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The Estimate Method of Erosion Rate of Cohesive Materials (CRL-AET)

THE ESTIMATE METHOD OF EROSION RATE OF COHESIVE MATERIALS (CRL-AET)

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River bank erosion has a considerable influence on sediment production in mountain area. Since river bank soils are generally cohesive, ordinary sediment transport equations are inapplicable. Because characteristic of the cohesive materials are different every place. And it is difficult to carry materials to the examination room. Therefore the relationship the cohesion of materials and the erosion rate are not clear. The river bank resistance to erosion or the erosion rate of river bank is evaluated by way of water jet tests (CRL-AET). From the results of erosion rate obtained by flume experiments, the erosion rates obtained by water jet tests are then converted into the relationships between the erosion rates and the frictional velocities. Moreover, it has been clarified that the erosion rate is proportional to the -0.4th power of erosion time. The erosion rate decreases as river bank cohesion increases. The erosion rate of cohesive material increases as d_{60} increases.

Key Words : *river bank erosion, anti-erosion test, cohesive material, jet test, flume test*

1. INTRODUCTION

River bank erosion influences the estimate of outflow sediment quantity volume in a river, which has an effect on erosion control planning. However, in many cases, river bank erosion is not included in numerical computations or physical experimental models because of paucity of field data and difficulty estimating it in practice.

There have been previous studies of the erosion of the cohesive soil and clay generally found in torrent banks. Ashida and Tanaka (1974) determined the relationship between the erosion rate and shear through erosion experiments with bentonite. Otsubo and Muraoka (1982) examined the relationship between the non-dimensional erosion rate and the non-dimensional tractive force for bottom mud with high water content. Ashida *et al* (1982) developed an equation for the relationship between the erosion rate and the pick-up rate when clay exfoliates in the form of lumps. In addition, Sawai (1994) conducted a detailed review of erosion and the sedimentation of cohesive materials, which included his own research results and pointed out a problem that erosion rate is different in the same materials because test method is different. More recently, Sekine and Nishimori (2004) reported the relationships between the erosion rate, water content in cohesive soil, clay composition, particle size, and the temperature of the current based on the results of systematic flume experiments with cohesive materials.

However, there has been little research regarding the erosion of cohesive materials in torrent banks. Ikeya and Bando (1982) carried out an erosion experiment using the jet from a pump, and Ou (1993) performed similar experiments using a ground erosion resistance testing machine. As the type of cohesive material differs from one location to another and it is difficult to test undisturbed materials in a laboratory setting, the relationship between cohesive material strength and erosion rate is still not understood. The prediction of river bank erosion is an important subject, and the development of a simple measurement technique for river bank erosion prediction is required.

The aim of this study was to determine the relationship between the erosion rate of a river bank caused by a jet of water and the flow in a rectangular flume. Attention was paid to the study of Ikeya and Bando (1982), which examined the erosion caused by the jet from a pump. Depth of the erosion of a river bank was measured using CRL-AET ("Civil Engineering Research Laboratory Anti-erosion Test"). We carried out separate erosion experiments using a jet and a rectangular flume, and studied the erosion rate of cohesive materials and other factors, such as the cohesive force.

2. JET EXPERIMENT SUMMARY

The jet experiment tests we carried out using river bank materials from twenty nine locations including samples from volcanic areas (Table 1). Clay samples with an initial water content of 10% were prepared by mixing bentonite with dry sand of mean diameter 0.25mm. The weight ratio of bentonite and dry sand are 2.5-40%. The cohesion of the material was measured by undrain triaxial compression test, and the grain size distribution was evaluated by sieve test and hydrometer analysis.

An electromotive type of spray (maximum capacity of 15 ℓ) with a 1.2 mm diameter nozzle was used for the jet experiment. The jet was directed perpendicular to the test material (Photo. 1).

The jet distance from the nozzle to the material surface was initially set at 50 cm. The jet was directed continuously at different points in the same material for 10 s, 20 s and 30 s, and the depth of erosion from the initial surface was measured for each case.

