An Experimental Study on Cohesive Soil Erosion due to Overland Flow at the Steep Slope Field in the Mrica Watershed, Indonesia

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Abstract

Soil erosion and sediment discharge due to deforestation at upper Mrica watershed and increase of cultivated fields at the deforested steep slope area have induced sedimentation in Mrica Reservoir, Central Java, Indonesia. Hydrological observations were carried out at an observation-plot of 200 m^2 within a study field of about 5,000 m^2 that located in the upper Mrica watershed. Laboratory experiments using soil samples collected from the study field were performed by single-shear surface test and flume test to examine erosion velocity. Sediment discharge hydrograph showed obvious response to rainfall. Erosion type at the study field was identified as sheet erosion due to overland flow. Relation between soil surface cohesion of saturated layer and soil water content at 5 mm depth revealed that as soil water content increased, soil surface cohesion fell exponentially. Erosion velocity decreased when cohesion increased. However erosion velocity increased sharply as the friction velocity increased. Based on hydrological observations and laboratory experiments results, an experimental erosion velocity equation of the study field in the Mrica watershed was proposed.

Keywords: cohesive soil, erosion velocity, hydrological observations, steep slope

Introduction

Soil erosion as one of the sediment-related disaster has become major environmental issue in Indonesia (Heusch, 1993; Kusumandari *et al.*, 1997; Van Dijk *et al.*, 2003; Hartanto *et al.*, 2003; Moehansyah *et al.*, 2004), recently. Compare to other islands, Java has experienced much stress from its increasingly intensive agricultural use (Purwanto, 1999) and according to the GLASOD project, the soil of Java was classified "very degraded soil" (soil erosion.net, 2004).

In the upper Mrica watershed, deforestation and increase of cultivated fields at the deforested steep slope area have been promoted since the last two decades. Most of the fields were arranged as forward sloping bench-terrace with ridge direction perpendicular to the contour (**Fig. 1**). During heavy rainfall, soil erosion and sediment discharges from the cultivated fields eventually caused siltation of the Mrica reservoir. Soil of the fields mostly contains 40–60% cohesive materials such as silt and clay with low dry bulk density of about 0.7 g/cm^3 (Suwartha, 2005).

Differ from non-cohesive soil where its incipient motion and erosion by flowing water greatly depends on diameter of soil grains; erosion of cohesive soils depends upon both characteristics of soil and flow. The characteristics of cohesive soil mostly depend on its physical and chemical properties, which affect the resistance force against erosion (Ariathurai *et al.*, 1978). The flow is acting as erosive agent on a cohesive soil that determines shear strength, which is also important in determining the critical shear stress (Partheniades, 1965; Krishnamurthy, 1983). When the surface of cohesive soil has already saturated, the interparticle bond known as cohesion strength will break up and results in declining cohesion strength. Consequently surface of cohesive soil starts to be eroded as the shear force exceeds the critical shear stress. Although studies on erosion model for cohesive soil (e.g. Kusaka *et al.*, 1981; e.g. Minami *et al.*, 2002; e.g. Sidorchuk, 2005) or erosion model over steep slope (e.g. Govindaraju, 1995, e.g. Zhang *et al.*, 2000) have been done in recent years, the number of studies on erosion model for both cohesive soil and steep slope on cultivated field are very limited. Fan *et al.* (2001) carried out study on interrill soil erosion rates based on simulated rainfall with slope up to 100% gradient. They found out that critical slope steepness is around 75%. Beyond this value, the slope steepness factor decreases with slope steepness, hence interrill soil erosion rate decreases. However, relationship between erosion rates and cohesion changes in response to soil water content was not described explicitly in the past

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Fig. 1. Actual condition of the cultivated fields.

studies.

This study aims to develop an experimental erosion velocity equation of the study field of Mrica watershed based on hydrological observation and laboratory experiments.

Materials and Methods

Study Area

The study area is located in Banjarnegara Regency, Central Java Province, Indonesia (between 7°10′15″–7°27′58″ N, and 109°30′47″–110°4′24″ E). Naturally, Mrica watershed (area of 905 km^2) lies in the Serayu River Basin and it is composed of three sub-watersheds, Serayu (678 km^2), Lumajang (8 km^2) and Merawu (219 km^2) (**Fig. 2**) (Suwartha, 2005). Altitude within this watershed ranges from 250 to 2,300 m. Wet season dominates over dry season, mean annual rainfall is about 3,500 mm and mean annual temperature is 19°C. According to the Soil Map of Central Java, the prevailing soil type is red-brown latosol and grey regosol. Major land use is mainly paddy field and dry field in the lower reach, bushes and forest in the middle reach and mostly cultivated fields in the upper reach (occupied about 30% of the Mrica watershed area). Along this area, remarkable cultivated fields were established in large scale on the steep slope ($\geq 20°$). The farmers applied forward sloping bench-terrace method to reduce and prevent further soil erosion. However, accelerated soil erosion has been occurring due to intensive tillage (three times a year), heavy rainfall and inappropriate ridge direction.

