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# Cohesive Sediment Transport Process and Practical Estimate: A Review

Ariva Sugandi Permana[1], Sholihin As'ad[2], Cahyono Ikhsan[3]

[1]Department of Civil Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Thailand
Email: ariva.pe@kmitl.ac.th
[2]Department of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret Surakarta, Indonesia
Email: sholihinasad@ft.uns.ac.id
3Department of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret Surakarta, Indonesia
Email: cahyonoikhsan@staff.uns.ac.id

## ABSTRACT

Transportation of sediment is an essential dynamic process in a natural river towards a hydraulic equilibrium state, as it affects the stability of the river itself. Extensive erosion and sedimentation in a natural river or irrigation canal will cause high maintenance costs for irrigation, and flood prevention works. It will cause reservoirs siltation, and scouring of bridges. This study attempts to explore the existing schools of thought and theories of sediment transport, by reviewing the existing theories of sediment transportation for cohesive materials of wash loads, and suspended loads. We review the sediment transport formulas for cohesive materials, based on their movement from the watershed to the stream, and present the underlying theories to estimate the quantity of sediment transport for cohesive materials. We identified that there are two entities of the transport process of the sediment for cohesive materials, which are in the watershed and in the stream. During the review, we found that the uncertainty in estimating the quantity of cohesive sediments is higher than non-cohesive sediment materials.

Keywords: suspended loads, wash loads, bed loads, sediment transport, cohesive materials.

## ARTICLE HIGHLIGHTS

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## 1 Introduction

Water flows in natural rivers or irrigation canals contain the capacity to transport the sediments stem from the river bed or bank when the shear stress occurred in the river bed due to the flow exceeded the shear resistant of the bed or bank materials. It has been generally known that the capacity of transporting sediments depends mainly on the governing variables of flow and sediment properties, which is mathematically expressed by:

$$T = f(\rho_w, \rho_s, h, d_s, S, g) \quad [1]$$

where $T$: capacity of flow in transporting sediment, $\rho_w$: water density, $\rho_s$: sediment density, $h$: depth of flow, $d_s$: diameter of sediment, $S$: Slope of the river or canal, and $g$: gravitational acceleration. However, other hydraulic variables of the river or canal, and hydrologic variables of may also come into picture. The importance of sediment transport has been known due to its significant impacts on the maintenance costs or irrigation canals, or flood control works, and it causes also siltation in the reservoirs, which may lead to the decrease of the life-span of the reservoirs, and therefore the services offered by the reservoirs such as hydro-electric power, irrigation, flood control, and tourism. Scouring surrounding piers of the bridge may cause the bridge collapsed and disruptions on traffics, and generating economic losses. These issues show the importance of sediment transport mechanisms beyond the understanding on the quantity of sediments transported per se. We understood very well on how to estimate the sediment transport. However, in a same stretch of river, for the constant discharge of the river, we found erosion mechanism at a section, meanwhile at another section in the same stretch, we also found sedimentation. A question may arise whether the sediment transport capacity of a river is constant for a given properties of flow along the river, similar to the continuity equation of flow rate, this is called a continuity of sediment transport, or the conventional belief of shear stress due to flow that dictates the quantity of sediment as current theories of transportation sediment, see for example Van Rijn (1993), Gomez & Church (1998), Wu et al. (2000), Vercruysse et al., (2017).

In estimating the sediment transported by the stream, the continuity equation for incompressible fluid, using cartesian coordinate is used:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_x}{\partial z} = 0 \quad [2]$$

Where $v_x, v_y, and\ v_z$ are flow velocity at x, y and z directions.

As the sediment transportation and deposition is governed by the Law of Physics through, among other, the equation [2]. The process of sediment transportation is commonly commenced with the sheet erosion in the river water shed, and transported to the stream. Nearing et al., (2017) and Zihua et al. (2018) asserted that the sheet erosion process involves at least six sub-processes that include soil particles detachment by rainfall, particles transport by runoff, another soil particles detachment by runoff as the shear stress of runoff exceeding the critical shear stress of the particles, and another particles transportation by runoff, and finally discharged to main stream, and transported or deposited by the stream flow in the river depending on the comparison between the shear stress by flow and critical shear stress of the particles. In line with the sheet soil particle erosion, Mutchler & Young 1975 have stated that the soil particles erosion depends primarily on the diameter of the raindrops. A normal or Gaussian distribution of the raindrops is usually used to determine the mean and median of the raindrops that generate soil particle erosions. Laws and Parsons (1943) estimated the size of the raindrops based on the rain intensity, as expressed by the following equation:

