EROSION RATE OF RESERVOIR DEPOSIT AS REVEALED BY LABORATORY EXPERIMENT

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ABSTRACT

The construction of dams and reservoirs in a river can give significant impacts on its flow of water and sediment, and can cause long-term morphological changes on the river. Reservoir sedimentation can reduce a reservoir's effective flood control volume, and in some severe cases can cause overtopping during floods. Sediment deposition against a dam can reduce its stability, and affect the operation of low-level outlet works, gates, and valves. The abrasive action of sediment particles can roughen the surface of release facilities and can cause cavitations and vibration. Sedimentation can also affect a reservoir's water quality, and reduce its flood control, water supply, hydropower, and recreation benefits. Consequently, taking sedimentation into consideration not only in the planning and design, but also in the operation and maintenance of a dam and reservoir is important.

Keywords: Erosion rate, reservoir deposit, shear stress.

1 INTRODUCTION

The Wonogiri multipurpose reservoir, which has been operated since 1982, began to face a serious problem in sedimentation in 2007. Since then, intensive studies on the mechanism of sedimentation within its catchment area and reservoir were considered necessary to support the strategy in the sedimentation management. One of these was the numerical study on the mechanism of sedimentation within the reservoir, or mathematical modeling. As stated by the previous researcher (Mahmood, 1978), such approach of numerical study needs some information on the important parameters which can only be obtained through laboratory experiment. Two of the aforesaid important parameters are the critical bed shear stress and the erosion rate of the deposit. This paper presents the results of the study through the laboratory experiment to determine the critical bed shear stress for several deposits taken from various locations and depths of Wonogiri reservoir, and to study the sediment entrainment or resuspension from the bed of each sample on various flow conditions. The study was carried out through the activities based on the implementation work flowchart as sketched in Figure 1. The work comprised the preparation, literature reviews and preliminary experiment, laboratory test (flume experiment), the analysis of critical bed shear stress and erosion rate, and the presentation of conclusion and recommendation for further necessary related research. The sensitivity of analysis regarding the uncertainty and inaccuracy of experimental reading contributed recommendations on further essential development of monitoring and data acquisition, as well as instrumentation techniques.

2 EXPERIMENTAL SETTING

The currently available flume of 12.00 m x 0.30 m x 0.40 m (Figure 2) was used throughout approximately 50 experimental runs. A part of the flume, about 2.00 m in length, was modified as a working section where the deposit material from Wonogori reservoir was arranged and studied. The above mentioned flume was modified by placing the wall of 10.00 m long and 0.40 m high in the middle of the flume to make 2.00 m x 0.40 m x 0.10 m working section flume (see Figure 2). The flume was provided with regulating overflow weir and a collector tank located in the downstream end of the flume to identify the flow rate being introduced. The model was provided with equipment to identify the various parameters, some of which were as follows:

a) miniature current meter to measure the flow velocity at a particular point,
b) depth gauges to measure water surface profile,
c) digital photo camera and video camera to see the particle motion.

The flow was arranged as steady uniform flow throughout the entire experiment. Due to the very fine material, the critical bed shear stress was presumed to be very low; the flow being introduced was supposed to have very low velocity. The steady state condition was obtained by applying a constant head tank at the upstream part of the modified flume system. The flow was performed by utilizing the submersible pump able to convey the flow of water at the rate ranging from 2 – 7 liter/second.