Most of the fields were cropped to potatoes (*Solanum Tuberosum L*) and cabbage (*Brassica oleracea*), intensively. Beside these two crops, corn (*Zea mays*) or tobacco (*Nicotiana tabaccum*) is planted sometimes to conserve and protect the soil from erosion due to the frequently plowing.

Hydrological Observation

Preliminary Observation. Due to antecedent rainfall, some rills and soil piles have already been formed on the study field. Soil piles were distributed in almost all field surfaces, while rills distributed sparsely. From these two types of eroded areas, it was necessary to determine which type of erosion dominated in the study field in order to understand the erosion process and mechanism. For this purpose, a preliminary observation was conducted by identifying and measuring the sediment volume of rills and soil pile formed. There are 11 rills found on the study field, with average length of the rills varied from 5 to 7.5 m, about 0.1 to 0.3 m in width and 0.1 to 0.4 m in depth. Average slope gradient near the rills were about 15 to 20°. We identified that most of the rills were developed because flow concentrate in the toe-drain as the surrounding areas have relatively steeper slope, which caused excessive water spill-out from the toe-drain channel to the terrace-field persistently. Total sediment volume of formed rills, considering the average rectangle shape of the rills, was estimated approximately 2.42 m^3. On the other hands, soil piles were formed and widely distributed in almost all of the study field surfaces, and averaged soil piles height (measured in 1×1 m^2 plot) was about 0.02 m and diameter varied from 0.01 to 0.03 m. The soil piles were assumed to be caused by sheet overland flow. Based on the averaged soil pile height obtained from 1 m^2 plot and to be extrapolated to the total are of the

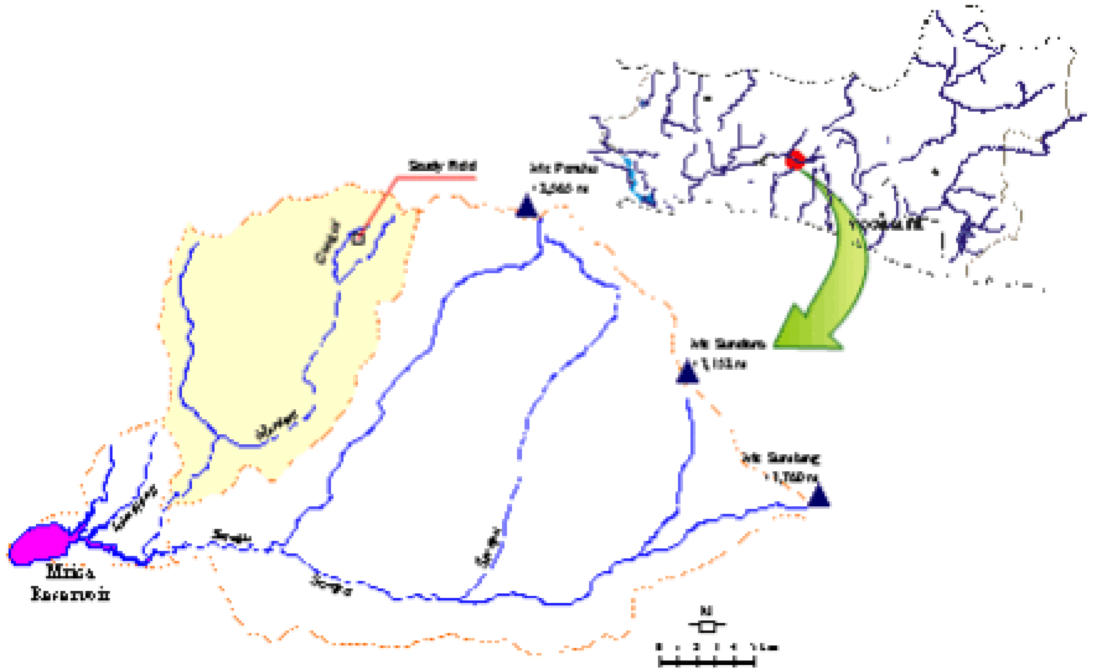

Fig. 2. Location of the Mrica watershed and the study field.

study field (about 5,000 m^2), hence total sediment volume of soil piles was estimated about 121.7 m^3. Thus, it was found that the sediment volume ratio of rills to soil pile is approximately 2%. This low ratio of sediment volume might be due to the fact that bench-terrace steps restricted rills length development. Based on the above finding, it was assumed that sheet erosion due to overland flow is the most prevailing phenomenon at the study field.

Hydrological Observation. It was conducted at the study field during February 13–22, 2004. Average slope gradient of the study field is ranging from 15 to 20° and vegetation cover ratio (cabbage planted two months) reached to about 30%. The ridges were constructed perpendicular to contour, and average slope gradient of the furrow's surface was about 15°. The distances between ridges were about 50 cm, and furrows were 20 to 30 cm in width and in depth, and 50 to 60 cm in length. Location of the observation-plot was selected at the upper-part of the study field, considering undisturbed soil surface, drainage system condition and it relatively unaffected by the rill formation. Naturally, it has a triangular shape, size of 16×25 m^2 (**Fig. 3**). The observation-plot was bounded by toe-drain at the end of the terrace, side-drain channel at the right side, and one outlet for collecting the sediment discharge.

