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On the Limitation of Turbidity Generation Unit

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1. INTRODUCTION

Quantification of sediment losses into the ambient waters associated with various works of coastal developments is highly required for predicting their possible detrimental impacts on the aquatic environments. Although there have been some studies especially related to dredging (e.g., Nakai, 1978; Kirby and Land, 1991; Collins, 1995; Pennekamp et al., 1996; Lorenz, 1999; Jin et al., 2003), none can be regarded as a general guidance up to date, which results from the facts that the amount of sediments released into the ambient waters is influenced by several site/case-specific conditions, and that the existing studies have been carried out using different methods. The variability of the results means that care should be taken in using them for environmental impacts assessments (EIAs).

One of the pioneering researches is Nakai's (1978) concept of turbidity generation unit (TGU) established based on the field investigations conducted by the Port Bureau of Japanese Ministry of Transport from 1973 to 1976. The 4th Port Construction Bureau (hereinafter referred to as 'the 4th Bureau') developed an informal manual for predicting water pollution caused by marine construction works in 1978, and revised in 1982. For the last decade, the TGUs in the manual have been widely used for the EIAs of various coastal development projects in Korea.

The TGU is a standardized loss rate of sediment at a reference current speed. Hence the rates at the higher and lower current speeds also can be calculated if the grain composition of dredged material and the target dredger are comparable to those at the sites where TGUs were previously provided.

At a first glance, it seems to be logical and very useful especially for numerical modeling on the area where current speed largely varies (e.g., Johnson and Pachure, 1999).

In the TGU method, the increase of current speed above the reference value is reflected in extending the particle size and corresponding weight fraction which can remain in suspension. However, Nakai (1978) neglected the behavior of aggregates by adopting the formula of Ingersoll et al. (1955) for the critical suspension velocities of the grains finer than 74 μm.

In this paper, critical limitation of the TGU method is indicated by reviewing the theory, and comparing with a grab dredging-induced loss rate evaluated based on the sediment flux measured by a vessel-mounted ADCP monitoring system.

2. REVIEW OF TGU

2.1 Basic Theory and TGUs of Dredging

As mentioned above, the TGU is the amount of sediments generated when a unit quantity of bed material is dredged under a standardized condition defined as follows:

> *A standard tidal current velocity is determined by the condition that soil particles with diameters larger than 74μm (silt) are not resuspended* (Nakai, 1978).

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With this definition Nakai expressed the TGU as

$$W_{74} = \frac{R_R \cdot Q_S}{V_D} = R_R \cdot K \cdot \gamma \qquad (1)$$

where,

W_{74} = turbidity generation unit (kg/m^3)

Q_S = total quantity of sediment generated by dredging works (kg)

R_R = R_{74}/R_o

R_{74} = fraction of particles with a diameter smaller than 74 μm

R_o = fraction of particles with a diameter smaller than the diameter of a particle whose critical resuspension velocity equals the current velocity in the field

V_D = volume of dredged materials (m^3)

K = a coefficient dependent on dredge type, soil condition, etc.

γ = specific weight of dredged materials (kg/m^3)

Based on the field measurements and Eq. (1), Nakai and the 4th Bureau provided the TGUs for various types and classes of dredgers as summarized in Table 1.

By denoting the quantity of sediment generated by unit volume of dredged material, Q_S/V_D, as W_o(kg/m^3), Eq. (1) can be rearranged as

$$W_o = \frac{R_o}{R_{74}} \cdot W_{74} \qquad (2)$$

The 4th Bureau asserted that the loss rate W_o at a new site where the dredger and R_{74} are similar to those in Table 1 can be estimated by using Eq. (2).

It should be noted that difference in current speeds at a new site and the corresponding TGU site is incorporated only in the ratio of the fractions, R_o and R_{74}.

