Evaluation of crush and abrasion phenomena in cobble gravels during transport in mountain rivers

Yasukazu KOSUGE 1, Yuji HASEGAWA 2, Yoshifumi SATOFUKA 3 and Takahisa MIZUYAMA 4

1 Japan Conservation Engineers Co., Ltd
(2-12-11 Kitaurawa, Urawa-ku, Saitama-shi, Saitama, 300-0074, Japan) E-mail: y-kosuge@jce.co.jp
2 Disaster Prevention Research Institute, Kyoto University (Gokasho, Uji-shi, Kyoto, 611-0011, Japan)
3 Departments of Civil Engineering, Ritsumeikan University (1-1-1 Noji-higashi, kusatsu-shi, Shiga, 525-8577, Japan)
4 National Graduate Institute for Policy Studies (7-22-1 Roppongi, Minato-ku, Tokyo, 106-8677, Japan)

Although the crush and abrasion phenomena associated with the downstream flow of riverbed gravel have long been studied, they still present a challenge. The crush and abrasion phenomena of gravel are not considered in river channel and erosion control plans in Japan. However, evaluating the crush and abrasion phenomena of gravel that flows down from mountain rivers is important from the viewpoint of the integrated management of sediment in a watershed. Thus, we conducted rotation crush and abrasion tests on nine cobble gravel rock types, ∼200 mm in diameter, which are normally distributed in mountain rivers, and determined the characteristics of the weight reduction rate ($\beta_r$) of cobble gravel by rock type and the grain size distribution of the sediment particles produced. Then, we conducted channel crush and abrasion tests to convert the crush and abrasion phenomena associated with the rotational movement of cobble gravel into those associated with the downstream flow of gravel in mountain rivers. The result of comparing the rates of weight reduction ($\beta_r$ and $\beta_s$) of cobble gravel in both tests showed that the rate of weight reduction ($\beta_r$) associated with rotation can be converted to the rate of weight reduction ($\beta_s$) closer to the downstream flow of cobble gravel in mountain rivers by multiplying the conversion rate $\alpha^*$ with the rotation-associated crush and abrasion coefficient $\alpha$ using Sternberg’s law.

Key words: Mountain river, reduction in grain size, crush and abrasion test, rate of weight reduction, crush and abrasion coefficient

1. INTRODUCTION

The size of riverbed gravel becomes smaller as it moves from upstream to downstream. However, this issue has long been a subject of debate (Sternberg, 1875; Wentworth, 1919). In river engineering in Japan, this is construed as being a result of the predominantly selective transport of running water (Yamamoto and Takahashi, 1993). However, in river geomorphology, some researchers consider this to result predominantly from crush and abrasion phenomena in the gravel (Kodama, 1990). Although it is generally considered to be due to both factors, this viewpoint is not universal. In the field of river engineering and erosion control, sediment transport and river bed variation can be explained by the selective transport of running water, without considering the crush and abrasion phenomena of gravel. Indeed, the crush and abrasion phenomena of riverbed gravel are not considered in river bed variation calculations performed when river channel and erosion control plans are developed (Japan Society of Civil Engineers editing, 1999; Japan Society of Erosion Control Engineering editing, 2000).

In a mountain river, the slope is steeper than in a downstream river and significant amounts of cobble gravel are distributed. In a watershed area where the geological conditions are fragile, it is expected that gravel will be crushed and abraded away to a small, rounded form at a comparatively early stage of transport, thus producing fine grain sediment. This fine grain sediment may have an influence on turbid water and dam sedimentation problems, as well as riverbed aggradation in the river area and in estuary and coastal areas.

In recent years, the need for integrated management of sediment, based on the concept of sediment transport systems, has been highlighted (The Integrated Management of Sediment Subcommittee, 1998). To determine the quality and quantity of sediment transported from a mountain river to a downstream...
river, the crush and abrasion phenomena of gravel need to be evaluated appropriately. For example, preventing movement of sediment from a bank collapse using a sabo dam and groundsel at a location near the source of the collapse not only reduces the transported sediment produced by crush and abrasion, but also the production of fine grain sediment; thus, sabo facilities should be reevaluated.