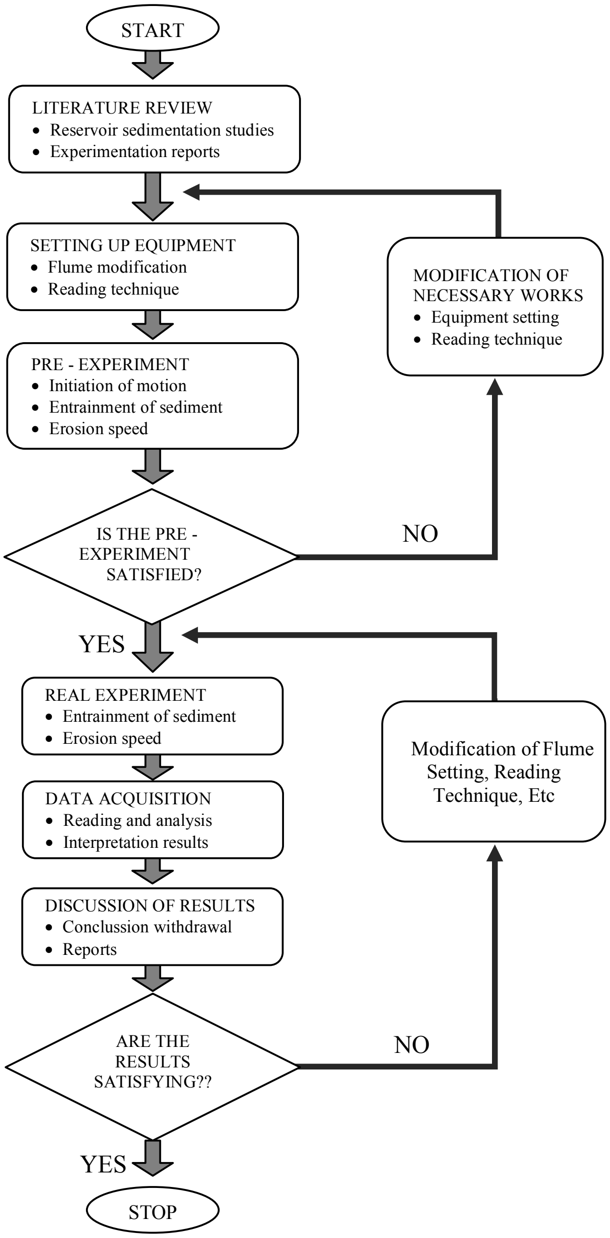

Figure 1. Sketch of research implementation

Figure 2. General purpose hydraulics tilting flume

The rate of flow was measured by a volumetric tank at the downstream end of the flume. The uniform flow condition was obtained by tilting the flume at a certain magnitude to meet the slope of flume bed which was nearly equal to the slope of flow energy. The reading technique was developed to measure the critical bed shear stress and the erosion rate. The critical bed shear stress is assumed to occur at the flow condition where the fine sediment was about to move. This was observed by utilizing the video camera. By assuming that the fine material was uniform, the critical bed shear stress was predicted based on the non-dimensional relationship between the sediment characteristics and the Shield constant. The flow was then introduced bit by bit from the condition so that the resulting bed shear stress was slightly lower than that of the predicted critical bed shear stress. At this condition, the fine particle should not yet move. The flow was then gradually increased and the bed material was again observed by utilizing the video camera. This situation was carried out repeatedly until the fine material is considered about to move, and at this situation, the critical shear stress due to the flow being introduced was the critical bed shear stress to be identified.

The erosion rate occurred at the flow condition where the bed shear stress was higher than the critical bed shear stress. The rate of the erosion rate was a function of the energy gradient of the flow. Five to seven different flow conditions were introduced on each sample investigation. All flow conditions were on the condition that the bed shear stress was higher than the critical bed shear stress. For each experiment or run, there must be some sediment discharge, thus also sediment concentration within the flow, and this was identified by measuring the turbidity. A special apparatus to measure the turbidity (in unit NTU) was adopted. Depending upon the magnitude of the sediment characteristics, particularly the size and mass density of the sediment, the mentioned correlation curve of one sample may be different from the other. This is considered common since the two parameters may contribute different sediment settling velocity, which further cause differences in the suspension magnitudes. Curves showing the correlation between the turbidity and the sediment concentration on each sample then need to be initially established. For cross checking, the sediment discharge is also measured by collecting some amount of flow of water, and then taken into the laboratory to identify the sediment concentration. The results were then put in the graphs to show the correlation between the bed shear stress and the rate of the sediment. From these experiments, sediment concentrations within the flow for all different soil samples were identified.

