SAND GRAIN PRODUCING–TRANSPORT PROCESSES ESTIMATED FROM GRAVEL–SAND GRAIN ROUNDNESS ON DAMS-CONSTRUCTED TENRYU RIVER, CENTRAL JAPAN

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Abstract Fluvial sand grain producing–transport processes were examined along the dams-constructed Tenryu River, central Japan. The authors focused on downstream changes in shale grain roundness on gravel–sand size fraction with 1 ϕ intervals. Roundness is a suitable parameter for assessing grain producing–transport processes since it reflects the extent of detritus breaking and abrasion. The effects of such physical actions on each size fraction were studied by means of a field survey (pebble gravels) and laboratory analyses (granule–coarse sand grains). The results suggest that pristine grains were produced from pebbles in both upstream and downstream reaches of the Funagira Dam, the nearest dam from the mouth of Tenryu River. Additionally, collected evidence demonstrates that grains finer than 1 mm in diameter were transported through the Funagira Dam, as indicated by their roundness. Thus, further studies on operating breaking and abrasion mechanisms acting upon detritus could enable contriving the appropriate countermeasure based on a model of "sand grain production from gravels during fluvial transport".

Key words: gravel–sand, roundness, breaking and abrasion mechanisms, dam construction, Tenryu River

1. Introduction

Dam reservoirs hold not only water resources but also sedimentary detritus produced in upstream reaches of rivers, thereby disturbing the fluvial sedimentary cycle. As such, they cause the important environmental and social concerns regarding fluvial–coastal areas, for instance, armor-coated gravel-bed river where finer grains were flushed out farther downstream at the lower reaches of a dam, and coastal erosion occurring due to reductions in sediment supply from the river mouth. Several countermeasures involving artificial sediment transport from dam reservoirs to downstream reaches of rivers, such as sand mining in the reservoir and sediment bypass tunnels, have already been carried out (e.g. Ashida *et al*. 2008). These measures are, however, generally based on the assumption that detritus have experienced only "transport–deposition" processes; in other words, that grains have not suffered further breaking or abrasion during transport in a stream, according to experimental results obtained during the first half of the 20th century (e.g. Wentworth 1919; Krumbein 1941a). In spite of this fact, the "producing–transport" processes acting upon detritus on dams-constructed rivers remain unclear.

The present study focuses on downstream roundness changes in gravels and sands, which the latter would be produced from gravels, in order to unravel the effects of dams on grain producing–transport processes. Roundness, a parameter firstly defined by Wentworth (1919), is a suitable parameter for assessing grain producing–transport pathways, as it is strongly responsive to both breaking and abrasion acting upon detritus (e.g. Krumbein 1941b; Barrett 1980) and has been utilized to interpret the transport history of sedimentary particles (e.g. Tafesse 2013).

2. Samples

The authors selected a watershed of the Tenryu River including huge dams located in central Japan, as the study area. This hydrographic configuration assured a clear supply source of detritus, in spite of local lithological heterogeneity described in the following sections.

Geographical and geological settings of Tenryu River

The Tenryu River is 213 km long with a drainage basin area of 5,090 km^2. It originates in Lake Suwa in central Japan and runs from the inland mountainous region to the Pacific coast (Fig. 1a), forming a coastal plain comprising fluvial terraces and alluvial lowlands (e.g. Muto 1987). The river system crosses the Median Tectonic Line (MTL), giving rise to high rates of detritus production. As shown in Fig. 1b, in the upstream reaches of the MTL, above Sakuma Dam; the main detritus source is a Cretaceous granitoid, while in the downstream reaches, below Sakuma Dam; detritus of Cretaceous schist (Sambagawa metamorphic zone) and Cretaceous sedimentary rock are supplied into the Tenryu River (Geological Survey of Japan, AIST. ed. 2015).

Dams and tributaries in downstream reaches of Tenryu River

The watershed of Tenryu River is characterized by the largest amount of sediment discharge among all Japanese rivers (Ashida *et al*. 2008) and includes fifteen dams. The largest, Sakuma Dam, has completely obliterated the transport of both detritus and water resources. This infrastructure constructed in 1956 is located approximately 73 km upstream from the river mouth (Fig. 1c), with a wall height of 155.5 m and a total reservoir storage of 326,848,000 m^3. In downstream reaches below this dam, there are two other water impoundments: the Akiha Dam and the Funagira Dam, with wall heights of 89 m and 24.5 m, and total reservoir storage capacities of 34,700,000 m^3 and 10,900,000 m^3, respectively.