2.2 Critical Suspension Velocity

Eqs. (1) and (2) mean that the critical suspension velocity, U_C, for a grain size plays the key role in estimating W_{74} and W_o. Nakai and the 4th Bureau selected the formula of Camp (1945) for the U_C of coarser grains than 74 μm, and that of Ingersoll et al. (1955) for the U_C of the finer. They were derived for the optimal design of a settling tank, and their original forms are respectively expressed as

$$U_C = \sqrt{\frac{8\alpha}{f} g(s-1)d} \qquad (3)$$

$$U_C = \frac{w_S}{\beta} \cdot \sqrt{\frac{8}{f}} \qquad (4)$$

Table 1. Turbidity generation units for different dredgers (Nakai, 1978; 4th Bureau, 1978; 1982)

Type of Dredger	Power or Bucket Volume	Dredged Materials			W_{74} (kg/m^3)
		d<74 μm (%)	d$^{1)}$<5 μm (%)	Classification $^{2)}$	
Pump	4,000 hp	99.0	40.0	silty clay	5.3
		98.5	36.0	silty clay	22.5
		99.0	47.5	clay	36.4
		31.8	11.4	sandy loam	1.4
		69.2	35.4	clay	45.2
		74.5	50.5	sandy loam	12.1
	2,500 hp	94.4	34.5	silty clay	9.9
	2,000 hp	3.0	3.0	sand	0.2
		2.5	1.5	sand	0.3
		8.0	2.0	sand	0.1
	1,000 hp$^{3)}$	74.0	12.0	silt	0.6 24.8
Trailing-suction	2,400 hp x 2	92.0	20.7	silty clay loam	7.1
		88.1	19.4	silty loam	12.1
	1,800 hp	83.2	33.4	silt	25.2
	8,000 hp$^{3)}$	5.5	-	sand	3.6
Grab	8 m^3	58.0	34.6	silty clay	89.0$^{4)}$ 9.9$^{5)}$
	4 m^3	54.8	41.2	clay	84.2
		74.0	12.0	silt	10.9$^{3)}$ 1.0$^{3)}$
	3 m^3	45.0	3.5	silty loam	15.8
		62.0	5.5	silty loam	11.9
		87.5	6.0	silty loam	17.1
Bucket$^{6)}$	0.2 m^3	10.2	1.5	sand	17.6
		27.7	12.5	sandy loam	55.8
Dipper$^{3)}$	2 m^3	74.2	6.0	silty clay	13.3 8.6

1) diameter of soil particle
2) according to the triangular soil classification system
3) included only in the 4th Bureau (1978)
4) during neap tide
5) during spring tide, not included in Nakai (1978)
6) bucket volume is not included in Nakai (1978)

in Eq. (3) of Camp (1945), α is a function of grain diameter and bed roughness, which may be assumed equal to a constant ($\fallingdotseq$0.04) without great error, f is bed friction factor (=0.025), g is acceleration due to gravity, s and d are specific weight and diameter of sediment particle, respectively.

In Eq. (4) of Ingersoll et al. (1955), β is a constant ranging 1.2 to 2.0, and w_s is the settling velocity of a grain calculated by the well- known Stokes' law:

$$w_S = \frac{1}{18} \cdot \frac{g(\rho_S - \rho)}{\mu} \cdot d^2 \qquad (5)$$

in which, ρ_S and ρ are the densities of grain and seawater, respectively, and μ is the viscosity of seawater.

Nakai and the 4th Bureau fixed α as about 0.0108 lower than that of Camp (1945) based on the field experiment of Matsda and Iwata (1964), and β as the minimum of 1.2, by which Eqs. (3) and (4) respectively reduce to

$$U_C = 1.86\sqrt{\frac{(\rho_S - \rho)}{\rho} gd} \qquad (6)$$

$$U_C = \frac{1}{1.2} \cdot w_S \cdot \sqrt{\frac{8}{f}} \qquad (7)$$

Hence, these relationships between d and U_C can be combined as in Fig. 1 (the 4th Bureau, 1978).

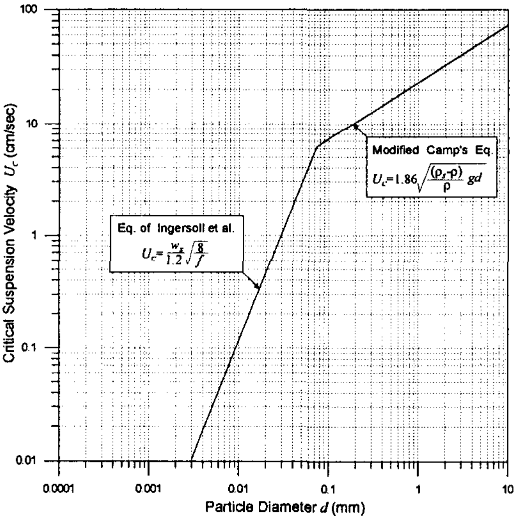

Fig. 1. Critical suspension velocity of the TGU method (the 4th Bureau, 1982).