$$d = 1.24\, I^{0.182} \quad [3]$$

In which $d$ is average diameter of the raindrops in mm, and $I$ is the rainfall intensity in mm/hour. But, unfortunately no one has attempted to approximate sheet soil erosion from the variables of rainfall intensity or diameter of raindrops, since it is too empirical that will lead to too erroneous approximation to be determined only a single variable, which in fact that many other variables governed the sheet erosion. Universal soil loss equation (Wischmeier and Smith, 1978) as stated in the general equation of soil erodibility of:

$$E = RKLSCP \qquad [4]$$

The equation shows that at least six variables dictate the quantity of sheet erosion. Those variables are $R$: rainfall-runoff factor, $K$: soil erodibility factor, $L$: slope length factor, $S$: steepness of the land factor, $C$: cropping management factor on the land, and $P$: erosion control practice factor on the land. This equation can be conveniently applied for the cohesive sediment materials, which is basically a pre-detachment stage of the process of disintegration of the clay becomes detached particles. After this phase has done, the conventional sediment transport equations to approximate the quantity of sediments, which are mostly based on non-cohesive sediments e.g. sands, and gravel, can be applied.

We limit our study in the tropical alluvial rivers, in the two tropical countries of Indonesia and Thailand. The tropical rivers are normally having the characteristics perennial, ephemeral or intermittent flows, depending on the region and their watershed conditions. The alluvial river itself refers to alluvium types of river bed and bank materials, and be focused on cohesive sediment materials, which predominantly consists of silt and clay. The size ranges of this sediment particle from a few $\mu m$ to a fraction of millimeter. Once the particles eroded from the river bed or banks, or as a result of sheet erosion, as discussed earlier, the material will be carried by the flow in suspensions and may eventually be deposited in the canal, reservoirs or brought to the estuary (Partheniades, 2009).

## 2 Objective and Methodology

The study aimed at acquiring the understanding of the process of transportation sediment by rivers with cohesive soil as the source, since cohesive materials such as clay and silt have different transportation process in the stream. While the cohesive materials will be transported as suspended and washed loads, as they are having very low settling velocity, the non-cohesive materials such as sand and gravel, will be transported mostly as bed loads. The study is therefore observed the two phases of the process. First phase is the process at source of the cohesive materials, we call this is a pre-detachment phase. The second is after the cohesive materials disintegrated by raindrops or runoff becomes sediment particles and ready to be transported downstream, we call this phase the post-detachment state. At post-detachment state, the conventional suspended and washed loads equation to approximate the quantity of sediment transport can be applied. The study was undertaken by exploring existing relevant references and critically review them for the clarity of the issues.

## 3 Cohesive sediment properties and behaviors

Cohesive sediments have primary properties of silt and clay with the diameter of around 1 to 50 $\mu m$. The clay may undergo a substantial plastic deformation, if it is under stress, with or without breaking, depending on water content. The clay has the ability to withstand a certain degree of shear stress, as expressed by the following correlation:

$$\tau_c = c + p \tan \phi \qquad [5]$$

In which $\tau$: critical shear stress, $c$: cohesion, $p$: normal stress, and $\phi$: angle of internal friction. When the critical shear stress of the clay is exceeded by the shear stress generated by the stream, the clay begins to detach and transported downstream as sediment. At the post-detachment period, the non-cohesive sediment transport can be applied. When the riverbed or bank materials are cohesive material, where on the surface of the riverbed and bank the normal force can be neglected or $p = 0$, the critical shear stress of the material depends entirely on the cohesion, and not on the diameter of the materials. This is at pre-detachment of the materials.

In addition to the theoretical critical shear stress for cohesive materials as exhibited by Eq. [5], Lane (1955) suggested the critical velocity and shear stresses for cohesive materials, as shown in Table 1.