Four main tributary streams supply water and detritus to the downstream reaches below Sakuma Dam (Fig. 1c): the Ohchise River, the water bypass from the Lake Sakuma (Dam), the Misakubo, and Keta rivers. The Keta River has no dams and is often considered as the tributary contributing with the largest sediment supply to downstream reaches (e.g. Fujiwara *et al*. 2007), because it is a confluent joining between Akiha and Funagira dams.

Sampling sites

The authors focused on three sampling sites along the Tenryu River, located at downstream reaches below the Akiha Dam (Fig. 1c).

Site A: Keta River

Geographical coordinates: 34°56′52″N, 137°51′55″E and 82 m of altitude.

This site is located approximately 7 km upstream from the confluence with Tenryu River. Sedimentary rock (sandstone, shale and chert) gravels are predominant.

Site B: Funagira Dam

Geographical coordinates: 34°53′18″N, 137°48′33″E and 41 m of altitude.

The authors sampled the gravel bar located downstream, just below the dam, which is often flushed. Sedimentary rock, schist, and granitoid rock gravels are the dominant lithologies.

Site C: Hiryu Bridge

Geographical coordinates: 34°51′16″N, 137°49′16″E and 31 m of altitude.

Following a river bend, the horizontal distance from Site B is approximately 7 km. This site stands 25 km upstream from the mouth of Tenryu River. Sedimentary rock, schist, and granitoid rock gravels are the main lithologies.