It should be noticed that w_s in Eq. (4) is the settling velocity of an individual fine grain, not of aggregate or floc consisting of fine grains.

3. TGU AT A TIDE-DOMINATED WATERWAY

The Ministry of Maritime Affairs and Fisheries (2002) of Korea (hereinafter referred to as the MOMAF) evaluated the rates of release of sediments generated by 16 dredgers at 5 coastal areas of Korea by measuring the sediment flux at about 40-50 m downstream of the sediment sources with a vessel-mounted ADCP system.

Site MP1 in Fig. 2 is one of the field measurement sites, where the approaching waterway to Mokpo Harbor at the southwestern tip of the Korean Peninsula was being dredged by a grab (13m^3) dredger. The spring rise of the Mokpo Tidal Station is 4.3 m. The rates of release of sediment for 9 measurements at site MP1 are shown in Table 2.

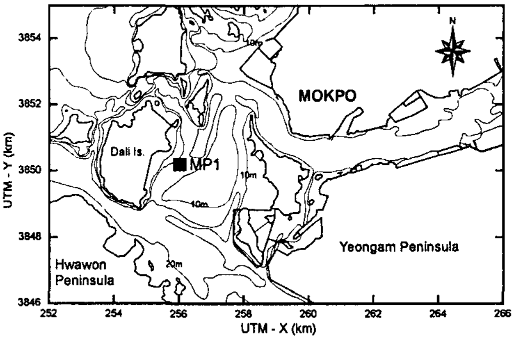

Fig. 2. Map showing a grab dredging site on the approaching waterway to Mokpo Harbor (MOMAF, 2002).

Table 2. Rates of release of sediments per unit volume of dredging at site MP1 (MOMAF, 2002)

Dredged Sediment			Obs. No.	$U^{2)}$ (cm/s)	W_o (kg/m^3)	W_{74} (kg/m^3)
d<74μm (%)	d<5μm (%)	Type$^{1)}$				
59.7	19.8	sandy Silt	1	71.31	102.81	61.41
			2	71.70	159.98	95.55
			3	67.94	134.35	80.24
			4	63.50	152.24	90.93
			5	62.30	126.33	75.45
			6	62.85	84.25	50.32
			7	60.80	61.85	36.94
			8	45.07	44.23	26.42
			9	55.17	25.49	15.22
Average				62.29	99.06	59.16

1) according to the classification of Folk and Ward (1957)
2) section mean

4. DISCUSSION

4.1 Theoretical Drawbacks of TGU Method

The background theory of the TGU method has two drawbacks in views of related phenomena.

The first is that estimating W_o at a new site by applying Eqs. (2), (5), (6) and (7) with Table 1 lies on the basic implicit assumption which the maximum grain size and weight percents of each size class released in to the ambient waters is determined by the grain size distribution of dredged sediments and current speed without consideration of the remaining parameters including the rotation and swing speeds of the cutterhead and cycle times of grab dredging, etc. If the assumption is proper, TGUs obtained under similar conditions of the dredgers and bottom conditions should be comparable.

The second drawback is related to the treatment of fine sediments. According to Fig. 1, all the particles below 74 μm still maintain in suspension even at about 7 cm/s. It is well known, however, that fine grained cohesive particles are not only transported as individual particles but as particle aggregates or flocs (e.g., Teeter, 1993). Hence the settling velocity increases with concentration up to about 5 to 10 g/l (Mehta et al., 1989). Table 3 of Mehta et al. (1989) also shows that while Stokes velocity decreases rapidly with particle size, aggregate settling velocity as well as diameter retain the same orders of magnitude due to increasing aggregate with decreasing particle size; nevertheless, only individual settling velocity is incorporated in the TGU method.