Main purpose of the observations is to observe and measure the rainfall intensity, sediment discharge volume, sediment concentration, water discharge, soil moisture, and grain size. Hourly rainfall was recorded using automated raingauge that was installed 400 meter upper the study field. During all through the rainfall event, runoff discharges was sampled manually from the plot-outlet by using five measuring cups (each cup volume 1000 ml). Sampling time was recorded and volumes of runoff were measured successively. The sediment discharge, Q is defined as volume of runoff divided by sampling time. After the suspended sediment settled, the water was drained from the measuring cups. Remain sediment and the suspension were collected and dried in the oven and to calculate the dried sediment volume. Sediment concentration was measured based on the ratio of dried sediment volume to the runoff discharge volume. Em5 probes data logger (Decagon Devices, Inc.) was installed inside the observation-plot area to record average volumetric soil moisture at 10 cm depth from soil surface. Amount of sediment was collected and analyzed in the soil mechanic laboratory, to investigate the grain size distribution.

Overland Flow as the Main Cause of Surface Erosion in the Study Field

During soil erosion process, raindrops act as the major cause of soil particle detachment. The kinetic energy of rainfall can be transmitted directly to the unprotected soil and breaks the bonds between the soil particles, dislodges them and splashes them into the air. The dislodged soil particles can then be easily

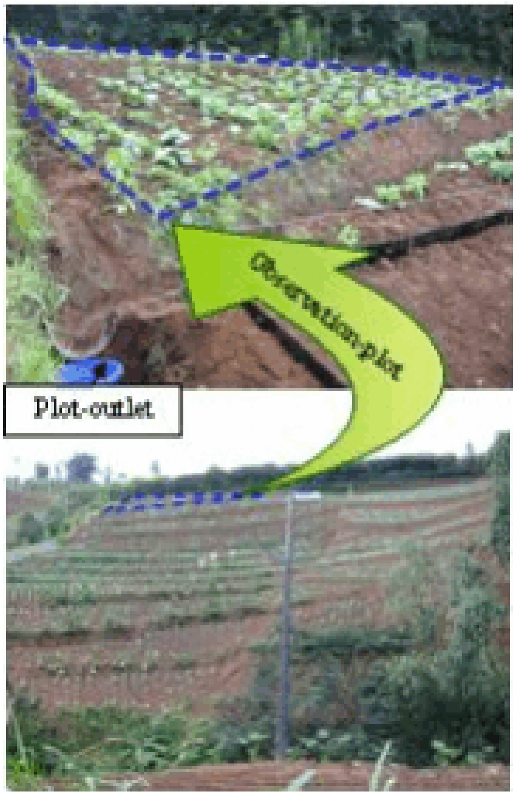

Fig. 3. Description of the study field and the observation-plot.

transported by the flow of accumulated surface water. Then the kinetic energy of raindrops is dissipated as the surface water level increase (Smith and Quinton, 2000). This means that splash erosion will discontinue and have less effect on further soil particle detachment. Dickey *et al.* (1986) also reported that when the flow depth (h) of accumulated surface water equal to the raindrops diameter (d), there is no effect to the soil particle detachment. In the study field, the same tendency mentioned above occurred in several areas, raindrops caused no further soil particle detachment since the water layer acts as a cushion (by using VTR analysis). It is common that interrill flow (wash) as the primary process by which sediment is transported, while splash erosion, though important in detaching sediment, is considered to be of limited significance in transporting sediment (Wan *et al.*, 1996). It has been recognized by a number of researchers that experimental separation of transported sediment by splash and wash is difficult, particularly in the field-scale. In this study, supporting data or parameters to analyze the potential splash erosion; such as fall velocity of raindrops, soil detachability, and coefficient of the slope-splash length, etc., is not available. The raindrop detachment effect, therefore, is omitted in this study and only focus on the sheet erosion due to overland flow.

Concept of the Proposed Erosion Velocity Equation

Initially, rain droplets hit the soil surface and its kinetic energy detaches soil particles, dislodges and transports them to the surrounding areas (rain splash). As the accumulated rainfall at soil surface increase, part of the water will infiltrate throughout subsurface. When permeable capacity of the soil surface reaches its limit, overland flow generates. During the flowing of water, friction velocity, a function of gravitational acceleration, water depth and slope gradient, acts as erosive agent to the soil surface. As long as the friction velocity maintains its critical point, only flowing of water occurs. Once the critical friction velocity has been reached, soil surface will be eroded to a certain depth. Next, erosion velocity can be estimated as average erosion depth per time unit.

Resistance of cohesive soil depends upon cohesion and flow condition (Krishnamurthy, 1983), also velocity and shear stress as external force (William, 1981). On the other hand, the excessive rainfall increases the soil water content and results in the decrease in the surface cohesion. In this study we examined the relation between soil water content, soil cohesion, and friction velocity, since they are to be presumed has significant interaction in erosion process of cohesive soil.