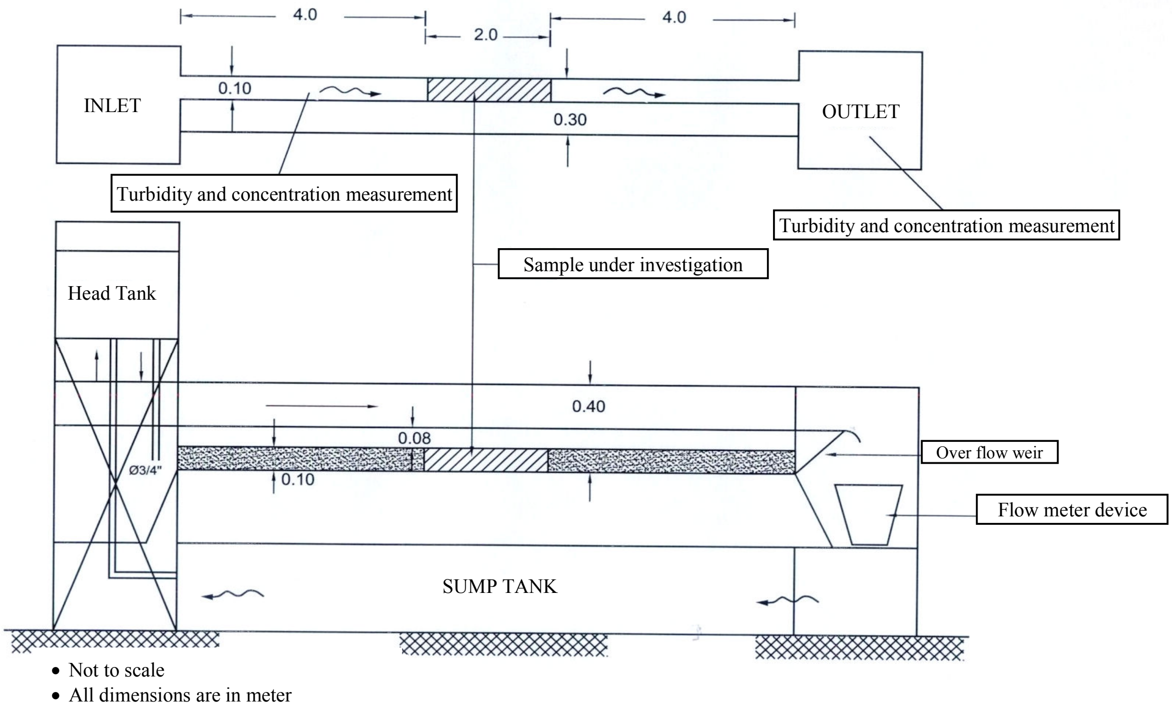

Figure 3. Sketch of experimental setting

A series of experiments at the condition where particles were in rest was conducted initially, continued by the condition where particles were about to move. At the condition where the particles were about to move, the bed shear stress was approximately equal to the critical bed shear stress (see Figure 3).

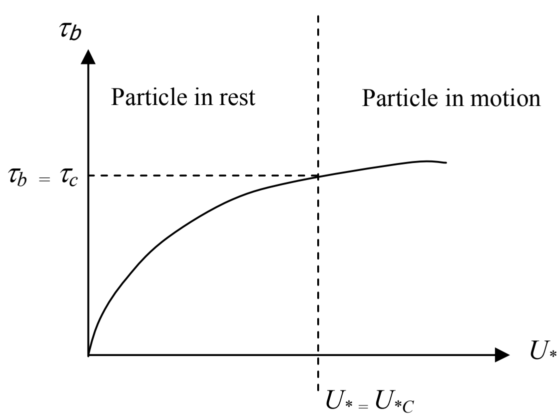

Figure 4. Bed shear stress Vs shear velocity

The experiment on the erosion rate was carried out at the condition where the flow causing bed shear stress τ_b is higher than the critical bed shear stress . The non dimensional expression of erosion rate ( ) as a function of shear velocity ( ) may be performed in the form of Equation (1) and as sketched in Figure 4;

— (1)

where:

: shear velocity, obtained from

: constant of occupation rate of sediment

: bed shear stress, obtained from

: critical bed shear stress

a, x : constants related soil property

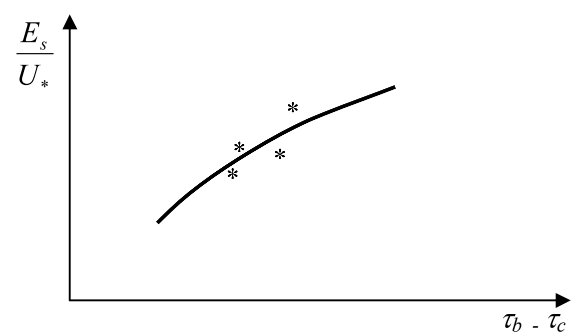

Figure 5. Non-dimensional erosion rate Vs net bed shear stress

3 PROPERTIES OF RESERVOIR DEPOSITS

The characteristics of reservoir deposit, further called sample, in the reservoir bed vary from one location to another location. This may be caused by many factors such as the characteristic of the material transported through the rivers entering the reservoir and the consolidation mechanism of the material after being deposited in the reservoir. The distribution of the deposition over the entire space of the reservoir highly depends upon the deposit property.

Three locations of the reservoir bed (see Figure 6), were selected as the locations where the deposit was to be taken, i.e., at the mouth of Bengawan Solo River (E-1), Tirtomoyo River (E-2), and Keduwang River (E-3 and E-4). Soil deposits were managed in such a way that these samples were still having natural water content during their conveyance to the Hydraulics Laboratory. Sample E-1 and E-4 were considered as the on land samples with the depth of 0.20 m. Sample E-2 and E-3 were underwater samples, with the depth of 0.00 m; 0.50 m; and 1.00 m. Therefore, there are eight samples altogether, and these are to be investigated to identify their critical bed shear stress and erosion rate. Figure 7 shows the visual appearance of each sample. It is shown clearly the E-1 and E-4 samples are relatively much drier than those of the E-2 and E-3 samples.

Prior to the flume experiment, the index property of the samples was investigated to identity the particle water content, the mass density, and the particle size distribution. All samples were mostly dominated by very fine material, i.e., fraction of clay or silty clay. It was found that sample E-3 apparently contained organic matter and contributed effects on the magnitude of critical bed shear stress.
The summary of the properties of water contents and mass density of the entire samples is presented in Table 1, whereas the summary of the particle size distribution is presented in Figure 8.