**Table 1:** Critical Velocities and Shear Stress for Open Channels

| **Void Ratio** | 0.20 – 0.30 | | 0.31 – 0.60 | | 0.61 – 1.20 | | 1.21 – 2.00 | |
|---|---|---|---|---|---|---|---|---|
| **Clay type** | $V_c\ [m/s]$ | $\tau_c[Pa]$ | $V_c\ [m/s]$ | $\tau_c[Pa]$ | $V_c\ [m/s]$ | $\tau_c[Pa]$ | $V_c\ [m/s]$ | $\tau_c[Pa]$ |
| Sandy clay (>50% clay) | 1.80 | 30.20 | 1.30 | 15.70 | 0.90 | 7.50 | 0.45 | 1.92 |
| Heavy clays | 1.70 | 27.00 | 1.25 | 14.60 | 0.85 | 6.75 | 0.40 | 1.50 |
| Clays | 1.65 | 25.40 | 1.20 | 13.50 | 0.80 | 5.94 | 0.35 | 3.30 |
| Lean clays | 1.35 | 17.00 | 1.05 | 10.25 | 0.70 | 4.60 | 0.32 | 0.32 |

On the other hand, for the non-cohesive sediment, and post-detachment of cohesive materials, the critical shear stress is expressed by the following formula:

$$\tau_c = \theta^* (s_g - 1) \rho_w g d_{50} \qquad [6]$$

Where $\theta^*$: Shield's factor, $s_g$: specific gravity of the river bed material, $d_{50}$: median particle size of river bed material. It is therefore the common ground of both cohesive and non-cohesive sediment materials is shear stress suffered by the them.

Each particle of clay material is built by a number of crystal unit cells and held together by valence bonds. Clay particle will detach and disintegrate when it is in the water. This depends on the nature and strength of the bonds. The clay with more resistant bonds will form sediment with grains composed of several unit cells in the form of block (Partheniades, 2009). In terms of chemical composition, the clay consists of silicates, aluminum, magnesium and iron (Mitchell, 1993). However, we will not discuss too far regarding this matter, as our concern is entirely on the appearance of cohesive sediment materials as reflected in equation [5], and to some degree of the interaction between water and clay, despite it has not been fully understood, Libohova et al., (2018), asserted that the clay particles hold very strongly the water absorbed, and free pore water subject to the laws of hydrodynamics, which is an important point in the cohesive sediment transportation.

## 4 Cohesive sediment transport processes

### 4.1 Pre-detachment of cohesive materials: The Universal Soil Loss Equation

At pre-detachment state of the cohesive materials, prior to be disintegrate by the rainfall or the overland flow, the sources of cohesive sediment materials are on land and in stream. For the on-land source of materials, the best and easiest ways to predict the presence of sheet erosion and estimate the quantity of them, but still acceptable result, is by employing the Universal Soil Loss Equation (USLE) presented in Eq. [4] and Eq. [5]. The USLE was developed based on 10,000 plot-year data collected over 70 years (Meyer & Moldenhauer, 1985; Renard, 1985).

The rainfall-runoff factor, $R$, was derived from many resources of research data in the USA, and therefore, it must be developed based on local condition for the use in other region (Renard, 1997). The data shown that when factors other than rainfall are held constant, soil losses from fields are directly proportional to a rainstorm parameter, $EI$, the total storm energy (E) multiplied by the maximum 30-minute rainfall intensity ($I_{30}$). The $R$ can also be determined through an iso-erodent map, providing that the accuracy of the spatial variability of the rainfall is maintained. The iso-erodent map is derived from the history of precipitations. Wischmeier (1974) suggested the following correlation of rainfall-runoff factor and precipitation:

$$R = 27.38 {P_2}^{2.17} \qquad [7]$$

Where $P_2$ is a two-year frequency of 6-hour rainfall (in inch). Or, it can also be approximated from the annual precipitation $P_A$:

$$R = -110.3 + 10.78\, P_A \qquad [8]$$

The equations [7] and [8] must be used with extra precaution as the equations purely based on empirical evidence. A locally-based observation to find the value of local R is therefore required.

The soil-erodibility factor in the USLE, K, was also developed based on the empirical and experimental data. A global data on 225 of measured K values, the mean values of the soil-erodibility factor is expressed as:

$$K = 7.594 \left\{ 0.0034 + 0.0405 e^{-\frac{1}{2}\left(\frac{\log(D_g)+1.659}{0.7101}\right)^2} \right\} \qquad [9]$$

In which $D_g$ is the geometric mean of the particle diameter in millimeter.