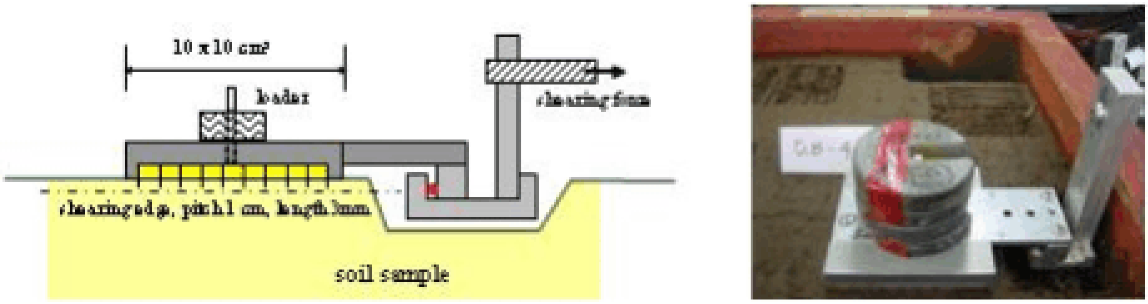

Fig. 4. Single-shear surface test apparatus.

Fig. 5. Flume test apparatus.

Laboratory Experiment

Single-Shear Surface Test. We have developed a tool for evaluating the shear strength of soil surface layer, namely single-shear surface tester (**Fig. 4**). With the use of this apparatus, the decline in strength of surface specimen caused by changes in soil water content was evaluated by measuring surface layer cohesion and critical cohesion. For these purposes, soil samples were collected from the study field by using 5 steel-frames with dimensions of 45 cm long, 45 cm wide and 15 cm deep. To obtain the relationship between cohesion and soil water content, eight cases of dry bulk density (ρ_d) at 0.65, 0.7, 0.753, 0.771, 0.8, 0.815, 0.835 and 0.864 g/cm^3 were used. The soil sample was adjusted by compaction up to specified weight and volume to determine each ρ_d. As the soil surface condition was assumed to be saturated when it was eroded by overland flow, the shear test was conducted using saturated soil sample (degree of saturation, Sr = 100%). The specimen of each ρ_d was tested by the single-shear surface tester for a given loader (N) varies from 0.5, 1.0, 1.5 and 2.5 kgf. Each case of ρ_d was tested and measured at similar shear velocity approximately 1 mm/min along 10 minutes of every given load.

Flume Test. Dimension of the flume channel is 165 cm long, 10 cm high and 6.5 cm wide (**Fig. 5**). Soil sample was prepared at $\rho_d = 0.7$ g/cm^3 (approximately equal to the actual dry bulk density in the study field = 0.7 g/cm^3). Slope gradient (θ) was set ranging from 1 to 20° and two kinds of unit water discharge, $q_w = 7.6$ cm^2/s and 3.8 cm^2/s were provided. There were 14 cases of experiments in total, as summarized in **Table 1**. The soil sample was poured into the flume channel and compacted to obtain desired dry bulk density. Roughness of soil surface was adjusted by surface compaction and water is sprayed to saturate soil surface. During the experiment, flow water depth (h), average flow velocity (v), measurement time (t), sediment discharge volume (Vs) and soil water content (w_s) were measured for each case of θ and q_w.

Table 1. Flume experiments cases and controlled parameter.

ρ_d (g/cm^3)	slope gradient, θ (°) for q_w = 3.8 cm^2/s	slope gradient, θ (°) for q_w = 7.6 cm^2/s
0.7	1	1
0.7	3	3
0.7	5	5
0.7	7	7
0.7	10	10
0.7	15	15
0.7	20	20

Total number of the cases: 14

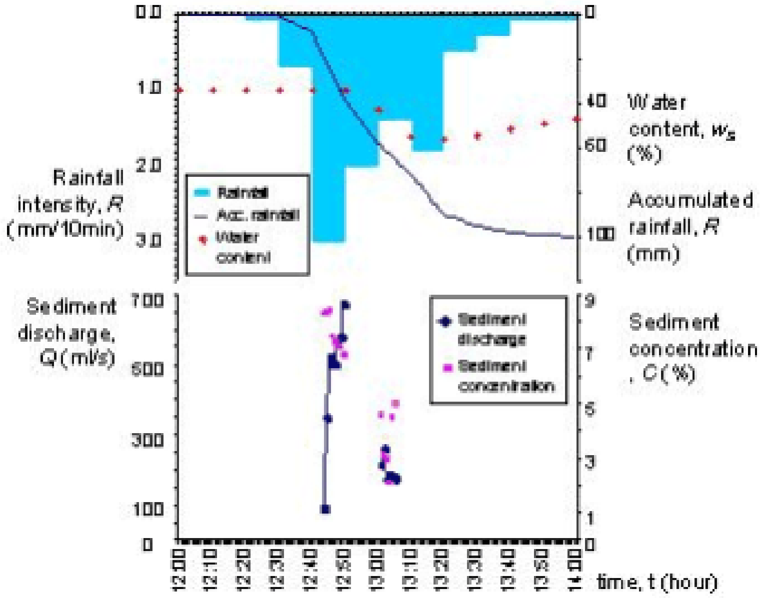

Fig. 6. Sediment discharge-rainfall relationship of Feb-21, 2004.