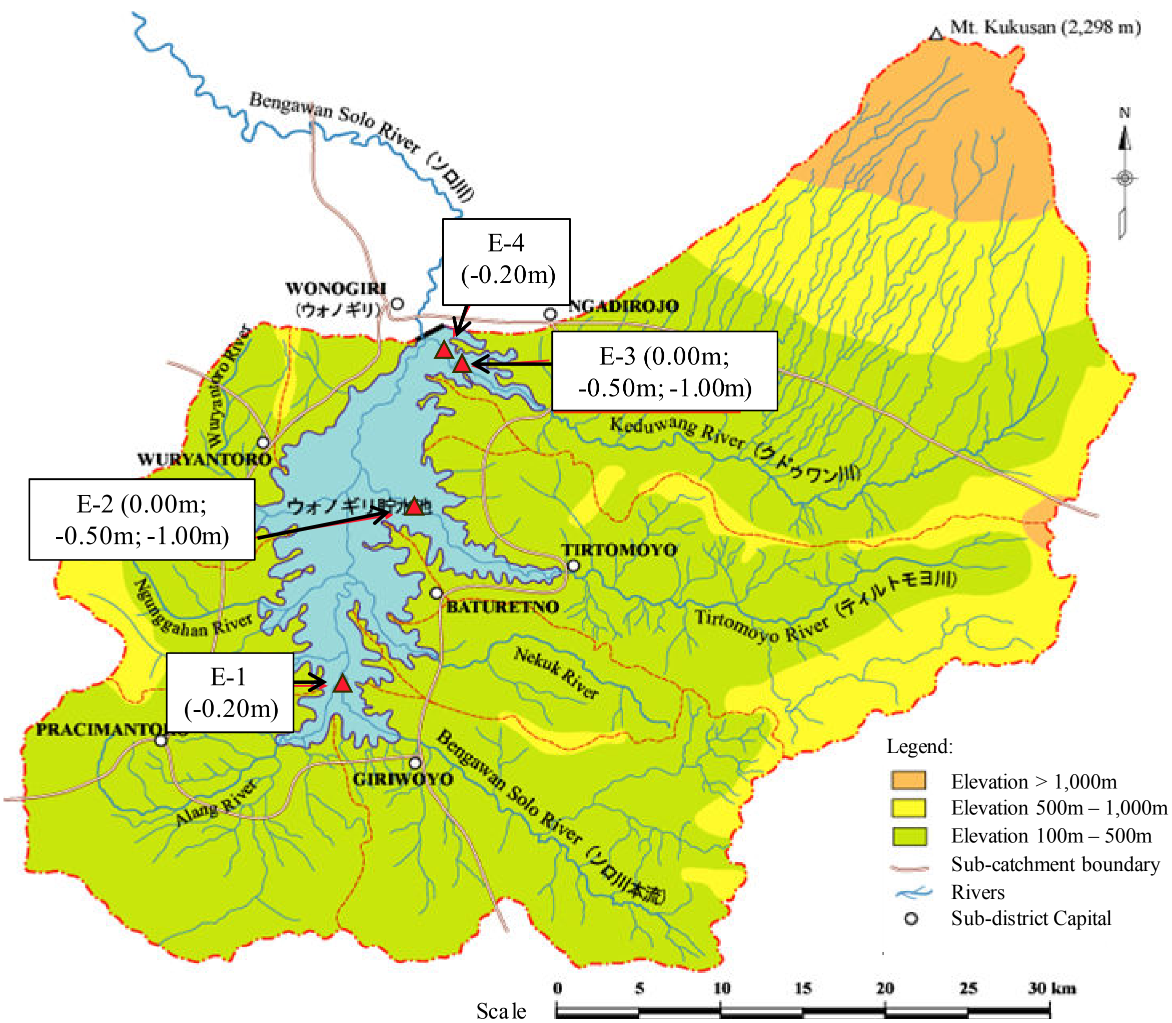

Figure 6. Location of soil sampling (JICA, 2006)

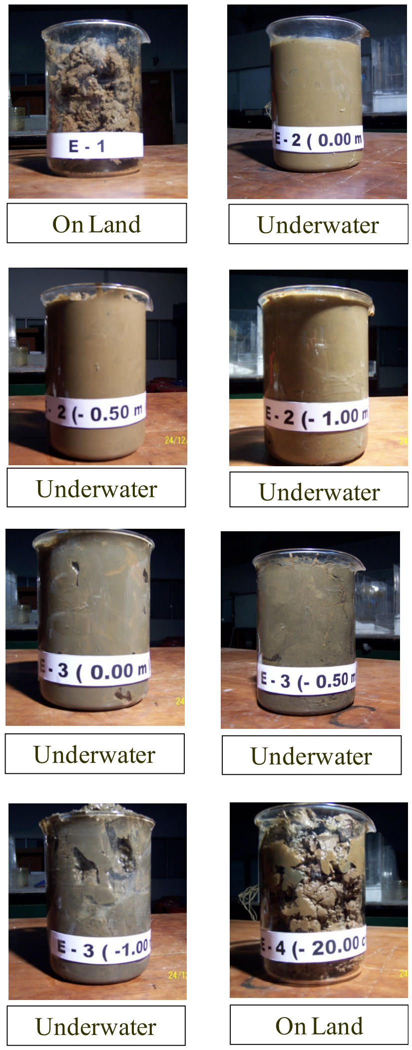

Figure 7. Location of soil sampling (JICA, 2006)

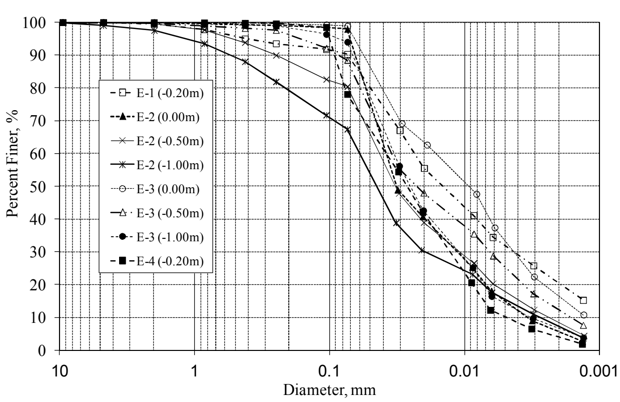

Figure 8. Particle size distribution of samples

Table 1. Index properties of soil samples

Samples	Depth (m)	Natural Water Content (%)	Specific Gravity (ton/m^3)
E-1 (-0.20m)	0.20	87.55	2.46
E-2 (0.00m)	0.00	72.69	2.53
E-2 (-0.50m)	0.50	58.27	2.60
E-2 (-1.00m)	1.00	49.36	2.57
E-3 (0.00m)	0.00	91.12	2.52
E-3 (-0.50m)	0.50	92.58	2.53
E-3 (-1.00m)	1.00	74.77	2.57
E-4 (-0.20m)	0.20	89.42	2.53