To date, abrasion tests of riverbed gravel have conventionally been conducted with a rotating cylindrical drum (Wentworth, 1919; Kuenen, 1956; Kodama, 1990; Mikos and Jaeggi, 1995). However, how to convert the abrasion phenomena of gravel due to rotational movement to those due to flow-down has not yet been determined. Based on the results of crush tests, in which gravel was made to be free-falling and crashed onto a test stand with a steel plate placed on a concrete chunk, Kosuge and Mizuyama (2001) evaluated grain size reduction in a saltation-focused model. However, if the basis of sediment transport is rolling and sliding rather than saltation, such an analysis will provide an overestimate. Additionally, because the abrasion phenomena of riverbed gravel primarily pertains a downstream river, most of test gravel is sand and small gravel. The largest gravel is typically ~128 mm; however, little research has examined gravel above 128 mm (Kodama, 1990; Mikos and Jaeggi, 1995). To our knowledge, there is no report comparing and studying the different, typical rock cobble gravel types found in Japan.

Thus, in this study, a rotation crush and abrasion test was conducted on gravel of ~200 mm that is found abundantly in mountain rivers, and on gravel of nine different rock types, using an easy-to-standardize method. Then, a channel crush and abrasion test was conducted to convert the crush and abrasion phenomena due to rotational movement to those due to downstream flow. Based on these results, the characteristics of the weight reduction of the various cobble gravel types by rotational movement, as well as the fine grain sediment produced, were determined; furthermore, how to convert rotational movement into the actual downstream flow is shown. Finally, how to apply the results from the rotation crush and abrasion test to the situation in actual mountain rivers is discussed.

2. TEST METHODS

2.1 Test gravel (Kosuge et al. 2010 a)

The cobble gravels used for the crush and abrasion test are the typical types of cobble gravel, ~200 mm in diameter, found in Japan. Of the rocks comprising the Japanese archipelago, sedimentary rocks are the most common, followed by volcanic, plutonic, and metamorphic rocks (Tamura and Shikano, 1995). Nine types of gravel, from mudstone and sandstone of the Tertiary era, shale, sandstone, chert, and limestone of the Paleozoic and Mesozoic era (all sedimentary rocks), andesite (volcanic rock), granite (plutonic rock), and greenstone (metamorphic rock), were selected for this study.

The gravels were collected in upstream areas of major rivers in the Kanto region (Fig. 1). Shale, sandstone, chert, limestone, and greenstone (Paleozoic and Mesozoic eras) were collected from the Kanna river of the Tone river system, andesite (Tertiary and Quaternary eras) from the Karasu river of the Tone river system, granite (Tertiary era plutonic rock) from the Komu river of the Fuji river system, and mudstone and sandstone (Tertiary era) from the Abe river. The collected test cobble gravels (average diameter ~200 mm, average weight ~9.6 kgf) were washed, dried, and weighed on a scale with a minimum unit of 1 g.

2.2 Rotation crush and abrasion test (Kosuge et al. 2010 a)

In this study, a standardized Los Angeles testing machine (Fig. 2; Japanese Standards Association, 2008) for abrasion testing of coarse aggregates was used as a rotating drum abrasion testing machine. In this crush and abrasion test of riverbed gravel, crush and abrasion were achieved by collisions between the gravel and the steel plate of the testing machine, or by direct contact between cobble gravels; therefore, steel balls were not used and the machine’s shelf was removed. Moreover, to facilitate testing, water was not added.

Three collected test gravel samples of each rock type were pooled into one sample, and three samples of each rock type – giving a total of 27 samples (9
rock types (3 samples) were prepared. Procedures for the rotation crush and abrasion test were as follows:
1) Place one sample in the testing machine and rotate it 30 times in 1 min.
2) Take out the entire sample, including the sediment produced.
3) From the sample, for gravel in diameter, including crushed gravel, measure the weight and diameter of gravels individually, and conduct a sieve-analysis test on sediment < 100 mm in diameter. Measure the weight of the sediment remaining on the screen using a scale with a minimum unit of 0.01 g.
4) After these procedures are finished, put the entire sample in the testing machine again and proceed to the next step: rotate the sample 30 times (giving a total of 60 rotations during 2 min), and repeat steps 2) and 3).
5) Repeat this operation for another 60 (total of 120 rotations during 4 min), 120 (total of 240 rotations during 8 min), 240 (total of 480 rotations during 16 min), and 480 rotations (total of 960 rotations during 32 min).

2.3 Channel crush and abrasion test (Kosuge et al. 2010 b)

This test was conducted to apply the results of the crush and abrasion test of cobble gravel with the Los Angeles testing machine to the crush and abrasion phenomena generated when cobble gravel flows downstream in an actual mountain river. For the test, an experimental channel that had an adjustable bed slope with a width of 30 cm, depth of 50 cm, and length of 500 cm was created (Fig. 3). On the experimental channel bed, cold finished steel bars of φ 30 mm were laid close together.

