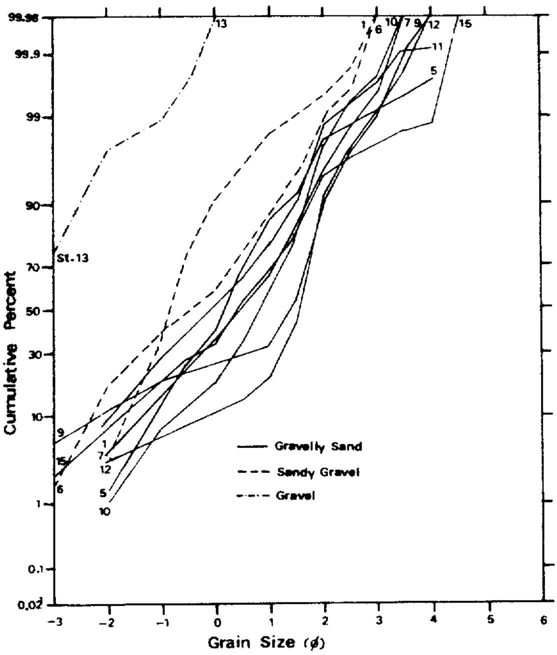

Fig. 5. Cumulative curves showing the grain size distributions of gravel, gravelly sand, and sandy gravel classes of surface sediments.

Table 2. Mean grain size, settling velocity, critical shear velocity, and transport stage of each stations of tidal sand ridge.

Station No.	Mean Grain Size (ϕ)	(mm)	Ws*	U_*c*	U_*/U_*c[+]
1	−0.87	1.83	137.90	11.99	0.2
2	1.57	0.34	4.74	1.40	1.7
3	0.86	0.55	11.00	2.81	0.9
4	1.21	0.43	6.35	2.34	1.0
5	0.08	0.95	33.87	5.00	0.5
6	−0.57	1.48	78.12	8.98	0.3
7	0.35	0.78	22.34	3.99	0.6
8	1.23	0.43	6.35	2.54	0.9
9	0.63	0.65	15.01	3.27	0.7
10	0.69	0.62	13.89	3.17	0.8
11	−0.14	1.10	43.32	6.15	0.4
12	1.38	0.38	4.89	2.19	1.1
13	−3.27	9.65	1672.02	86.32	0.0
14	1.56	0.34	4.74	1.40	1.7
15	0.27	0.83	25.74	4.24	0.6

*Settling velocities (W_s) and critical shear velocities (U_{*c}) are calculated using the settling velocity curve and Modified Shields' diagram of Madsen and Grant (1974).
[+]Transport stage (U_*/U_{*c}) is the ratio of the boundary shear velocity (U_*) to the critical shear velocity (U_{*c}). The U_* values of the other stations are assumed to be same to that at station Al.

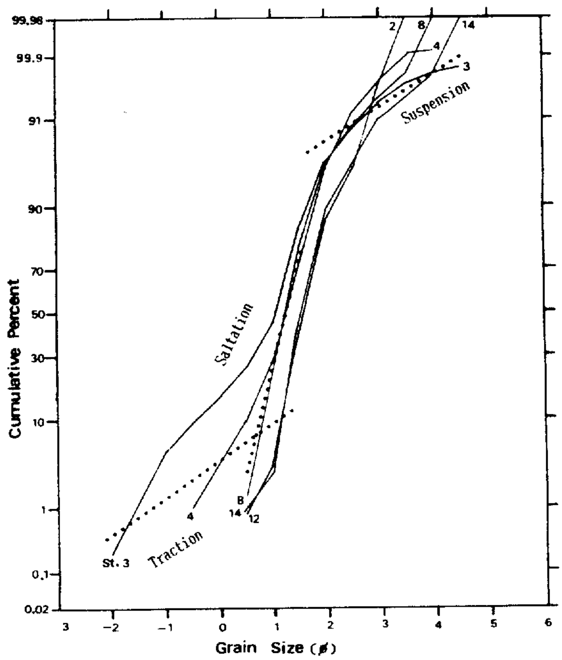

Fig. 6. Cumulative curves of grain size distributions and sub-populations of sand (with slightly gravelly sand) class of surface sediments. Curves can be segregated into three sub-populations (dotted line) following the method of Visher (1969).

(1.57 ϕ) (Table 1). On the other hand, poorly sorted gravelly sands are present in the trough (Station 9). The gravelly sands are coarse-skewed in skewness and platy-kurtic in kurtosis, so that all the sediments cannot be represented as a single mean grain size. The median diameter (1.40 ϕ) of sediments at Station 9 is very different from the graphic mean (0.63 ϕ).