4 EXPERIMENTAL PROCEDURES

The following experimental procedures were introduced prior to the implementation of the study on both the critical shear stress and the erosion rate, i.e;

1) A soil sample was taken out from the bin and mixed carefully on the wider container, in such a way that the water content remains unchanged.
2) After the soil sample had reached a well mixed condition, the soil sample was then placed in the working section of the flume and arranged in such a way that the surface was flat or even.
3) The flume was then cleaned by means of wiping with soft napkin or tissue.
4) At the same time, all of the apparatus (the turbidimeter, the flow measurement device, the video camera, the camera, etc.), and the people in charge of taking the sample, measuring the flow rate, measuring the turbidity, were ready to proceed with the investigation.

There were two possibilities of how the soil sample would move due the flow being introduced. Firstly, they might be moving such as small particles role, slide, or even jump. Secondly, they would initially resuspend, followed by joining the flow and moving in the suspension form. Unless the particles were rather coarse, the fine and cohesive particles would move to follow the second mechanism. The resuspension of the soil sample were affected by the strength of the interparticle bond and the stresses imparted by the flowing water. Initially, a very low flow velocity was introduced to the prepared system. It was guaranteed that at the first time of flow introduction, none of the particle was moving. This method was kept continuing until the flow met the uniform depth of flow which has been approximated before. At this situation, the flow was having the shear stress far below the critical bed shear stress. The flow was then gradually increased to meet a certain magnitude and wait until the steady flow condition was obtained. The bed slope was always checked and increased to meet the approximate calculation of the energy gradient. Furthermore, a careful observation was carried out to identify whether there was some re-suspension of the soil sample. If not, the higher flow was then introduced, and accordingly, the same method was applied by introducing a relatively higher flow rate, until the indication that the particle was about to resuspend was found. At this situation, the value of shear stress was found to be the critical bed shear stress. The following empirical critical velocity graph (Yang, 1986) as shown in Figure 9 was used to estimate the initial flow velocity where the sediment was about to resuspend.

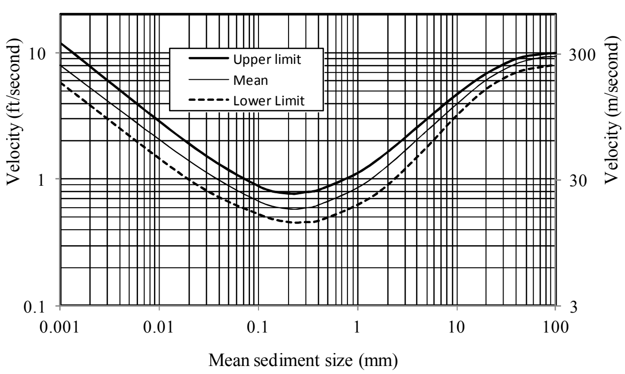

Figure 9. Critical velocity as a function of sediment size diameter (Yang, 1986)

After the observation of critical bed shear stress was identified, a slightly higher flow rate was then introduced to study the sediment entrainment from the bed. There were about twelve to thirteen series of observations applied within each run, and these were carried out as soon as the flow was considered steady. A series of observations was carried out comprising the following experiments, i.e.;

a) the flow rate measurement at the downstream tank,
b) the sediment concentration measurements and NTU readings,
c) the photograph taking,
d) the video movie taking.