The practical K factors for different type of sediment materials with particular organic matter contents (OMC) are given in Table 2.

**Table 2** Values of K

| Cohesive material texture | K (tons/hectare) | | |
|---|---|---|---|
| | Average OMC | OMC < 2% | OMC ≥ 2% |
| Clay | 0.49 | 0.54 | 0.47 |
| Clay loam | 0.67 | 0.74 | 0.63 |
| Heavy clay | 0.38 | 0.43 | 0.34 |
| Silty clay | 0.58 | 0.61 | 0.58 |
| Silty clay loam | 0.72 | 0.79 | 0.67 |

The topographic factor $LS$ comes into picture, as the erosion increases as the length of the slope, L, and the slope, S, itself increase. The slope length is the horizontal distance from the origin of overland flow to the point where the slope gradient begins to decrease or runoff becomes concentrated in a channel (Wischmeier & Smith, 1978). The slope steepness factor, *S*, reflects the influence of slope gradient on erosion. In British unit, the slope length factor is given by:

$$L = \left(\frac{\lambda}{72.6}\right)^{m} \qquad [10]$$

$$m = \left[\frac{\sin\theta}{0.0896\{3(\sin\theta)^{0.8}+0.56\}}\right] \Big/ \left\{1 + \left[\frac{\sin\theta}{0.0896\{3(\sin\theta)^{0.8}+0.56\}}\right]\right\} \qquad [11]$$

In which $\lambda$ is length of horizontal projection of the slope in foot, and $\theta$ is angle of the slope. The steepness factor S is given by:

$$S = 10.8\sin\theta + 0.03 \quad for\tan\theta < 9\% \qquad [12]$$

$$S = 10.8\sin\theta - 0.50 \quad for\tan\theta \geq 9\% \qquad [13]$$

Eq. [12] and [13] are valid only for slope length shorter than 15 ft (4.50 m). For the slope length longer than 15 ft, the following equation can be used:

$$S = 3.0(\sin\theta)^{0.8} + 0.56 \qquad [14]$$

The cropping management factor, *C*, uses erosion in the continuous fallow and tilled land as a standard of soil loss. Despite theoretically complicated to define the $C$ factor, it is determined from the ratio between the soil loss from land under a certain crop and land management system and the standard of soil loss. It considers the type and density of vegetative cover on the soil as well as land management practices, i.e. time between operations, weed control, tillage, watering, fertilization, and crop residues. For the guidance and practical purpose, however, the C can be approximated by the multiplication of crop-type factor, *a*, and tillage-method factor, *b*. The C is therefore equal to $a \times b$. The values of a and b are shown in Table 3.

**Table 3** Factors determining C (for practical use)

| Crop Type | Factor, *a* | Tillage method | Factor, *b* |
|---|---|---|---|
| Hay and pasture | 0.02 | No till | 0.25 |
| Fruit trees | 0.10 | Zone tillage | 0.25 |
| Cereals | 0.35 | Ridge tillage | 0.35 |
| Grain corn | 0.40 | Mulch tillage | 0.60 |
| Silage corn, bean, canola | 0.50 | Wet season plow | 0.90 |
| Seasonal horticulture crops | 0.50 | Dry season plow | 1.00 |

Notes: Other crop types and tillage methods can be approximated or interpolated from the above values

The erosion control practice factor, $P$, reflects the effects of erosion control practices on the land, which will reduce the amount and rate of the overland flow and thus reduce the quantity of sheet erosion. The $P$ factor represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope. The most commonly used supporting cropland practices are cross-slope cultivation, contour farming and strip cropping. Subject to local conditions and research, the following P factor with corresponding erosion control practices can be used (Table 4).

**Table 4** P Factors (for guidance and practical use)

| Erosion control practice | Factor |
|---|---|
| Strip cropping follows the land contour | 0.25 |
| Strip cropping follows the cross slope | 0.35 |
| Contour farming | 0.50 |
| Cross slope | 0.75 |
| Up and down slope | 1.00 |

After the process of detachment of the cohesive materials due to erosion by overland flows or raindrops, the sediment materials will not be immediately transported to the stream. Depending on many factors, some of them will be deposited on the land. Therefore, the quantity of sediment estimated by the USLE, may not be automatically equal to the quantity of sediment in the stream. They are two different entities, but interconnected one another.