Table 2 Properties of materials.

Material No.	Material type	Erosion rate of 30 s, E_j (cm/s)	d_{60} (mm)	Cohesion c(kN/m^2)
1	Silt and clay (river bank)	0.15	0.037	29.7
3		0.52	0.27	4.75
6		0.073	0.035	58.1
7		0.17	0.069	10.6
9		0.27	0.026	31.8
10		0.070	0.0084	42.9
11		0.19	0.17	15.4
12		0.26	0.39	5.46
13		0.28	0.29	15.7
14		0.13	0.058	23.2
15		0.053	0.048	34.2
16		0.15	0.084	16.0
17		0.32	0.043	18.3
18		0.053	0.031	82.3
19		0.22	0.036	31.0
20		0.023	0.065	60.4
21		0.33	0.43	5.75
22		0.14	0.038	39.2
23		0.18	0.060	21.5
24		0.18	0.052	33.7
25		0.027	0.063	39.1
26		0.25	0.087	22.2
27		0.16	0.043	17.7
28		0.26	0.083	8.30
29		0.24	0.088	20.9
30		0.13	0.081	32.8
31		0.16	0.080	19.6
32		0.51	0.16	22.1
33		0.17	0.069	15.7
34	Sieved clay	0.073	0.010	32.1
35		0.078	0.011	30.0
36		0.14	0.0045	16.3
37		0.083	0.011	22.7
38		0.083	0.0080	22.5
39	The mixture of dry sand and bentonite	0.67	0.25	6.02
40		0.68	0.25	11.2
41		0.72	0.25	9.62
42		0.92	0.25	7.99
43		0.49	0.24	18.0
44		0.28	0.22	30.7
45		0.14	0.025	21.1
46	Volcanic clay(Miyake island)[1)]	0.22	0.065	32.4
47		0.15	0.11	21.4
48		0.27	0.097	21.7

Photo.1 Situation of the jet experiment for river bank.

3. JET EXPERIMENT RESULTS

(1) Erosion rate

Figure 1 shows the relationship between the jet duration time (t) and the erosion rate ($E_j=z_i/t_i$: z_i is erosion depth at $t=t_i$) for each type of natural material. In table 2, GS refers to sand, GS-F refers to sand with fine sand, MH refers to silt, and SF refers to fine sand. The erosion rate for all materials decreased with increasing jet duration. This tendency was similar for clay and a mixture of dry sand and bentonite. As erosion progresses, back flow occurs in the hole eroded by the jet, and this reduces the jet velocity at the bottom of erosion hole (Fig.2, Mining and Materials Processing Institute of Japan, 1994). The relationship between the jet time and the erosion rate is shown by the Eq. (1) :

$$E_j = f(t) \tag{1}$$

where E_j is the erosion rate due to the jet, and t is the continuous jet duration.

The erosion rate of sample No.2 did not change, and the erosion rate of was initially extremely low (Fig.1). The reasons for this are as follows.

In many cases, cohesive materials such as silt in a torrent bank are mixed with stone. After a stone is dislodged by the jet, the erosion rate increases significantly. On the other hand, the erosion rate decreases significantly when the stone does not move. No.2 in Fig.1 was river bank material, which included 5% stones approximately 10 mm in diameter. For this sample, the erosion rate did not change because these stones did not move during the jet experiment.

(2) Relationship between cohesion and erosion rate

Figure 3 shows the relationship between erosion rate (E_j) and cohesion (c) for a jet time, t of 30 s. The erosion rate decreased as the cohesion increased. Even if the cohesion is the almost same, the erosion rates were plotted widely. This may be because the changes in erosion rate also depend on some factor(s) other than the cohesion. This tendency was similar for continuous jet times of 10 s and 20 s.

(3) Relationship between particle size and erosion rate

The erosion rate seemed to depend on some factor(s) other than the cohesion of the material. We considered the particle size and examined the relationship between the 30-second erosion rate. The results are shown in Fig. 4.