Four rock types — mudstone, chert, granite, and andesite — that showed characteristic results among the nine used in the rotation crush and abrasion test were selected for this test. The diameter of the gravel was again ~200 mm, and three gravel samples of each rock type (4 rock types × 3 gravels = 12 samples) were prepared.

The slope of the experimental channel was fixed at 30° so that the gravel would flow downstream without stopping. The test was conducted according to the following procedures:
1) Make cobble gravel ~200 mm in diameter flow downstream 5 m from the top of the experimental channel, and measure its weight afterwards using a scale with a minimum unit of 1 g.
2) With reference to the test results from the Los Angeles testing machine, repeat this downstream flow operation 110 times to match the result of 240 rotations (total rotation distance of 535 m; see below). The total downstream flow over 110 operations corresponds to a downstream flow of 550 m in the experimental channel.
3) When cobble gravel is crushed markedly, make all crushed gravel ~100 mm in diameter flow downstream individually.

3. RESULTS

3.1 Result of rotation crush and abrasion test

3.1.1 Rotation characteristics of testing machine and movement pattern of cobble gravel

The rotational speed, \( n \), of the Los Angeles testing machine was the same during the tests of all samples: \( n = 32.1 \) rpm. Because the inside diameter, \( D \), is 710 mm, the speed, \( v \), in the cylinder is:

\[
v = \frac{0.71 \times \pi \times 32.1}{60} = 1.19 m/s.
\]

This speed is high for the moving speed of gravel in an actual river.

Because the rotational distance of one rotation in the cylinder is 0.71 × \( \pi \) (m), the total rotational distance, \( L \), for the total number of rotations, \( n \), is expressed as in
Eq. (1): 67 m for a total of 30 rotations, 134 m for 60 rotations, 268 m for 120 rotations, 535 m for 240 rotations, 1,070 m for 480 rotations, and 2,141 m for 960 rotations.

\[ L_r = 0.71 \times \pi \times n \]  

Judging by the sounds emitted during testing, the movement patterns of the samples in the Los Angeles testing machine included a case in which rolling occurred with rotation of the testing machine, as well as a case in which, after sliding several times, rolling started; then, after again sliding several times, rolling started again. The flat cobble gravel shapes of the shale and mudstone samples showed the latter movement pattern, while the other rock types showed the former pattern.

### 3.1.2 Rate of weight reduction of gravel by rotation

Collision and friction between the cobble gravel and the steel plates in the cylinder of the testing machine, and collision and friction between cobble gravels, occurs with rotation of the testing machine: weight (grain size) is reduced, and finer sediment is produced. Weight reduction of cobble gravel associated with rotation is defined by Eq. (2), where \( \beta_r \) is rate of weight reduction of the cobble gravel after a total of \( n \) rotations, \( w_{0} \) is the weight of the cobble gravel before rotation, and \( w_{n} \) is the weight of the cobble gravel after \( n \) rotations.

\[ \beta_r = \frac{w_{n}}{w_{0}} \]  

**Fig. 4** shows the change in the average rate of weight reduction of cobble gravel by rock type according to the total number of rotations. Based on observations during testing, the characteristics of the rate of weight reduction (\( \beta_r \)) of cobble gravel are as follows:

1) With an increase in the number of rotations, the rate of weight reduction for cobble gravel is described by a curve, in which it decreases gradually; the change in rate of weight reduction varies by rock type.

2) The rate of weight reduction is in the order of shale (Paleozoic and Mesozoic eras) > mudstone (Tertiary era) > chert > greenstone > limestone > sandstone (Tertiary era), granite > andesite, sandstone (Paleozoic and Mesozoic eras).

3) For cobble gravel of shale (Paleozoic and Mesozoic eras), mudstone (Tertiary era), chert, and greenstone, with a high rate of weight reduction crush phenomena occur, showing a tendency whereby crush is larger in the initial stages of rotation, and then decreases.

4) For cobble gravel of limestone, granite, sandstone (Tertiary era), andesite, and sandstone (Paleozoic and Mesozoic eras), with a low rate of weight reduction, abrasion phenomena are more important than crush phenomena.