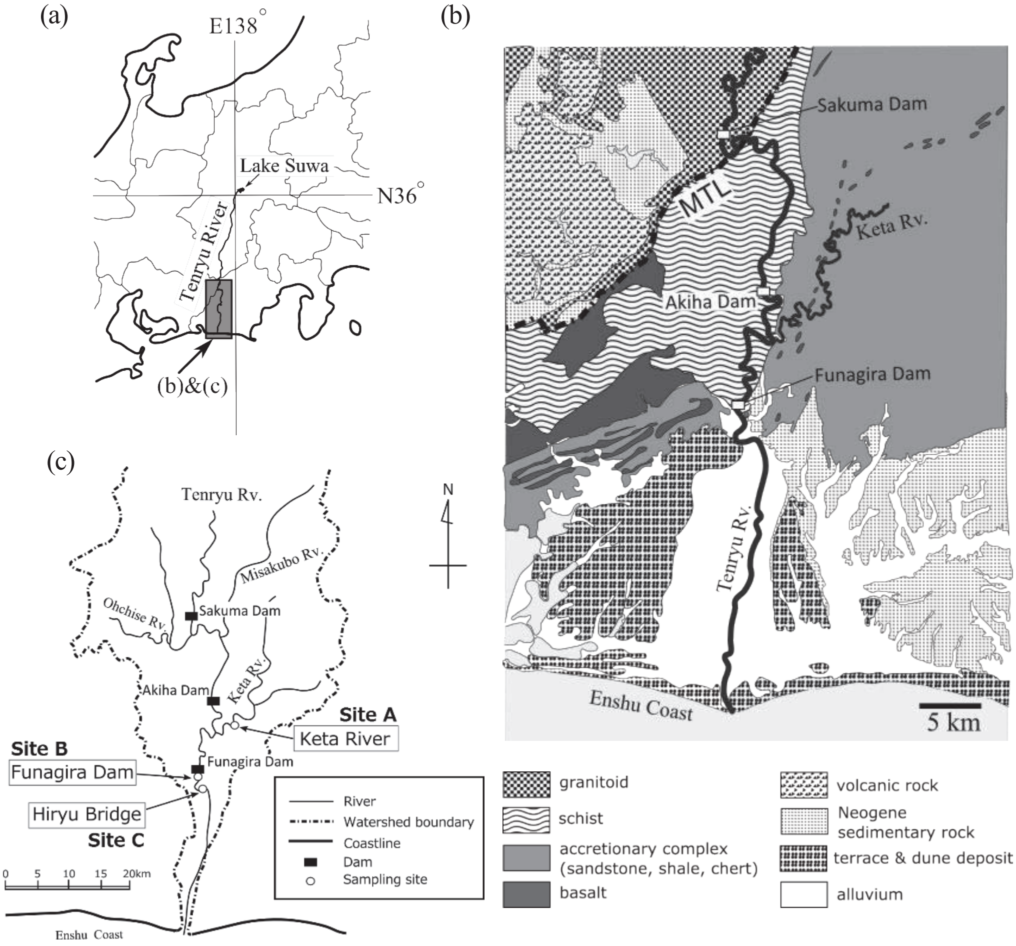

Fig. 1 (a) Index map; (b) Geological map; (c) Locality map of the study area in the watershed of Tenryu River in downstream reaches. Modified from Ashida *et al*. (2008).

3. Methods

Field survey

The authors collected 4–64 mm pebble gravel from lateral bars at sites near the stream shore. Intermediate diameter was selected for size evaluation, in agreement with sieving methodologies for grain size laboratorial determination. Gravel sizes of long, intermediate, and short axes were determined by first setting the minimum projection area (the product of orthogonal intermediate and short axes; Blott and Pye 2008).

The lithological composition of all sites indicates that shale grains are adequate for examining downstream changes in roundness, since this is a fragile, easily rounded lithology, and well represented in gravel and sand grain-sizes. Following the widely employed roundness silhouette chart, based on nine sets of standard roundness images (Krumbein 1941b) of which the parameter was originally defined by Wadell (1932), the roundness of approximately 100 shale pebble gravels were measured randomly in a 1 m × 2 m rectangle. In this study, the authors determined the roundness of the maximum projection area corresponding to the product of orthogonal long and intermediate axes (Sneed and Folk 1958). After gravel measurements, the finer sediments depositing beneath the gravels were sampled for laboratory analyses.

Laboratory analyses

The roundness of granules (2–4 mm in diameter), very coarse sand grains (1–2 mm in diameter), and coarse sand grains (0.5–1 mm in diameter) of shale was determined in the laboratory. Finer sediments obtained during the field survey were treated with 10% H_2O_2 for organic matter decomposition and sieved in 1 ϕ scale intervals. Approximately 100 shale grains of each size fraction were randomly extracted from finer sediment samples using a VHX-1000 digital microscope (KEYENCE Co. Ltd.). Approximately 50 grains were extracted for Site C, due to the insufficient amount of shale granules.

Grain roundness may be quantitatively assessed with adequate image analysis methodologies in an automated fashion. The authors used a particle image analyzer FF-30 micro installing the software PIA-Pro (Jasco International Co. Ltd.) to evaluate the grain roundness of each size fraction in this study. This computer software calculates a roundness parameter defined as “O. Bluntness” (Pirard 1993). Because the “Krumbein Roundness” was selected for measurement of pebble size fraction, “O. Bluntness” was converted to this standard roundness with a simple numerical treatment. Firstly, a series of hypothetical silhouettes yielding 0.1 to 0.9 roundness in 0.1 intervals, were drawn using suitable software. This parametric roundness was defined by Wadell (1932) as follows:

$$\text{Wadell (Krumbein) Roundness} = \sum {r_i}/{nR} \qquad (1)$$

where r_i is the individual radius of a circle inscribed in the ith corner of a grain, n is the number of corners and R is the radius of the maximum inscribed circle (Fig. 2a). Secondly, the prepared silhouettes (Fig. 2b) were analyzed with the FF-30 micro and their “O. Bluntness” were determined. As shown in Fig. 2c, it was confirmed that “O. Bluntness” was strongly correlated to “Krumbein Roundness” (R^2=0.96), and therefore a "Revised Roundness" may be determined from the following relationship:

$$\text{Revised Roundness} = 1.283 \times (\text{O. Bluntness}) - 0.272. \qquad (2)$$

This revised roundness was expressed by rounding off obtained values to one decimal place. For instance, a revised roundness ranging from 0.050 to 0.149 is expressed as “0.1.”