The erosion rate tended to increase with increasing particle size. As well as the cohesion, the 60% particle size d_{60} appears to have a large effect. It was assumed that the void between the sand particles is filled with clay, and that the cohesion between particles decreases as the quantity of clay decreases. The porosity, λ, for grains of sand alone is shown in Eq. (2). If particle size becomes large, then λ declines (Komura,1982).

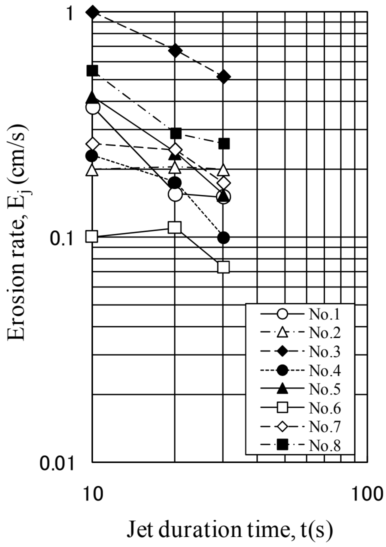

Fig.1 Relationship between the jet duration time and the erosion rate for natural materials.

Table 2 Properties of natural materials.

Material No.	Simbol of classification of materials	Water content (%)	d_{60} *) (mm)	Cohesion c(kN/m^2)
1	MH	38.7	0.037	29.7
2	MH	40.0	0.054	—
3	SF	18.9	0.27	4.75
4	GS	2.90	8.2	—
5	GS-F	10.9	7.8	—
6	MH	43.6	0.035	58.1
7	MH	40.9	0.069	10.6
8	GS	4.80	16	—

*) d_{60} is the 60% particle size of cumulative curve.

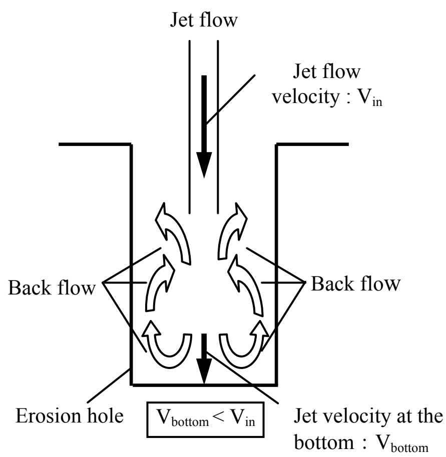

Fig.2 Sketch of the flow patern in an erosion hole.

$$\lambda = 0.245 + 0.0864 d_{50}^{-0.21} \tag{2}$$

where d_{50} is the median diameter (cm).

And this may be because erosion of clay under the effect of a jet takes place in lups, as reported by Sekine (2004) in flume erosion experiments.

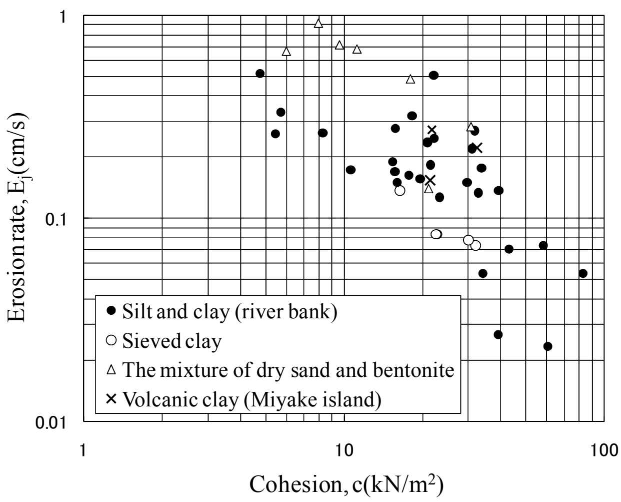

Fig.3 Relationship between cohesion and the erosion rate.