### 3.1.3 Crush and abrasion of cobble gravels and fine sediment production by rotation

**Fig. 5** shows changes in the average grain-size accumulation curve of sediment produced from cobble gravel of each rock type by crush and abrasion, according to an increasing number of rotations. The figure shows the following:

1) The grain size accumulation curves of sediment produced from cobble gravel of shale (Paleozoic and Mesozoic eras) and mudstone (Tertiary era), with a high rate of weight reduction show a pattern of change in which sediment of each grain size is produced roughly evenly and becomes finer with an increasing number of rotations.

2) The grain size accumulation curves of sediment produced from cobble gravel of chert and greenstone, i.e., the rocks with the next highest rate of weight reduction, also show roughly the same pattern of change as those of shale and mudstone; however, there is a tendency to produce a large amount \( \leq 2 \text{ mm} \) in diameter.

3) The grain size accumulation curves of sediment produced from cobble gravel of limestone, granite, sandstone (Tertiary era), andesite, and sandstone (Paleozoic and Mesozoic eras), with a lower rate of weight reduction, show a pattern of change in which fine sediment \( \leq 2 \text{ mm} \) in diameter is produced mostly due to an increasing number of rotations.

### 3.2 Channel crush and abrasion test

#### 3.2.1 Downstream flow speed and pattern of gravel flow

The average downstream flow speed of cobble gravel \( \sim 200 \text{ mm} \) in diameter that flowed down the experimental channel with a slope of 30° is 1.9–2.6
m/s (average, 2.2 m/s) for each rock type. Downstream flow patterns of cobble gravel include sliding, rolling, and saltation; with flat mudstone in particular, sliding was observed more often than with cobble gravel of the other rock types. The downstream flow patterns of cobble gravel of chert, granite, and andesite were primarily rolling and saltation.

3.2.2 Rate of weight reduction of cobble gravel due to downstream flow

Fig. 6 shows the change in the rate of weight reduction ($\beta_s$) when cobble gravel of each rock type, ~200 mm in diameter, flowed down a 5 m experimental water channel bed 110 times (total flowing-down distance, $L=550$ m). Fig. 6 shows the following:

1) Changes in the rate of weight reduction of cobble gravel of each rock type due to downstream flow showed a trend similar to that caused by rotation with the Los Angeles testing machine; the rate of weight reduction is in the order of mudstone > chert > granite > andesite.
2) The rate of weight reduction for cobble gravel of each rock type due to downstream flow is equal to or less than that caused by rotation with the Los Angeles testing machine.

4. DISCUSSION

4.1 Rate of weight reduction and sediment production due to rotation of cobble gravel of different rock types

The rate of weight reduction ($\beta_r$) of cobble gravel
of weight reduction (β) of cobble gravel produced by rotation in a Los Angeles testing machine to that obtained using an experimental channel was considered. If the rate of weight reduction (β) of cobble gravel of each rock type, according to the downstream flow in an actual river, can be found, then the grain-size accumulation curve of produced sediment corresponding to the rate of weight reduction can be estimated from the results of the Los Angeles testing machine rotation test.

Generally, as gravel flows down, it collides with other gravel, is abraded, and becomes smaller gradually. H. Sternberg (1875) considered the weight reduction of gravel due to downstream flow to be proportional to abrasion resistance and also that, although riverbed gravel flows down a small distance, it is still subject to abrasion and its weight, W, decreases by $dW = W_0 e^{-\alpha L}$. Thus, Eq. (3) was derived and is referred to as Sternberg’s law (Aki, 1951).

\[ W = W_0 e^{-\alpha L} \]  

(3)

where $W_0$ is the weight of the riverbed gravel (g) at $L=0$, $W$ is the weight of the riverbed gravel (g) after it flowed down $L$ (m), $L$ is the flowing-down distance (m), and $\alpha$ is the abrasion resistance (crush and abrasion coefficient is constant due to the quality of the gravel, m$^{-1}$). If Eq. (3) is transformed, the rate of weight reduction (β) can be expressed as follows:

\[ \beta = \frac{dW}{W} \]
Then, the total rotational distance, $L_r$, shown in Eq. (1), obtained from the crush and abrasion test of gravel by rotation with a Los Angeles testing machine is used and assumed to be the downstream flow distance, $L$. Then, the total downstream flow distance, $L$, obtained from the channel crush and abrasion test is assumed to be the same as the assumed downstream flow distance, $L_r$, obtained from the rotation crush and abrasion test, to allow comparison of relationships between the downstream flow distances and rates of weight reduction on semi-logarithmic paper (Fig. 7). The figure shows that the rate of weight reduction ($\beta_r$) in the Los Angeles machine rotation crush and abrasion test, and the rate of weight reduction ($\beta$) obtained from the channel crush and abrasion test, show the same trends. Moreover, with each rock type, the rate of weight reduction ($\beta_s$) obtained from the channel crush and abrasion test is equal to (in the case of mudstone) or lower than the rate of weight reduction ($\beta_r$) obtained with the rotation crush and abrasion test.