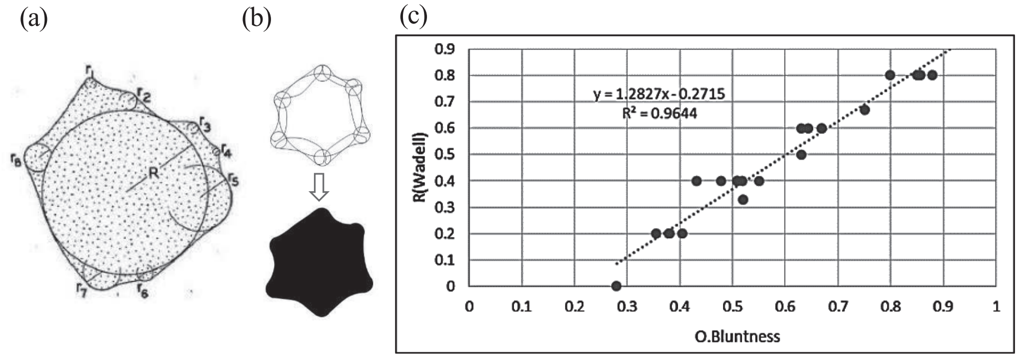

Fig. 2 Procedures for conversion from “O. Bluntness” to “Krumbein Roundness”:
(a) Scheme of roundness definition (Krumbein 1940).
(b) Schemes of original silhouette.
(c) Correlation between “O. Bluntness” and “Roundness”.

4. Results and Discussions

Definition of “breaking” and “abrasion”

In this study, the sand grain producing process is classified into two major types: breaking and abrasion. Considering the two mechanisms separately facilitates the evaluation of changes in both grain size and roundness affecting the original particles. As depicted in Fig. 3, the breaking process leads to grain size reduction and higher angularity. Inversely, the abrasion process gives rise to grain rounding while keeping nearly unchanged size (e.g. Barrett 1980). Note that, the pristine produced finer particles are angular.

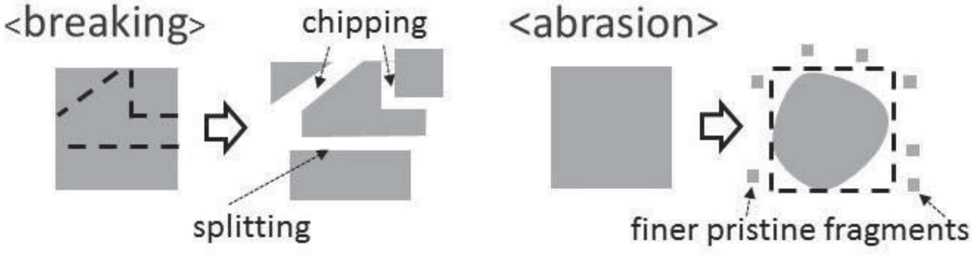

Fig. 3 Schemes of breaking and abrasion. Modified from Frings (2008).

Roundness

The shale grains from all sites yielding 0.5–0.7 roundness values were studied. The obtained statistical tendencies for shale roundness, concerning each grain size fraction are depicted in Fig. 4.