As soon as the flow was considered steady, a flow rate was measured by collecting the flow at the outlet tank and by utilizing the volumetric tank. A timer was used to calculate the time required for filling a certain volume of water collected in the volumetric tank. Sediment entrainment from the bed or erosion was determined by measuring the suspended sediment upstream and downstream of the soil sample arranged on the working section. The suspended sediments were collected via ½" diameter plastic tube and placed with the centre of the opening at about the half of the depth of the flow or about 4.0 cm above the bed of the flume. The collection was initially carried out at 0.50 m upstream of the working section and then at the downstream tank. The value of the NTU of the collected water sample was then tested. Especially for the first and the last series of observations, the collected samples were also taken to identify their sediment concentration value by means of oven technique. Photographs on each observation of each run were taken, therefore, there were about twelve to thirteen photographs on each run. The video movies on each observation of each run were also made, similar to the photographs taken, there were about twelve to thirteen videos on each run. The documents prepared in video clips which have relatively small memory size were reported separately. Analysis of the erosion rate for one particular soil sample and one particular run was carried out to follow the following procedure of calculations:

1) The flow rate reading q, in liter/second, was identified,
2) The turbidity reading, in NTU, was identified,
3) The sediment concentration C, in mgr/liter, on each observation was calculated by utilizing the corresponding correlation curve of NTU and sediment concentration, both at upstream of the soil sample and at downstream of the soil sample (outlet tank).
4) The suspended load in gram/second, was calculated by deducting the downstream concentration with upstream concentration, and then multiplied by the flow rate q. The value should be greater than zero. The value of erosion rate of less or equal to zero was assumed to be not valid and was not used for further analysis.
5) The erosion rate in gram/hour/cm^2 was calculated by dividing the value of suspended load as calculated in Item 4) with the surface area of the soil sample under investigation of 10 cm x 200 cm, and also by adopting a conversion on time dependent.
6) The same procedures were applied to the other observations within one particular run to meet twelve to thirteen observations, where the average flow rate and average erosion rate were obtained.
7) There were about 5 to 7 runs on each soil sample to have 5 to 7 average values of flow rate being introduced with their corresponding values of erosion rate.

5 EXPERIMENTAL RUNNING AND ANALYSIS

The measurement of sediment concentration within the flow was carried out by taking samples of identified flow rate and then being analyzed by means of oven technique. Analysis of concentration by oven technique requires at least 24 hours. The measurement of the sediment concentration was then carried out by initially establishing a correlation curve to obtain the relationship between the sediment concentration (mgr/liter) and the turbidity (NTU). The correlation curves of eight different samples, i.e. E-1 (-0.20 m), E-2 (-0.00 m), E-2 (-0.50 m), E-2 (-1.00 m), E-3 (0.00 m), E-3 (-0.50 m), E-3 (-1.00 m), and E-4 (-0.20 m) are presented in Figure 10. Each sample has a specific correlation; calculation of the sediment concentration was then carried out based on the corresponding correlation curve.

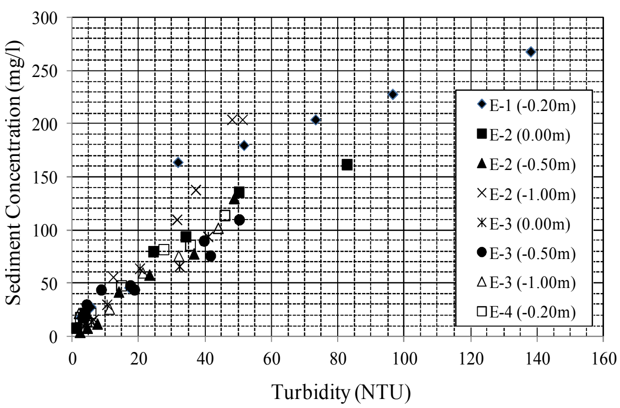

Figure 10. Correlation between NTU and sediment concentration

6 RESULTS AND DISCUSSIONS

As stated by a previous researcher (Papanicolaou, 2002), the available literature on cohesive sediment transport lags behind that of sand and gravel transport processes, due largely to the complex nature of particle bonds in cohesive soil. These complex particle bonds greatly complicate the calculations of settling properties and a critical stress for erosion.