4.3 Application of results of the rotation crush and abrasion test of cobble gravel to a mountain river

Based on the results above, a method of converting the rate of weight reduction ($\beta_r$) of cobble gravel obtained from the Los Angeles machine rotation crush and abrasion test to approximate the rate of weight reduction ($\beta_s$) in an actual mountain river was developed, as follows:

1) Apply Eq. (4) to relationships between downstream flow distances ($L_r$ and $L$) and rates of weight reduction ($\beta_r$ and $\beta_s$) by rock type to evaluate $\alpha$.

2) Compare the crush and abrasion coefficient $\alpha_s$ obtained from the rotation crush and abrasion test with the crush and abrasion coefficient $\alpha_r$ obtained from the channel crush and abrasion test to calculate the conversion rate $\alpha^* = \alpha_s / \alpha_r$. That is, with the conversion rate $\alpha^*$ of each rock type determined, multiply this conversion rate $\alpha^*$ by the crush and abrasion coefficient $\alpha_r$ obtained from the Los Angeles machine rotation crush and abrasion test to convert it to the crush and abrasion coefficient $\alpha_s$ in an experimental channel, that is, an actual river.

Table 1 shows $\alpha$, $\alpha_s$, and $\alpha^*$ values obtained from Fig. 7 according to the method above. From the table, the following are assumed:

1) The rate of weight reduction ($\beta_r$) of cobble gravel obtained from the Los Angeles machine rotation crush and abrasion test can be converted to a value close to the rate of weight reduction due to the downstream flow in an experimental channel (that is, an actual river) by multiplying the conversion rate $\alpha^*$ by the crush and abrasion coefficient $\alpha_r$.

2) The conversion rate $\alpha^*$ of a rock type, such as mudstone, which is easy to crush and abrade away is 1.07; that of a rock type such as chert, which is easy to crush and abrade away, is 0.41, and that of rock types, such as granite and andesite, that are more difficult to crush and abrade away are $0.09 \sim 0.58$.
That is, with the conversion rate $\alpha^*$ of the crush and abrasion coefficient of each rock type determined, the crush and abrasion coefficient $\alpha$, which is close to that in an actual mountain river (experimental channel), can be calculated by multiplying $\alpha^*$ by the crush and abrasion coefficient $\alpha$, obtained from the Los Angeles machine rotation crush and abrasion test. The rate of weight reduction ($\beta$) of cobble gravel due to downstream river flow can also be estimated. If the rate of weight reduction ($\beta$) can be calculated, the volume of nonuniform sediment can also be calculated according to grain size from the grain-size accumulation curve describing the sediment produced, obtained from the rotation crush and abrasion test and based on the rate of weight reduction.

However, because the average downstream flow speed in the channel crush and abrasion test conducted in this study was 2.2 m/s, larger values relative to the actual crush and abrasion may have resulted. In the application of these values to an actual river, correction of the conversion rate discussed here needs to be studied further. Additionally, more studies are needed regarding how to calculate sediment discharge in consideration of the crush and abrasion phenomena in cobble gravels.

5. CONCLUSIONS

The conclusions of this study are as follows:

1) The rate of weight reduction ($\beta$) of cobble gravel ~200 mm in diameter, and the grain-size accumulation curve of the produced sediment, can be obtained from a rotation crush and abrasion test using a Los Angeles testing machine and characterized by rock type.

2) The rate of weight reduction ($\beta$) of cobble gravel ~200 mm in diameter, of each rock type due to downstream flow obtained from a channel crush and abrasion test, showed changes similar to those in the rate of weight reduction ($\beta$) obtained from the rotation crush and abrasion test. The rate of weight reduction ($\beta$) obtained from the channel crush and abrasion test was equal to or lower than the rate of weight reduction ($\beta$) obtained from the rotation crush and abrasion test; these also were characterized by rock type.