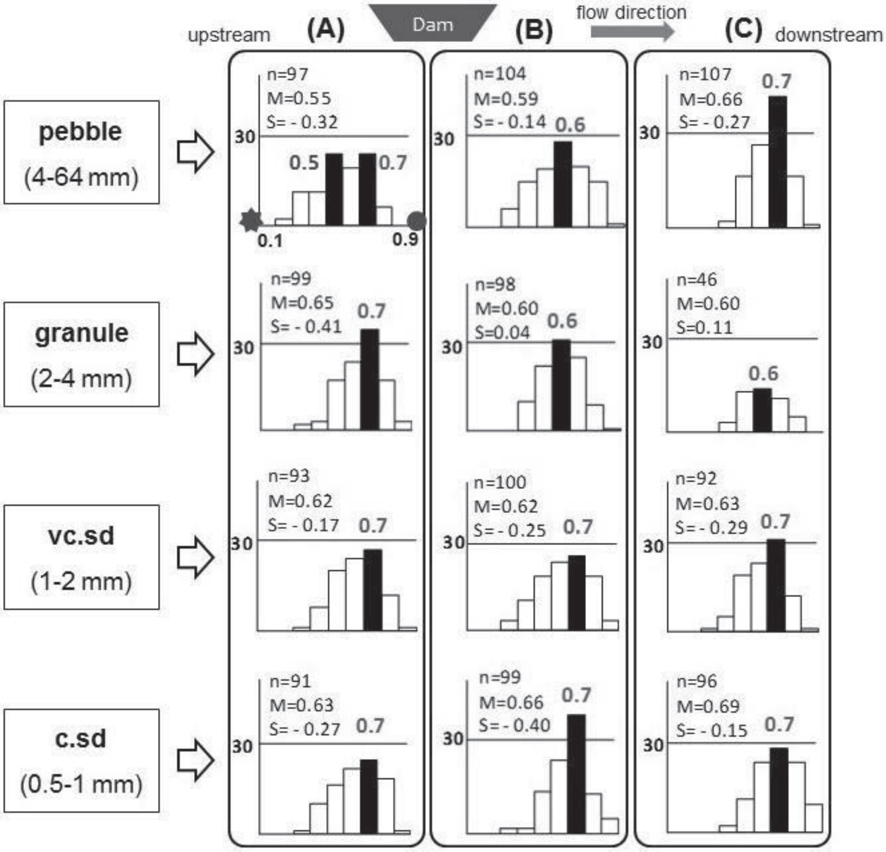

Fig. 4 Histogram of shale grain roundness based on the Krumbein silhouette chart (Krumbein 1941b). (A), (B) and (C) indicate each site shown in Fig. 1c and black columns indicate the mode in each histogram.
n = number of grain; M = mean; S = skewness.
vc.sd: very coarse sand, c.sd: coarse sand. Dam: Funagira Dam.

The modal roundness value of pebble size fraction at Site A reveals a wide roundness range and low skewness, reflecting the angular and rounded composite nature of shale grains in Keta River. As distance increases downstream from Site A to Site C, the pebbles become rounder as indicated by a progressively better-defined roundness modal value for each site. The mean roundness follows a downstream changes in 0.55 (A), 0.59 (B) and 0.66 (C), the latest being a particular high roundness value for pebble sized particles. These tendencies suggest that pebble sized grains are actively broken along tributary and downstream sites just below the dam, being predominantly abraded in downstream reaches. Therefore, pristine angular grains may have been produced from pebbles transported along the Tenryu River and its tributaries.

The mean roundness displayed by the granule size fraction of Site A is higher than those found for Sites B and C further downstream. If the granule size grains transported from the tributary passed through the dam, the more rounded grains should occur in downstream reaches. Therefore, the transport of granule grains was prevented by the dam and judging from the low roundness value of pebble gravels at Site B, new granule grains were necessarily produced from gravels deposited before dams construction in downstream reaches.

There are minor downstream changes in roundness affecting very coarse sand size fraction compared to granule size fraction, involving similar mean roundness values for all sites (0.62 for A and B, 0.63 for C). However, skewness values for Sites B and C are lower than that in Site A, pointing towards the formation of more angular grains in downstream reaches. Bearing in mind that particles passing through the dam should become rounded due to transport and abrasion, a downstream increase in angular grains reflects sedimentary transport interruption by the impoundment for very coarse sand, alongside granule-sized particles.

The mean roundness of coarse sand size fraction becomes higher downstream, in other words, coarse sand sized grains were rounded along the flow direction. Focusing on the values obtained for Site B, both mean roundness and skewness are high, suggesting the coexistence of two grain types within this size fraction in downstream sites. The more rounded grains could have been transported across the dam, and the angular grains could be related to breaking and abrasion of coarser grains (e.g. pebbles) in downstream reaches of the dam.

Consequently, pristine granule–sand sized grains can be produced from pebble gravels transported along the tributary of the Tenryu River and deposited on downstream reaches of the Funagira Dam. Additionally, although the impoundment obstacle interrupts the transport of coarser than ~1 mm-sized particles, active sand grain production occurs not only in upstream reaches but also in downstream reaches.

5. Conclusions

The sand grain producing–transport processes through the Funagira Dam were examined based on downstream changes in roundness of gravel–sand grains along the Tenryu River, focusing on downstream reaches. The authors focused on pebble–coarse sand grains of fragile shale.

The observed changes in roundness of shale particles show that:

i) Breaking and abrasion of pebbles may produce finer grains in both upstream and downstream reaches of the Funagira Dam;

ii) Particles finer than ~1 mm in diameter can be both transported through the Funagira Dam and produced from coarser grains in downstream reaches of the watershed.

Finally, investigating the mechanisms of sedimentary grain breaking and abrasion delivers important contributions for contriving appropriate countermeasures, based on a model of “fluvial sand grain production from gravels”. Considering effective sand grain production, the release point of dredged detritus will be set adequately in a river.

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