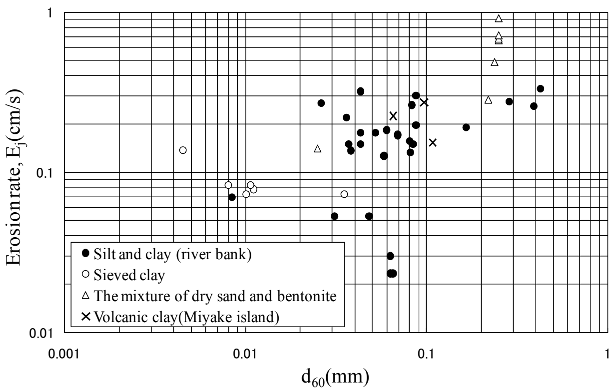

Fig.4 Relationship between d_{60} and the erosion rate.

4. FLUME EXPERIMENT SUMMARY

The rectangular flume used for the experiment was 50 cm wide with a 1 V : 20 H bottom slope. The mixture of dry sand (the 60% particle size (d_{60}) of cumulative curve is 0.25mm) and bentonite was in a rectangular pit 10 cm wide, 2.0 m long, and 5.0 cm deep in the bottom of the flume (Photo.2 and Table 3).

Before the initial discharge, the flume was filled with water so that no erosion would take place. Once the flume was full, we opened the weir at the downstream side. The experiment started once the water depth of the downstream edge of the pit section was equal to the uniform flow depth. Once we had measured the erosion depth, the water level was raised slowly by operating weir so that erosion do not occur near edge of the pit section.

5. FLUME EXPERIMENT RESULTS

(1) Erosion rate in the flume experiment

The relationship between the time and the erosion rate of No.44 and No.45 is shown in Fig.5. As in the jet experiment, the erosion rate decreased with time. After a certain time, the surface of the cohesive material was lower than the fixed flume bottom surface, and it is likely that the tractive force decreased .From these figures, the experimental data were arranged as shown in Eq. (3), as in the jet experiment. However, in the experiment with a 20% weight ratio of bentonite to dry sand, the material surface rose early because of the swelling of bentonite, and these data were not used in the analysis because the erosion rate E was extremely low.

$$E = g(t) \tag{3}$$

where E is the erosion rate due to the flow, and t is the continuous experiment duration.

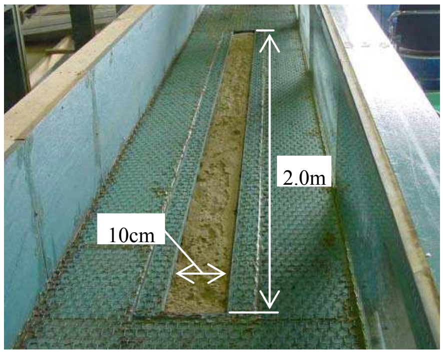

Photo.2 The rectangular flume for experiment.

Table 3 Flume experiment conditions.

Material No.	Weight ratio of bentonite to dry sand(%)	Discharge(ℓ/s)**			
		2.0	5.0	10	20
39	2.5	○			
40	2.5	○			
41	2.5	○			
43	10	○	○	○	○
44	20	○		○	○
45	40	○		○	○

**) ○:Expreimented

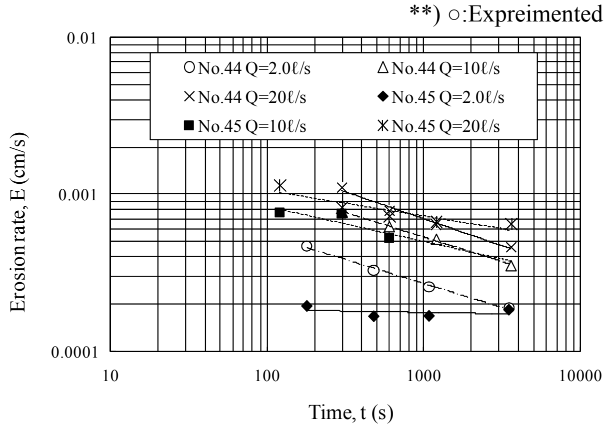

Fig.5 Relationship between the time and the erosion rate.