3) With the conversion rate $\alpha^*$ determined, the crush and abrasion coefficient $\alpha$ in an actual mountain river in Eq. (4) can be calculated by Sternberg’s law using the results of the rotation crush and abrasion test with the Los Angeles testing machine. If the crush and abrasion coefficient $\alpha$ is found, the rate of weight reduction ($\beta$) of gravel due to downstream flow can be determined. Using the grain-size accumulation curve corresponding to the rate of weight reduction ($\beta$) obtained from the rotation crush and abrasion test, the volume of sediment produced can be calculated by grain size.

4) However, because the channel crush and abrasion test in this study may give larger values relative to crush and abrasion in an actual mountain river, for application of the values to an actual river the conversion rate $\alpha^*$ discussed here needs to be corrected.

ACKNOWLEDGMENT: This work was an independent study by the Civil Engineering Laboratory. For the on-site collection of riverbed cobble gravel, we express our gratitude to the persons involved at the Tone River System Sabo Office and the Fuji River Sabo Office, Kanto Regional Development Bureau, the Ministry of Land, Infrastructure, Transport and Tourism, the Shizuoka River Office, Chubu Regional Development Bureau, the Ministry of Land, Infrastructure, Transport and Tourism, the Gunma-prefecture Fujioka Civil Engineering Office, and the Takasaki Civil Engineering Office.

REFERENCES

Aki, K. (1951) : Kashoron, Iwanami Shoten, pp. 66-67 (in Japanese)

Japanese Standard Association (2008) : IIS Handbook <Civil Engineering 12008 >, pp. 1563-1569 (in Japanese)

Japan Society of Civil Engineering, Hydraulic Engineering Committee Editing (1999) : The Collection of Hydraulic Formulae [1999 version], pp. 174-176 (in Japanese)

Japan Society of Erosion Control Engineering Editing (2002) : Numerical calculation method of river bed variation in mountain rivers, 143 p. (in Japanese)

Kodama, Y. (1990) : ERC-ABRATION-MIXER Experiment of River-Bed Gravels from the Watarase River, Bulletin of the Environmental Research Center, the University of Tsukuba, No. 14, pp. 115-130 (in Japanese)

Kosuge, Y. and Mizuyama, T. (2001) : Sutady on the reduction in grain sizes of river bed material being in downstream transport, Japan Society of Erosion Control Engineering, Vol. 54, No. 1, pp. 39-47 (in Japanese with English abstract)

Kosuge, Y., Hasegawa, Y., Satofuka, Y and Mizuyama, T. (2010 a) : Experiments on crush and abrasion of cobble gravels during transport, Japan Society of Erosion Control Engineering, Vol. 62, No. 5, pp. 3-11 (in Japanese with English abstract)

Kosuge, Y., Shozawa, M., Hasegawa, Y., Satofuka, Y and Mizuyama, T. (2010 b) : Crush and abrasion tests of cobbles and grabels, Japan Society of Erosion Control Engineering, Vol. 63, No. 2, pp. 3-11 (in Japanese with English abstract)

Kuenen, Ph. H. (1956) : Experimental abrasion of pebbles 2. Rolling by current, Journal of Geology, 64, pp. 336-368

Lama, R. D. and Vutukuri, V. S. (1992) : Handbook for rock and rock bed engineers, Dynamic properties of rock II —
Technology and results relevant to test 

Mikos, M. and Jaeggi, M. R. (1995) : Experiments on motion of sediment mixtures in a tumbling mill to study and fluvial abrasion, Journal of Hydraulic Research, Vol. 33, No. 6, pp. 751-772

Sternberg, H. (1875) : Untersuchungen über Längen und Querprofil geschiebeführender Flüsse, Zeitschrift für Bauwesen, 25, pp. 483-506

Tamura, Y. and Shikano, K. (1995) : Distribution area of rocks that construct the Japanese archipelago obtained from the “Millionth Japanese geological map, ver. 3, CD-ROM”, GSJ Chishitsu News, No. 493, pp. 26-29 (in Japanese)

The integrated management of sediment subcommittee (1998) : For the integrated management of sediment in a sediment system, The River Council General Policy Board, Report, 17 p. (in Japanese)

Wentworth, C. K. (1919) : A laboratory and field study of cobble abrasion, Journal of Geology, 27, pp. 507-522

Yamamoto, K. and Takahashi, A. (1993) : River channel characteristics and river channel improvement in alluvial fan river, Technical note of Public Works Research Institute, No. 3159, pp. 236-247 (in Japanese)

Received : 24 August, 2016
Accepted : 3 October, 2016