Sediment transport pathways on the modern microtidal sand flat reconstructed by the new method of sediment trend analysis (P-GSTA): Case studies of Kushida River and Obitsu River deltas, Japan

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A new method to reconstruct the sediment transport pathways, which is based on the sediment grain-size distribution and uses principal component analysis (P-GSTA), is proposed here. In this method, a linearly-combined value of six grain-size parameters (mean, coefficient of variance, skewness, kurtosis and log-ratios of mud and gravel contents) with different weighting factors is used as a proxy of sediment transport processes. The combination of this method and cluster analysis is very effective to reconstruct sediment transport patterns in the depositional environments where compositive depositional processes exist.

Key words: grain-size trend analysis, GSTA, microtidal, tidal flat

Introduction

Spatial variance of surficial grain-size distribution patterns is an important clue in the reconstruction of sediment-transport pathways. Many researchers have attempted to identify spatial variations of grain-size parameters, which have been referred to as ‘grain-size trends’, associated with net sediment-transport pathways. McLaren and Bowles (1985) discussed the combination of three grain-size parameters (mean grain-size, sorting, and skewness), and concluded that sediments always become better sorted during transport, whereas the mean grain-size and skewness vary with specific combination patterns (FB−: finer mean grain-size, better sorting value and more negative skewness, or CB+: coarser mean grain-size, poorly sorting value and more positive skewness). Gao and Collins (1992) applied their assumption to the two-dimensional data set of grain-size distribution in modern depositional environments. This method was named as Grain Size Trend Analysis (GSTA), and has been applied in a variety of sedimentary environments.

However, discrepancies between the GSTA model and actual sediment transport patterns have also been reported (Asselman, 1999; Masselink et al., 2008). This is probably because the sediment trend does not always follow the assumption of McLaren and Bowles (1985) especially under compositive transportational processes. Therefore, more flexible method is needed to recognize spatial variation of grain-size parameters in specific depositional settings.

To this end, the grain-size trend analysis based on principal component analysis (P-GSTA) (Yamashita et al., submitted) is proposed herein. P-GSTA can detect unique grain-size trend in each depositional setting, and therefore is effective under compositive transport processes, in which sediment-transport function is difficult to be assumed.

Study areas

The new GSTA method proposed here was applied to the two modern sandy tidal-flat systems developed in (1) the Kushida River and (2) the Obitsu River deltas.

(1) The Kushida River flows into Ise Bay, and forms bayhead delta. The tidal range of Ise Bay is about 2 m during spring tide (microtidal). The gross area of tidal flat is...
about 0.4 km$^2$, and sediment is mainly composed of medium to coarse sand. The sandy tidal flat is characterized by sand bars and shallow braided channels, and it is interpreted that fluvial processes and wave activities dominate sediment transport (Yamashita et al., 2009).

(2) The Obitsu River Delta is progressing into Tokyo Bay, and associated tidal flat spreads about 8 km$^2$. The tidal range is about 2 m during spring tide (microtidal). The sediment on the tidal flat is mainly composed of fine to medium sand. Sand bars and shallow channels are primary geomorphologic features. It is interpreted that wave and littoral currents dominate sediment transport (Uchiyama, 2000).

Methodology

P-GSTA (Yamashita et al., submitted) employs principal component analysis (PCA) to define sediment-transport function. PCA is a technique for explaining the correlation between explanatory variables and automatically organizing them into a few linear synthesis variables with different weights.

Let $x_1, x_2, ..., x_p$ be variables, and let $z_1, z_2, ..., z_m (m \leq p)$ be their respective weighted synthesis variables. These synthesis variables are defined as the principal components. Then, we have the following:

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\begin{align*}
  z_1 &= L_{11} x_1 + L_{12} x_2 + \cdots + L_{1p} x_p \\
  z_2 &= L_{21} x_1 + L_{22} x_2 + \cdots + L_{2p} x_p \\
  z_m &= L_{m1} x_1 + L_{m2} x_2 + \cdots + L_{mp} x_p
\end{align*}
\]

where, $L_{ii} + L_{i2} + \cdots + L_{ip} = 1, \ (i=1, 2, \cdots, m)$ (1)