Results and Discussions

Sediment Discharge-Rainfall Relationship

During the-ten-day-hydrological-observations, one rainstorm occurred on February 21, 2004 for about one hour. It was observed that when excessive rainfall exceeds infiltration capacity, sheet overland flow generates. The overland flow transporting the detached soil particle and it triggered sediment discharges from the surface of the study field. Erosion type during this event is identified as sheet erosion due to overland flow. **Figure 6** shows the relation between rainfall intensity and sediment discharge hydrograph along with sediment concentration and soil moisture changes. Despite the sediment discharge hydrograph had not completely reached the recession stage, it showed obvious response during rising stage. It increased sharply near the peak of the rainfall to about 680 ml/s. Volumetric sediment concentration also increased up to 8.5% near the peak of sediment discharge and decreased gently on recession stage. Rainfall intensity triggering the sediment discharge was found to be ranging from 42 to 58 mm/hour. Grain size analysis of collected sediment from observation-plot during the rainfall revealed that about 40% of discharged materials were silt and clay, while from other spot in the study field showed that silt and clay contents reached about 60%. Based on this percentage by using textural triangle (Hillel, 1998), soil texture of the study field is ranging from Sandy Loam to Silt Loam. According to the grain size, it was estimated that sediment of the study area was discharged as wash load and suspended load. It correlated to the grain size of soil sampled from deposited area of the reservoir inundation at lower reach, which contains 78% silt and 18% clay.

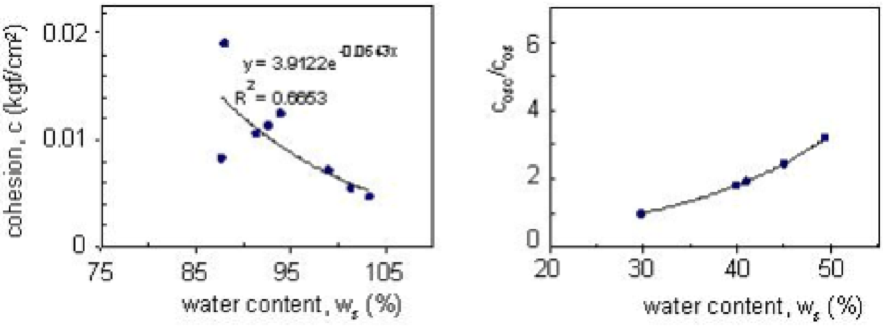

Fig. 7. Relation between soil water contents and soil surface cohesion

Cohesion and Water Content Relationship

Soil surface cohesion was calculated using Coulomb formula based on shearing strength of soil and effective normal pressure to shear plane. Relation between soil surface cohesion of saturated layer and soil water content at 5 mm depth is showing that when the soil water content increased, soil surface cohesion fell exponentially (**Fig. 7**).

This tendency corresponded to the experiment conducted by Minami *et al.* (2002). Conversely, ratio of cohesion [critical cohesion/cohesion] will increase as the soil water content increased. It can be understood that when soil water content increased near to the saturated condition, cohesion of the soil surface will decline while critical cohesion is constant. This relationship is one of the important parameters for developing equation of the cohesive soil erosion, which can be formulated as:

$$c_{os} = 3.9e^{-0.06w_s} \tag{1}$$

where c_{os} is soil surface cohesion (kgf/cm^2), and w_s is soil water content (%).

Erosion Velocity and Water Content Relationship

The flume tests were conducted to evaluate sediment discharge, friction velocity and soil water content changes at a simulated unit discharge and slope gradient. The experiment was conducted for five kinds of moderate slope gradient (ranging from 1 to 10°) at two conditions of unit discharge, as shown in Table 1. Additional experiments were then carried out for steeper slope gradients (15 and 20°), as reference cases of sediment discharge type identification. Result shows great differences between erosion type of moderate and steeper slope gradients. Sediment discharge on the moderate slopes was mainly identified as sheet erosion. The slope had never been etched by rills, due to sheet overland flow. It was mostly similar to the actual phenomena at the study field during the February 21 rainfall event, whereas runoff discharged as sheet overland flow on the surface of the study field. Conversely, rill erosion that leads to gully erosion was developed at steeper slope. The difference between the phenomena observed and that simulated in the flume might be due to effect of the microtopography on the furrow bed of the study field where it has micro-steps along the furrow and relatively gentle slope (< 15°). However, since the purpose of flume experiments was to clarify sheet erosion condition due to overland flow, hence experiment result of the steeper slope was not discussed further in this study. In order to understand the effect of cohesion on erosion velocity, relation between erosion velocity and soil water content was clarified. The soil water content was measured by collecting modest samples from the surface of specimen every time after the water run thoroughly for each case. Next, the weight of soil samples in both wet and dried condition was measured. Mass wetness was defined as ratio between weight of water to the weight of dried soil. The measured soil water contents were then converted into cohesion by employing Equation 1. During the experiments, it was assumed that sediment discharge was produced by eroded soil from the whole surface area. Erosion velocity was calculated by dividing sediment discharge volume in dried condition by plane area of the soil surface and measured time. Relation between erosion velocity and cohesion shows that when the cohesion increased, erosion velocity decreased (**Fig. 8**). It also agrees with the result of Minami *et al.* (2002), which reported that erosion rate rise sharply when the viscosity is low. In contrast, erosion velocity increased sharply as the friction velocity increased (**Fig. 9**). The above findings suggested that surface erosion on the study field due to overland flow was controlled by two contrary factors: first, cohesion as the soil resistance force against erosion; and second, friction velocity as erosive agent.