To present the results of the study in the form of correlation between the erosion rate and the net bed shear stress , the following calculation procedures were applied:

1) The value of was calculated by dividing the previous average value of erosion rate by the mass density of the corresponding soil sample as presented in Table 1.
2) The which is a function of , was calculated by initially calculating the energy gradient from the Manning formula, by assuming that the roughness coefficient n-Manning was equal to 0.01.
3) Correlation between the value of ( ) and ( ) was carried out by means of least square curve fitting, for two different approaches of equations as presented below;

$$\frac{E_s}{U_*} = a(\tau_b - \tau_c)^b \quad (2)$$

or

$$\frac{E_s}{U_*} = a(\tau_b - \tau_c)^{1.5} \quad (3)$$

Equations (2) and (3) require two constants of power equation and one constant power equation respectively. The constants of both equations are presented in Table 2, whereas Figure 11 presents the comparison between the results of this experiment with previous workers.

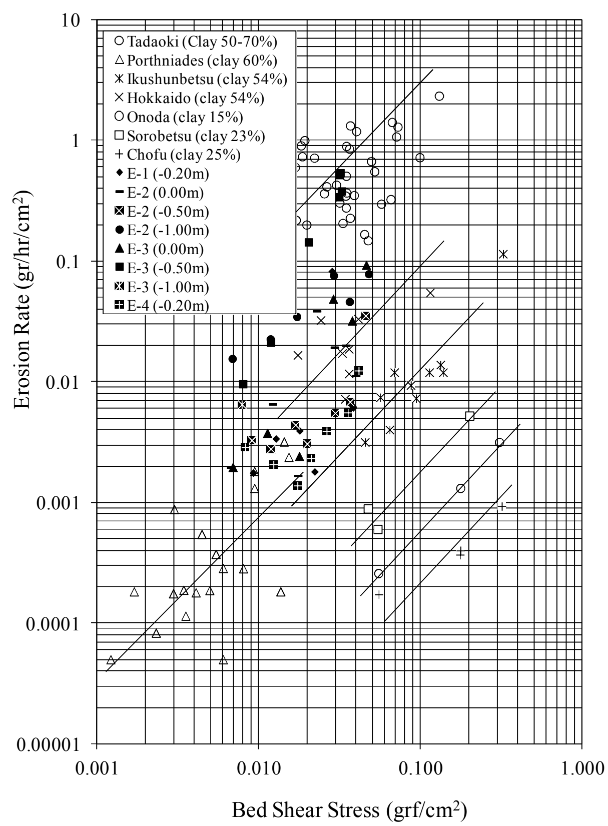

Figure 11. Erosion rate Vs Bed shear stress

Table 2. Constants of (E_{sk}/U_*) and ($\tau_b - \tau_c$) relationship

Sample	$E_s/U_* = a\,(\tau_b - \tau_c)^b$		$E_s/U_* = a\,(\tau_b - \tau_c)^{1.5}$
	Constant a	Constant b	Constant a
E-1 (-0.20m)	1.027 x 10^{-8}	0.073	9.036 x 10^{-9}
E-2 (0.00m)	2.131 x 10^{-7}	0.342	2.873 x 10^{-7}
E-2 (-0.50m)	8.440 x 10^{-9}	0.749	6.185 x 10^{-9}
E-2 (-1.00m)	9.277 x 10^{-7}	0.153	9.249 x 10^{-7}
E-3 (0.00m)	4.716 x 10^{-7}	0.335	1.106 x 10^{-6}
E-3 (-0.50m)	1.176 x 10^{-7}	2.028	1.529 x 10^{-6}
E-3 (-1.00m)	9.809 x 10^{-8}	-0.159	1.784 x 10^{-6}
E-4 (-0.20m)	7.465 x 10^{-8}	0.236	4.711 x 10^{-8}

7 CONCLUSIONS

The slope/gradient of the NTU over the sediment concentration (mg/l) of the samples ranged from 2.0 to 3.9; where the higher value were dominated by sample E-3 (-1.00 m). In terms of erodibility, it is assumed that the sediment from Keduwang is relatively more erodible than that from Bengawan Solo River. The increase in shear stress of E-3 (-1.00 m) sample was not significantly causing the increase of its erosion rate. This may be due to the relatively high cohesive property of E-3 (-1.00 m) sample. This paper suggests further similar research taking into account the identification of degree of cohesive property of samples, the organic property, and an adoption of better techniques to identify the initiation of motion (critical velocity of the deposited material).

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