## 4.2 Sediment transport at post-detachment of cohesive materials

The cohesive materials will be transported by the stream in the form of suspended load and washed load, as their settling velocity is very small. The sediment is therefore will not be transported as bed load. For the diameter of clay in order of $\mu m$, the Stoke's settling velocity is expressed by the following equation:

$$w = \frac{(s_g - 1) g d^2}{18\nu} \qquad [15]$$

In which $d$: diameter of sediment, and $\nu$: kinematic viscosity of water. Unlike the sediment transport of non-cohesive materials like bed load, the sediment transport mechanism of the cohesive materials cannot be estimated in explicit and straightforward ways, since it involves, at least, four processes, which are advection, molecular diffusion, turbulent mixing, and dispersion (Julien, 2010). Due to this state, the cohesive materials in the stream flow as suspended sediments, will travel individually to the downstream, despite they come from the same point source, they will not arrive at the same section of the stream. Therefore, to estimate the suspended sediment discharge, the time-dependent concentration of sediment is approximated. The time-dependent concentration of wash load sediment will also be depending on the flow depth $h$, and downstream propagation of the suspended sediment $x$. For one-dimensional diffusion, the suspended sediment concentration is estimated by the following equation:

$$C(y,t) = \frac{m}{A\sqrt{4\pi Dt}} e^{-\frac{y^2}{4Dt}} \tag{16}$$

Where the mass $m = \int_\forall C\, d\forall$ is the concentration given the cross-sectional area A, $D$ is molecular diffusion coefficient, $y$ is the distance of measurement from the point source in lateral direction of the river, and $t$ is given time. For two-dimensional diffusion i.e. in $x\ and\ y$ directions, the estimated sediment concentration is expressed by:

$$C(x,y) = \left[\frac{\dot{m}}{h\sqrt{4\pi\varepsilon_t xV}}\right] e^{-\frac{y^2 V}{4\varepsilon_t x}} \tag{17}$$

In which $\dot{m} = m/t, V = x/t, \varepsilon_t = D, x\ and\ y$ are longitudinal and lateral directions of the flow.

The maximum concentration of the suspended sediment in the stream flow for longitudinal dispersion of an instantaneous point source is approximated by:

$$C_{max} = \frac{m}{Wh\sqrt{4\pi K_d t}} \tag{18}$$

Where $W$and $h$are width and depth of the stream, $K_d$ is dispersion coefficient, which can be approximated by the following equation:

$$K_d \cong 250\ hu_* \tag{19}$$

In which $u_*$: the flow velocity that generates critical shear stress → $u_* = \sqrt{ghS}$ [20]

By the above series of approximation, the quantity of suspended sediment in the stream can be estimated. The suspended sediment materials are only part of the total sediment transported by the stream. The total sediment transport itself is equal to the quantity of the suspended load and quantity of bed load. The total load is important for the overall maintenance of the irrigation canal, navigation canal, reservoirs, and other hydraulic infrastructures.

## 5 Conclusions

Unlike non-cohesive sediment transport, the cohesive sediment transport cannot be determined in straightforward way at particular point and time, as the properties of the cohesive sediment materials of colloids, suspended and dispersed as insoluble materials in the stream. The diameter of the cohesive sediment materials in the range of 1 to 50 $\mu m$ makes more complication in the estimate. For the non-cohesive sediment, the theories are sufficiently available, see for example Du Boy's (1879), Meyer-Peter-Muller (1948), and Einstein-Brown (1942). However, for the cohesive materials, the approximation is rather based on theoretical approach of spatio-temporal-dependent sediment concentration, as it involves four process, which are advection, molecular diffusion, turbulent mixing, and dispersion. The mixture of sediment in the stream depends on time i.e. when we estimate it, and space i.e. where is the location. Another complication for cohesive sediment is that, the sediment materials must be traced back in the to consider the sources of sediment on the land in the watershed and in the stream. Despite its interconnectivity, the transportation process of the sediment materials is disconnected, since some parts of the sediment is deposited in the source, while some other parts are transported to the stream by the overland flow. However, the quantity of sediment materials transported on the land and in the stream can still be estimated by existing formulas.

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