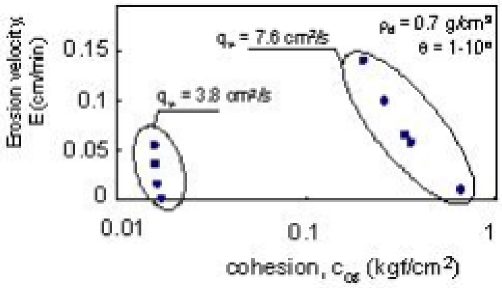

Fig. 8. Relation between cohesion and erosion velocity

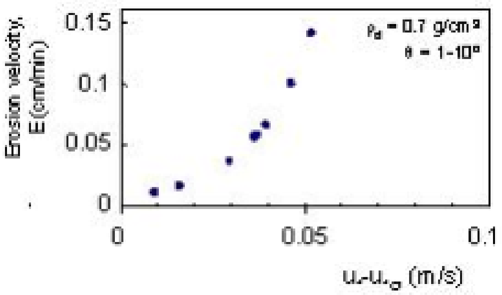

Fig. 9. Relation between friction velocity and erosion velocity

Proposing Erosion Velocity Equation

The proposed equation was governed by the relationship between non-dimensional erosion velocity ($\bar{e}$) and non-dimensional cohesion ($\bar{c}$), formulated as follows:

$$\begin{aligned} E &= \alpha(u_* - u_{*c})\left(\frac{c_{osc}}{c_{os}}\right)^m \qquad (2)\\ \bar{e} &= \frac{E}{(u_* - u_{*c})}\\ \bar{c} &= \frac{c_{osc}}{c_{os}} \end{aligned}$$

where E is erosion velocity (cm/min), u_* is friction velocity (cm/s), u_{*c} is critical friction velocity (cm/s), c_{osc} is critical surface cohesion (kgf/cm^2), c_{os} is surface cohesion (kgf/cm^2), α is coefficient and m is exponential power determined by experiment. Equation 2 is similar to the erosion velocity model of cohesive soil (Minami *et al.*, 2002), which is applicable on gentle slope 1 to 3°. Basic consideration of selecting this equation is due to it requires simple data (parameter of soil cohesiveness and friction velocity) and its challenge to be applied in the study field.

Based on the experiments result in the case of dry bulk density, $\rho_d = 0.7$ g/cm^3, it was found that coefficient $\alpha = 0.0002$ and $m = 0.66$, critical friction velocity; u_{*c} was constant at about 0.02 cm/s. The critical cohesion, c_{osc} was estimated to be approximately 0.638 kgf/cm^2. Next, the Equation 2 can be rearranged as follows:

$$E = 0.0002(u_* - 0.02)\left(\frac{0.638}{c_{os}}\right)^{0.66} \qquad (3)$$

The equation was calibrated in laboratory-scale, and the result, defined as calculated erosion velocity, was then compared with the measured one. Relation between calculated and measured erosion velocity is presented in **Figure 10**. Despite a little discrepancy between the calculated and measured erosion velocity, many data shows well agreement, indicated by distribution of data points are close to the line of perfect agreement. It suggests that proposed equation could successfully reproduce the measured erosion velocity in laboratory scale.

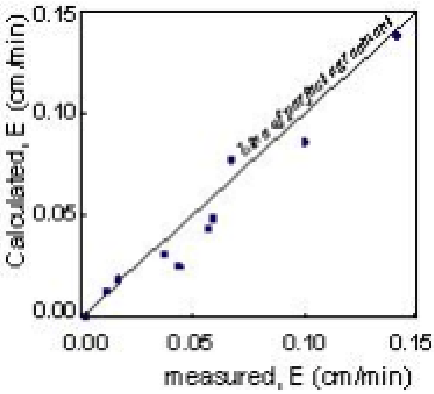

Fig. 10. Calculated and measured erosion velocity at laboratory-scale

Evaluating the Equation

Evaluation was carried out in laboratory-scale by comparing the proposed equation with a soil loss equation employed by Kusaka *et al.* (1981). This adopted-equation was selected since mostly it has similar parameters involved with the proposed equation. It includes the parameters of dry bulk density, surface roughness, and clay ratio in order to clarify the resistance mechanism of the soil layer to the tractive force due to overland flow. It is governed by the relationship between non-dimensional unit sediment discharge ($\bar{q}$) and non-dimensional tractive force ($\bar{\tau}$), formulated as follow:

$$\begin{aligned} \frac{q_e}{u_* d_k} &= a \exp\left(\alpha \frac{u_*^2}{(\rho_d/\rho_w)\cdot g \cdot d_k}\right) \qquad (4) \\ \bar{q} &= \frac{q_e}{u_* d_k} \\ \bar{\tau} &= \frac{u_*^2}{(\rho_d/\rho_w)\cdot g \cdot d_k} \end{aligned}$$

where q_e is loss of soil (soil erosion volume, or weight), u_* is friction velocity, d_k is equivalent (representative) surface roughness, ρ_d is dry bulk density, ρ_w is water density, g is gravitational acceleration, a and α are coefficient determined by experiment. Based on the parameters obtained from the flume experiment for each simulated ρ_d, q_w and θ; the estimated roughness k, $\bar{q}$ and $\bar{\tau}$ were then calculated. Evaluation of Reynolds number for$\rho_d = 0.7$ g/cm^3 mostly showed "roughness surface"; hence the d_k was substituted from each calculated k. Relation between $\bar{q}$ and $\bar{\tau}$, for all simulated q_w and θ shows clear tendency. Sediment discharge rises sharply at the beginning and then increases gradually. As the tractive force increases, soil loss increases exponentially. This indicates that erosion rates are greatly affected by tractive force as the external driving force against soil resistance. Firstly, erosion rates increased exponentially and gradually reach stable condition. The stable condition might be caused by decrease in the moveable sediment as smooth surface has already formed. Initial condition of the soil surface in the flume has a roughness (mixture between fine and coarse sediment) that was managed during soil sample compaction. It was then saturated and dislodged by flowing of the constant unit discharge. The smooth surface formed when the coarse sediment has discharges thoroughly. The interparticle bond of fine sediment (silt and clay) was then exposed by water flow that greasy enough to be eroded. As the result, no further detachment of the soil surface.

The coefficient $a = 0.0023$ and $\alpha = 42.656$ was then determined. Since the unit of the adopted equation was in volume (cm^3) of soil loss, the proposed erosion velocity equation was then converted into volume unit. Volume of soil loss (Ve) was simply calculated based on the flume experiment that multiplying erosion velocity (E) by surface area (A) and measured time (t). The relation between calculated and measured soil loss of both proposed equations and adopted equation at simulated q_w and θ is shown in **Figure 11**. The proposed equation demonstrates better agreement between the calculated and measured soil loss. However, the adopted equation reveals less agreement. The discrepancy between the calculated and measured soil loss of the adopted equation might be due to effect of the d_k. The same value was employed for all of the measured time, while it might be different in actual situation. According to our observation, bed surface was changed with time. Before the experiment the bed had a certain roughness, and gradually smoothed down. This prevail that the d_k changes with time. Therefore, based on these considerations the adopted equation was neglected, and Equation 3 was proposed as the experimental erosion velocity equation of the cohesive soil and steep slope for the study field in Mrica Watershed.

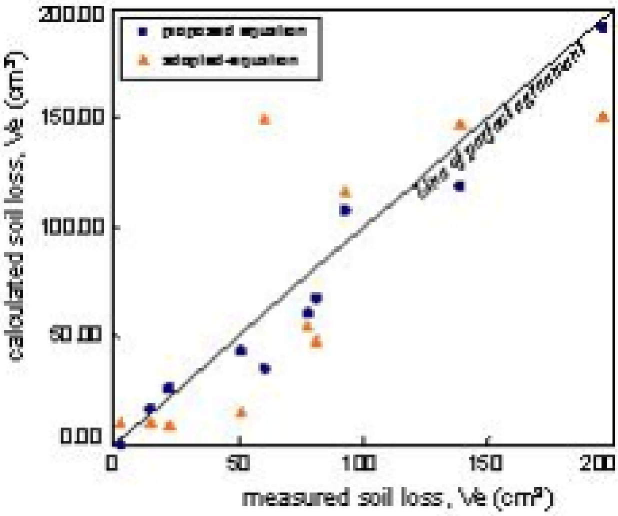

Fig. 11. Calculated and measured soil loss

Conclusions

Hydrological observations at the observation-plot within the study field revealed that rainfall intensity of 42 to 58 mm/hour has triggered sediment discharge. The sediment discharge hydrograph obtained from the observation-plot showed obvious response to the hyetograph, which rise sharply near the peak of the rainfall up to 680 ml/s. Erosion type was identified as sheet erosion due to overland flow. Soil of the study field contained 40 to 60% of cohesive materials (silt and clay).

On the basis of actual sediment discharge, laboratory experiments of single-shear surface test and flume test were conducted using the study field soil. The relation between soil surface cohesion of saturated layer and soil water content at 5 mm depth showed that soil surface cohesion decreased exponentially when the soil water content increased. Conversely the ratio of cohesion increased as soil water content increased. The flume test result revealed that when cohesion increased, erosion velocity decreased. On the contrary, erosion velocity increased sharply as the friction velocity increased.