Figs. 5 and 6 show the cumulative percentages of the sediment grain size of each station, which are plotted on log probability paper. The curves are symbolized differently according to the textural groups. The sand group and slightly gravelly sand group are plotted together in one figure because they show similar textural characteristics and cumulative curve patterns (Fig. 6).

The settling velocities (W_s) and critical shear velocities (U_{*c}) are calculated using Modified Shields' diagram and settling velocity curve of Madsen and Grant (1976) (Table 2). U_{*c} is the velocity needed for the initiation of sediment movement. For those calculations, the mean grain size (D) and density (ρ_s) of the grain, and the density (ρ) and kinematic viscosity (ν) of sea water are used. The density of the grain is assumed to be that of quartz grain (2.65 g/cm^3). And the hydraulic conditions (U_{100}, U_*, ν, ρ) of the other stations (esp. on the crest) are assumed to be roughly the same as those at Station A1.

Transport Mode of Sand Grain

Once the grains are moved by the fluid, they are transported in three different ways: by rolling, saltation, and suspension. The distinction among these three modes is not apparent. Bagnold (1973) argued that the major distinction in the modes of grain movement is in suspended and unsuspended transport, the latter comprising rolling, saltation, and sliding (Dyer, 1986). Unsuspended transport is the same concepts as bedload.

From his extensive textural studies of modern and ancient sands, Visher (1969) proposed that the analysis of log-probability grain size distribution curves appears to be a fruitful method for studying sedimentary dynamics. Analysis is based on recognizing the sub-populations within individual log-normal grain size distribution. Visher (1969) suggested that each log-normal sub-population might be related to a different mode of sediment transport and deposition. Even though there are no sharp distinctions between subpopulations, log-probability grain size distribution curves of sediments on the tidal sand ridge in the present study area can roughly be distinguished into three sub-populations (Fig. 6). Cumulative curves of the present study resemble roughly the examples of tidal inlet or fore-set bed of modern delta suggested by Visher (1969). It can be conjectured from Fig. 6 that the most of the sand grains are transported as bedload either by traction or by saltation mode of movement.

Sundborg (1967) presented the graph (Fig. 7) which shows the relationship between the flow velocity, grain size of sediment, and the state of sediment movement. The curves in Fig. 7 are the so-called "competency curves", relating the mean velocity at one meter from the bed to the mean

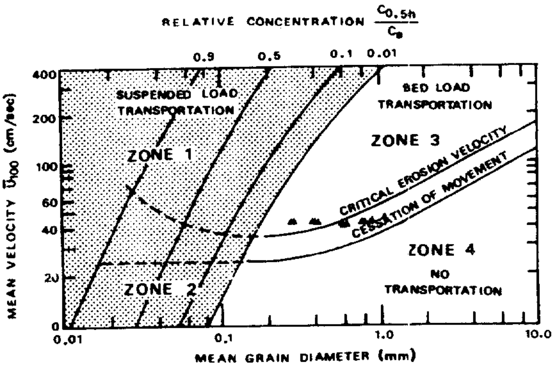

Fig. 7. The relationship between flow velocity, grain size and state of sediment movement (After Sundborg, 1967). Ca and $C_{0.5}h$ are the suspended sediment concentration at a reference height near the bed and at the mid-depth of the flow, respectively. The mean velocities at one meter above bottom (U_{100}) and mean grain diameter of each stations are plotted.

grain diameter of sediment. Although Fig. 7 were made from the study in the flume and river flow, it can be used to roughly delineate the mode of sediment transport on sandy bottom consisting of relatively small quantities of fine material (Sternberg, 1972). All the sediments in the present study area are composed of sands or gravelly sands with few fine sediments (mud) (Table 1).

The mean velocities at one meter above bottom (U_{100}) and mean grain diameter of each stations are plotted in Fig. 7. The positions of the data of the present study is above or near the curve of critical erosion velocity (Fig. 7). Because of the large grain size and the assumption that the U_{100} values at all stations are same, the stations in the trough are mostly located below the critical erosion velocity curve (Fig. 7). However, the U_{100} values at stations in the trough may be higher than that at Station A1 due to the channel effect of the flow. If so, the data position below the curve would be above the curve. Thus, the greater part of sands of the tidal sand ridge (esp. on the crest) can be considered to be moved as bedload.