Here, the matrix ($L_{ij}...L_{jp}$) is the eigenvector of the $i$-th principal component. The $m$ synthesis variables have the following two properties: 1) the correlation of every two synthesis variables is zero (orthogonal) and 2) satisfies the following inequality for the variances of synthesis variables ($\text{Var}(z_1) \geq \text{Var}(z_2) \geq \cdots \geq \text{Var}(z_m)$). The amplitude of the variance of principal components can be regarded as the amount of information in each principal component. The factor loading, which represents the relative importance of each variable in the principal component, is defined as the product of the root of the eigenvalue and the eigenvector. Factor loading, that is the weight of each parameter, depends on its variance (Davis, 1986; Middleton, 2000). In other words, the parameters that exhibit substantial changes in a certain region are heavily weighted, and those showing small variances are less heavily weighted. Therefore, it can be expected that the parameters that strongly reflect the sediment transport are emphasized by PCA.

The methodology of P-GSTA (Yamashita et al., submitted) is described here. As described above, six grain-size parameters (mean grain size, CV [dimensionless sorting value divided by mean grain-size], skewness, kurtosis, and mud and gravel contents) were employed. First, the zero values of mud and gravel contents are replaced by the method of Martín-Fernández et al. (2003), and mud and gravel logratios are obtained by the method of Aitchison (1986, 2003). Then, all values are standardized. After these preliminary procedures, the principal component analysis (PCA) is conducted using these transformed six parameters (Eq. 1). Each principal component is then interpreted, and the sediment transport function is chosen from the principal component scores. Then, the interpolated map of the scores of the chosen principal component is calculated by kriging method (Burgess and Webster, 1980a, b; Kohsaka, 1998).

The trend vectors are calculated based solely on this interpolated map. After comparing the principal component scores of adjacent grid points, vectors of unit length are drawn between two grid points if they are confirms to the ‘rule’ (sediment-transport function is satisfied). These vectors are calculated from every point with respect to the intermediate eight neighboring grid points. Summing the vectors at each sample point produces a single vector, which is the trend vector of P-GSTA.

Results

Kushida River Delta At the tidal-flat system in the Kushida River Delta, P-GSTA successfully reconstructed sediment transport pathways on the microtidal sand flat (Fig. 1). PC1 of statistic parameters indicated that the grain-size distribution of sediments on the surface of microtidal sand flat becomes finer, better sorted, less gravelly and more negatively skewed downcurrent through the sediment-transport processes by fluvial and wave activities. Then, we employed the eigenvector of PC1 as weighting factors of grain-size parameters to calculate the linearly-combined value, and estimated the sediment transport pathways in the system. In contrast to the result of our method, results of other GSTA models previously proposed were inconsistent with actual sediment transport processes, suggesting effectiveness of our method throughout a microtidal sand-flat system. In addition, other minor depositional processes on the sand flat, namely, constant-wave activities and the deposition of muddy particles were recognized by PC2 and 3.

Obitsu River Delta In the case of the Obitsu River Delta, the predominant grain-size trend was not detected by
PCA. The scatter diagram of PC1 against PC2 shows two distinct grain-size trends (Fig. 2). One trend is composed of almost 80% of samples and shows positive correlation between PC1 and PC2, and another subsequent trend shows faint negative correlation between them (Fig. 2). Both trends cross to the axis of PC1 and PC2, and therefore, they cannot represent both of these trends (Fig 2). Actually, the sediment transport patterns reconstructed on the basis of these principal components are not coincided with net sediment transport directions inferred by the existing geomorphological features.

P-GSTA combined with clustering method

The cluster analysis was applied in order to distinguish two sediment trends observed in the sandy tidal flat along the Oblitus River Delta. Cluster analysis is a method of multivariate data classification based on the Euclidian distances. We employed k-means clustering, which is one of typical nonhierarchical clustering methods, specifying two clusters. After the clustering, PCA was conducted into each cluster to clarify grain-size trends.