A similar phenomenon was reported by Fukuoka et al. (1993) who carried out an experiment on the natural sedimentation bank of a river.

The governing factors in this process was examined. The discharge rate and the weight ratio of the bentonite to dry sand are important parameters in the relationship between the time and the erosion rate (Fig.5).

(2) Relationship between friction velocity and erosion rate

Focus was placed on the friction velocity as it was related to the discharge. Eq. (3) was expressed in the form shown in Eq. (5), and subsequently plotted these as functions of the coefficient *a*. The friction velocity u_* was calculated from the depth of the water *h*, which was measured at the start of the erosion experiment using Eq. (4).

$$u_* = (ghi)^{0.5} \tag{4}$$

where *g* is acceleration of gravity and *i* is the flume bottom slope (*i* = 1/20).

$$E = a \cdot t^b \tag{5}$$

The resulting relationship between *a* and u_* is shown in Fig.6 for different weight ratios of bentonite. The weight ratio of the bentonite was related to the changes in the erosion rate over time in the flume just as it was for the jet.

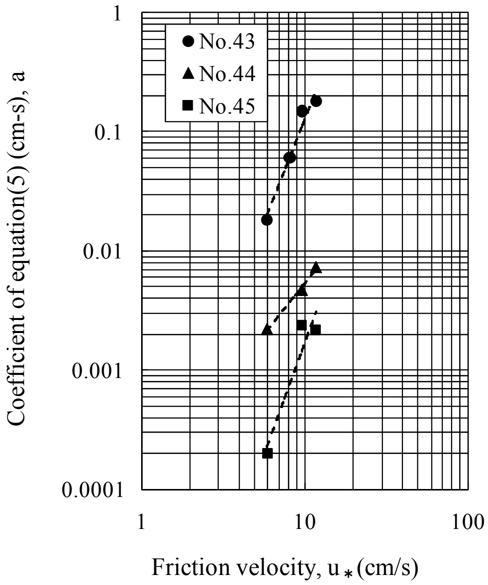

Fig.6 Relationship between *a* and u_*.

6. DIMENSIONAL ANALYSIS OF THE RELATIONSHIP BETWEEN EROSION RATE AND TIME

It was clear that each coefficient in the jet and flume experiments was influenced by the properties of the cohesive materials. Therefore, we combined the data of the jet and flume experiments to determine an equation relating erosion rate and time using dimensional analysis. It was clear that each coefficient in the jet and flume experiments was influenced by the properties of the matter value of the cohesive materials. Therefore, we combined the data of the jet and flume experiments to determine an equation relating erosion rate and time using dimensional analysis.

(1) Relationship between erosion rate and time in the jet experiment

Equation (6) shows the basic physics related to the erosion rate in the jet experiment. From this relations, we determined the erosion rate and non-dimensional time arranged by experimental value.

$$F\left(E_j, t, v, d_{60}, c, \rho_s\right) = 0 \tag{6}$$

where v is average velocity at the jet nozzle exit and ρ_s is the wet density of cohesive materials. Equation (7) follows Eq. (6).

$$\phi\left(\frac{E_j}{v}, \frac{t}{d_{60}}\sqrt{\frac{c}{\rho_s}}\right) = 0 \tag{7}$$

Figure 7 shows the results arranged by the data for the erosion rate according to Eq. (7) excluding sandy materials. The relationship between E_j/v and is shown in by Eq. (8).

$$\frac{E_j}{v} = 3.428\left(\frac{t}{d_{60}}\sqrt{\frac{c}{\rho_s}}\right)^{-0.420} \tag{8}$$

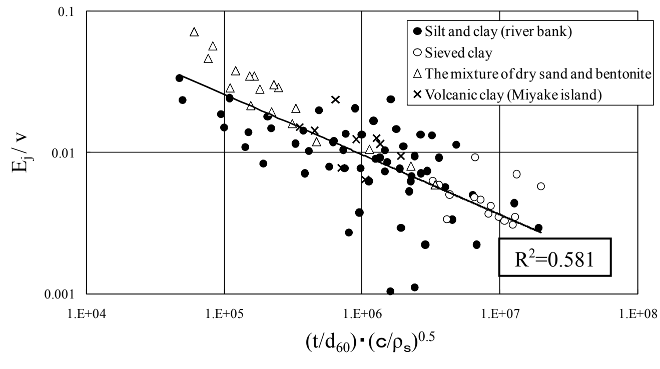

Fig.7 Relationship between $(t/d_{60})/(c/\rho_s)^{0.5}$ and E_j/v.