Experimental erosion velocity equation of the cohesive soil and steep slope for the study field in Mrica Watershed (Equation 3) was proposed.

Acknowledgements

The authors would like to thank Dr. Agr. Katsuo SASAHARA of the Public Works Research Institute (PWRI) Tsukuba, Japan for the discussion. Some part of this study has financially supported by the Foundation of Hokkaido River Disaster Prevention Research Center, Japan.

References

Ariathurai R., and Arulanandan K. (1978) Erosion rates of cohesive soils. Journal of the Hydraulics Division, *Proceedings of the American Society of Civil Engineers 1978*. **104**, No.HY2, p.279–283.

Dickey E.C., Shelton D.P., Jasa P.J. (1986) Residue Management for Soil Erosion Control, *electronic version*: www.ianr.unl.edu/pubs/fieldcrops/g544.htm. Accessed on May 2003 (now being reviewed and revised by the publisher).

Fan J. C., and Wu M. F. (2001) Estimation of interrill soil erosion on steep slopes. *Transactions of the ASAE*, **44**(6), 1471–1477.

Govindaraju, R.S. (1995) Non-dimensional analysis of a physically based rainfall-runoff-erosion model over steep slopes. *Journal of Hydrology*. **173**, 327–341.

Hartanto H, Prabhu R, Widayat A.S.E., and Asdak C. (2003) Factor affecting runoff and soil erosion: plot-level soil loss monitoring for assessing sustainability of forest management. *Forest Ecology and Management*. **180**, 361–374.

Heusch B. (1993) Soil erosion in Catchments and Experimental Plots on Java (Indonesia) and Luzon (The Philipines). *Soil Technology*. **6**,191–202.

Hillel, D. (1998) *Environmental Soil Physics*, Academic Press, USA, p.64.

Krishnamurty M. (1983) Incipient motion of cohesive soils. Frontiers in Hydraulic Engineering. *American Society of Civil Engineers.* p.96–101.

Kusaka T., Tanaka K., and Shikasho S. (1981) A method for estimating soil loss due to runoff — Characteristics of soil erosion caused by rain water flow (III) —. *Transaction of JSIDRE.* **94**, 1–6.

Kusumandari A., and Mitchell B. (1997) Soil erosion and sediment yield in forest and agroforestry areas in West Java, Indonesia. *Journal of Soil and Water Conservation.* **52**(4), 376–380.

Minami N., Nakano M., Yamada T., Shimomura S., and Onodera M. (2002) Red soil erosion at the oversaturated layer formed at the Pineapple field surface in Okinawa. *Journal of the Japan Society of Erosion Control Engineering.* **55**(3), 3–11.

Moehansyah H., Maheswari B.L., and Armstrong J. (2004) Field evaluation of selected soil erosion models for catchment management in Indonesia. *Biosystems Engineering.* **88**(4), 491–506.

Partheniades E. (1965) Erosion and deposition of cohesive soils. *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers.* **91**, No.HY1, p.105–139.

Purwanto, E. (1999) *Erosion, sediment delivery and soil conservation in an upland agricultural catchment in West Java, Indonesia: a hydrological approach in a socio-economic context*, PhD Thesis, Vrije Universiteit, Amsterdam, 218 pp.

Schmidt J. (2000) *Soil Erosion: Application of physically based models*, Springer-Verlag, Berlin Germany. p.3–31.

Sidorchuk A. (2005) Stochastic modelling of erosion and deposition in cohesive soils. *Hydrological Processes.* **19**,1399–1417.

Sirvent J., Desir G., Gutierrez M., Sancho C., and Benito G. (1997) Erosion rates in badland areas recorded by collectors, erosion pins and profilometer techniques (Ebro Basin, NE-Spain). *Geomorphology.* **18**, 61–75.

Soil erosion.net (2004) *Web URL*: http://soilerosion.net/. Accessed November 2004.

Suwartha N. (2005) *Soil erosion and sediment discharge from cultivated slope linking with sedimentation in the Mrica Watershed, Central Java, Indonesia*, Master Thesis, Hokkaido University, Japan.

Van Dijk A.I.J.M., and Bruijnzeel L.A. (2003) Terrace erosion and sediment transport model: a new tool for soil conservation planning in bench-terraced steeplands. *Environmental Modelling & Software.* **18**, 839–850.

Wan Y, El-Swaify, Sutherland R.A. (1996) Partitioning interrill splash and wash dynamics: a novel laboratory approach. *Soil Technology.* **9**, 55–69.

William E.K., and Ronald C.G. (1981) Erosion resistance of cohesive soils. Journal of the Hydraulics Division, *Proceedings of the American Society of Civil Engineers*, Vol.**107**. HY10. p.1211–1224

Zhang X.B., Quine T.A., Walling D.E., and Wen A.B. (2000) A study of erosion on steep cultivated slope in the Mt. Gongga Region near Luding, Sichuan, China, using the 137Cs Technique, *ACTA GEOLOGICA HISPANICA*, **35**(3–4), 229–238.