The predominant grain-size trend (PC1 of Cluster 1) represents that sediment becomes finer and better sorted with
small increase of skewness and kurtosis value, and this value of PC1 of cluster 1 increases radially from the river mouth to offshore. Then, we employed the eigenvector of PC1 of cluster 1 as weighting factors of grain-size parameters to calculate the linearly-combined value, and estimated the sediment transport pathways in the system. As a result, the sediment transport patterns on this system were successfully reconstructed (Fig. 3). Constant wave process was inferred by the subsequent trend (PC1 of cluster 2), representing that sediment becomes finer and better sorted with significant decrease of skewness value and increment of kurtosis value especially in the lower subtidal zone.

Discussion

In the tidal-flat system in the Kushida River Delta, the grain-size trend analyzed by the P-GSTA method shows good agreement with the actual net sediment transport that was estimated from the geomorphological features on the sand flat. The reason probably is that the P-GSTA method can detect the unique grain-size trend in each depositional setting and so is effective even under compositive transport processes, in which the precise sediment transport function is difficult to assume. PCA can easily explore the characteristic changes of the grain-size distribution curves in a specific depositional setting by a linear combination of multiple grain-size parameters (Eq. 1). PCA can automatically weight multiple grain-size parameters and combine these parameters in a linear function. In addition, the magnitude of the weight is proportional to the amount of spatial variation of each parameter (Middleton, 2000). Therefore, the resultant linear combination of grain-size parameters summarized by the first principal component (PC1) represents the spatial variation of the grain-size distribution curves in the surveyed area.

On the other hand, in the tidal-flat system in the Obitsu River Delta, the sediment transport pathways were not adequately reconstructed solely by P-GSTA method. The reason is that the sediment transport function was not uniform in this region. Although P-GSTA is a flexible method, it can be applied only into the specific environment in which sediment transport function is consistent which is represented by the linear function (Yamashita et al., submitted). If the properties of the sediment transport function vary remarkably within a surveyed region, it is difficult to reveal deformation patterns of grain-size distribution curves by PCA, because the resultant first principal component will be representative of the averaged variation of the grain-size trend. In this case, the individual transport functions cannot be identified.

However, the result in the Obitsu River Delta shows that the combination of P-GSTA and clustering method is effective to distinguish multiple grain-size trends. After clustering, PCA can recognize linear grain-size trend as the first principal component in each cluster, and detect sediment-transport function. Therefore, the combination of P-GSTA method and cluster analysis is effective to reconstruct sediment transport patterns in depositional environment in which multiple sediment transport functions exist.

Conclusions

1. A new method to reconstruct the sediment transport pathways, which is based on the sediment grain-size distribution and using principal component analysis, (P-GSTA) is proposed.
2. P-GSTA method is solely successful to reconstruct sediment transport patterns in the sandy tidal flat along the Kushida River Delta.
3. The combination of this method and cluster analysis is effective to reconstruct sediment transport patterns in the sandy tidal flat along the Obitsu River Delta, in which multiple sediment transport functions exist.
Fig. 3 Grain-size trend vectors calculated by the P-GSTA method coupled with cluster analysis over observational sediment-transport patterns in the sandy tidal flat along the Obitsu River Delta.

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堆積物粒度特性に基づいた現世干潟環境における砕屑物輸送パターンの復元：
伊勢湾櫛田川，東京湾小楡川河口干潟の例

山下翔大・成瀬 元・中条武司. 2011, 堆積学研究, Vol. 70, No. 1, 31−36

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Case studies of Kushida River and Obitsu River deltas, Japan

粒度分布の空間的変異に基づいて砕屑物輸送パターンを復元するための新手法（P-GSTA）を提唱した. P-GSTA では主成分分析によって得られた，異なった重みを持つ 6 つの粒径分布パラメータ（平均粒径，変異係数，歪度，尖度，含泥率，含礫率）を合計した線形関数を砕屑物輸送のプロキシとして使用する. さらに，P-GSTA とクラスター分析を組み合わせることで，複数の物質輸送営力が卓越する環境においても，砕屑物輸送パターンを適切に復元することが可能となる.