(2) Relationship between erosion rate and time in the flume experiment

Equation (9) shows the basic physics related to the erosion rate in the flume experiment. This is very similar to the case of the jet experiment with the friction velocity u_* in place of the average jet velocity. This is because the erosion rate in the flume experiment is related to the friction velocity, as shown in Fig. 10, and the results of a great deal of previous research have shown that the erosion rate is a function of the shear force(Sawai (1994), Sekine and Nishimori (2004) etc.). From these relationships, the erosion rate and non-dimensional time can be arranged by the data for the erosion rate.

$$G\left(E, t, u_*, d_{60}, c, \rho_s\right) = 0 \tag{9}$$

Equation (10) follows from Eq. (9).

$$\varphi\left(\frac{E}{u_*}, \frac{t}{d_{60}}\sqrt{\frac{c}{\rho_s}}\right) = 0 \tag{10}$$

The results are shown in Fig. 8 arranged by the data for the erosion rate according to Eq. (10). The relationship between E/u_* and $(t/d_{60})/(c/\rho_s)^{0.5}$ is shown in by Eq. (11).

$$\frac{E}{u_*} = 0.0362\left(\frac{t}{d_{60}}\sqrt{\frac{c}{\rho_s}}\right)^{-0.437} \tag{11}$$

(3) Relationship between erosion rate and time in the jet and flume experiment

The right-hand sides of both Eqs. (8) and (11) are non-dimensional time produced by dimensional analysis. As the variables are the same in both the jet and flume experiments, we eliminated these non-dimensional times from both equations to produce Eq. (12), which shows the relationship between time and erosion rate in the jet and flume experiments.

$$\frac{E}{u_*} = 0.0100\left(\frac{E_j}{v}\right)^{1.04} \tag{12}$$

If we can determine the erosion rate with a jet experiment, then we can estimate the erosion rate of the cohesive materials of the river bank.

7. CONCLUSIONS

We performed dimensional analysis based on the erosion results of cohesive materials by jet and flume experiments, and determined the relationships between erosion rate and time for both. Furthermore, we combined the erosion rates from the two experiments using non-dimensional time, and proposed Eq. (12).

We have shown that it is possible to estimate the river bank erosion rate through a jet experiment (CRL-AET), which could be used as a simple testing and prediction technique for river bank erosion. However, limited actual data are available to allow the technique to be tested under field conditions, and we have not yet studied the effects on the erosion rate of changes in shape of the erosion aperture in the jet experiment. Further testing is therefore required to confirm the validity of Eq. (12).

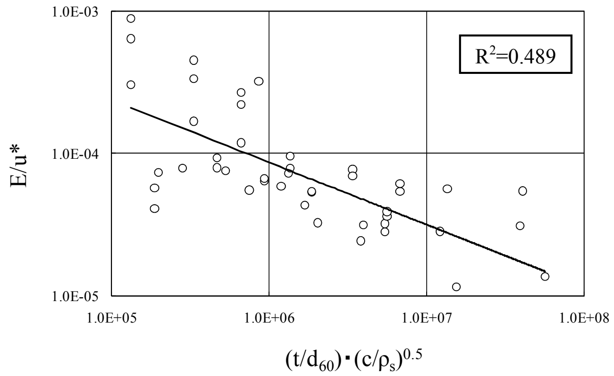

Fig.8 Relationship between $(t/d_{60})/(c/\rho_s)^{0.5}$ and E/u_*.

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