It is commonly assumed that suspension occurs when the upward components of the turbulent velocity fluctuations exceed the fall velocity of the grains (Bagnold, 1956). From the relations between

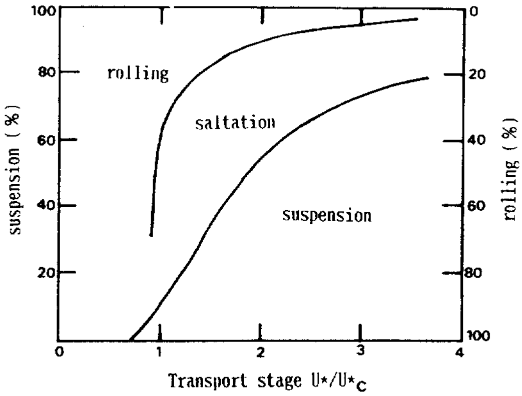

Fig. 8. Relative percentages of rolling, saltation, and suspension as a function of transport stage (After Dyer, 1986). The transport stage (U_*/U_{*c}) is the ratio of the boundary shear velocity (U_*) to the critical shear velocity (U_{*c}).

the turbulent velocity fluctuations, root mean square (rms) of the vertical velocity fluctuations, and the shear velocity, he estimated that full suspension occurs when

$$W_s = 1.25\ U_{*s} \qquad (1)$$

where W_s: settling velocity of the grain
U_{*s}: boundary shear velocity for full suspension

Table 2 shows the settling velocities (W_s) which vary remarkably according to the grain size. The minimum W_s and U_{*s} are 4.74 cm/sec and 3.8 cm/sec, respectively. On the other hand, U_{*c} are mainly from 1.40 cm/sec to 3.99 cm/sec (Table 2). Comparing the ranges of U_* (Fig. 2) and U_{*c} (Table 2), and the minimum valus of U_{*s}, it can be suggested that the most sand grains of the tidal sand ridge are moved as bedload.

Fig. 8 shows the modes of grain movement according to the transport stage (U_*/U_{*c}) (Francis, 1973). The transport stage is the ratio of the shear velocity (U_*) to the critical shear velocity (U_{*c}). Near the threshold (when $U_*/U_{*c}=1$), rolling is dominant (Dyer, 1986). But, as the flow velocity increases, the proportion of grains moved by rolling decreases very rapidly, and saltation becomes the dominant mode of grain movement. In the saltation mode, grains are transported making a "ballastic" trajectory which is continuously concave downwards (Middleton and Southard, 1984). The ballastic trajectories differ considerably according to the shapes and densities of grains, and the flow intensity (Francis, 1973). Francis (1973) has shown from his experiments that saltation occurs in transport stages (U_*/U_{*c}) between 1.0~2.2 for angular grains, and 1.0~5.5 for rounded grains.

From the mean boundary shear velocity (2.39 cm/sec) and critical shear velocities of the present study, the transport stage ($U_*//U_{*c}$) of each stations is calculated to be less than 1.70 (Table 2). The U_*/U_{*c} values of the stations in trough are near the threshold (Table 2). Thus, it can be suggested from Fig. 8 that the most of the sands of the tidal sand ridge (esp. on the crest) in the study area are transported as bedload (saltation and rolling).

According to the facts shown in the cumulative curves (Fig. 6), competency curve (Fig. 7), and transport stage curves (Fig. 8), it can be concluded that almost all the sands of the tidal sand ridge (esp. on the crest) are transported as bedload (mainly as saltation mode).

CONCLUSIONS

The bottom sediments of the tidal sand ridge of the study area are composed of five groups; gravel, sandy gravel, gravelly sand, slightly gravelly sand, and sand. The textural characteristics of the bottom sediments are diverse depending on the sample locations on tidal sand ridge. Well sorted sands on the crest are lepto-kurtic in kurtosis and near symmetric in skewness. On the other hand, poorly sorted gravelly sands in the trough are coarse skewed in skewness and platy-kurtic in kurtosis. The sands of Station 2 located on the crest of tidal sand ridge are unimodal in peakedness, and have mean grain size of 1.57 (0.334 mm).

The mean values of U_{100} (velocity at one meter above bottom) and U_* (boundary shear velocity) on the crest are calculated to be 41.4 cm/sec and 2.39 cm/sec, respectively. And the kinematic viscosity (ν) and density (ρ) of sea water in near bottom are estimated to be 1.01×10^{-2} cm^{-2}/sec and 1.02 g/cm^3, respectively.

From the sediments and currents data of the tidal sand ridge, the transport mode of sand are estimated using the cumulative curves, competency curve (Sundborg, 1967), and transport stage diagram (Dyer,1986). From the above results, it can be concluded that almost all the sand grains of the tidal sand ridge (esp. on the crest) are transported as bedload (mainly as saltation).

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