Additionally, mud suspension generally starts to deposit below a critical bed shear stress (τ_{cd}) of 0.04-0.15 N/m^2 (Mehta, 1986). Corresponding current velocity in the water depth of 10m ranges 14 to 27 cm/s when applying the following equation (van Rijn, 1989)

$$\tau_b = \rho g \frac{U^2}{C^2}, \qquad C = 18 \log\left(\frac{12h}{k_s}\right) \tag{8}$$

where, τ_b is bed shear stress, U is depth mean current velocity, C is Chèzy-coefficient, h is water depth, and k_s is effective bed roughness height ($=30z_o$). Zero-velocity level(z_o) is 0.05 cm approximated based on the summary of the existing studies (Soulsby, 1983).

Hence, neglecting the behavior of aggregates in the TGU method results in underestimating the critical suspension velocity of fine sediments. Consequently it means that loss per unit dredging volume W_o of a new site should be overestimated if based on the corresponding TGU previously provided.

Table 3. Primary particle and aggregate diameter and settling velocity (Mehta et al., 1989)

Primary particle diameter (μm)	Stokes settling velocity (mm/s)	Aggregate settling velocity (mm/s)	Aggregate diameter (μm)	Aggregate velocity divided by Stokes velocity
2×10^1	2.4×10^{-1}	2.7×10^{-1}	8.8×10^1	1.1×10^0
2×10^0	2.4×10^{-3}	1.7×10^{-1}	5.6×10^1	7.1×10^1
2×10^{-1}	2.4×10^{-5}	1.1×10^{-1}	3.4×10^1	4.6×10^3

Considering the above drawbacks, thus, it is expected that TGUs obtained in field may not agree with it's own background theory.

4.2 Inconsistency of TGUs

In spite of the convenience of the TGU method especially for numerical modeling on the behavior of sediment plumes generated by dredging works, Table 1 indicates that the TGUs have no consistency, which seems to be due to the drawbacks described above.

First of all, the upper 3 cases of the cutter suction dredgers of 4,000 hp have nearly the same composition of dredged sediments and current velocity of about 15 cm/s (Aburatani et al., 1993); nevertheless, the first TGU (5.3 kg/m^3) is about 4 and 7 times lower than the second and third TGUs (22.5 and 36.4 kg/m^3), respectively. Additionally, the fifth TGU (45.2 kg/m^3) is 9 times higher than the first, even though the R_{74} is lower by 30% than the first.

Furthermore, the TGUs of the 8m^3 and the second 4m^3 grab dredgers vary by approximately ten times even when they worked at the same sites.

The results at MP1 (Table 2) also show considerable variation in TGU. Especially, the average TGU of 59.2 kg/m^3 is too high considering the W_o of 25.5 kg/m^3 at 55.2 cm/s, which means possible overestimation of the TGU method.

Such discrepancy and inconsistency may be a kind of natural results, which reflects that the TGU method cannot play the role of a standardized method for estimating the rate of release of sediment associated with dredging works.

4.3 Alternatives

Then, how can we estimate the amount of sediments to be released into the water column by dredging operation? Pilot dredging may be the best solution although there are some efforts to develop numerical models to predict the release (e.g., HR Wallingford, 1999).

If a pilot dredging is not planned, however, some empirical relationships between the loss rate and major parameters may be still useful until a reliable model is established.

The basic concept of the TGU method that current speed and grain size determine the rate of sediment release into the ambient waters seems to be appropriate especially in macrotidal coastal areas. As described above, however, the TGU of reference rate at 7 cm/s has high potential to overestimate the loss rate.

In order to make an empirical formula including the effect of current speed more reasonably, three types of correlation between W_o and section-mean current speed at about 50m downstream from the grab dredger at MP1 are shown in Fig. 3. All the regressions show the coefficient of determination of about 0.55. The linear relationship seems to be not proper because the rate of 2.68 kg/m^3 at 40 cm/s is too low comparing with the existing data. The exponential relationship has the highest confidence coefficient, but the power relationship seems rather reasonable in that bed stress influencing the potential of sediment suspension has close relation with the power of depth-averaged current speed.

5. CONCLUSIONS

The TGU method of Nakai (1978) and the 4th Bureau (1978, 1982) which has been widely used for the EIAs in Korea has been reviewed.

The method has two critical drawbacks in the aspect of real phenomena. Hence, the existing TGUs have no consistency with the background theory. It should overestimate the loss of sediment into the ambient waters in some degree because of the method's treatment of fine sediments.

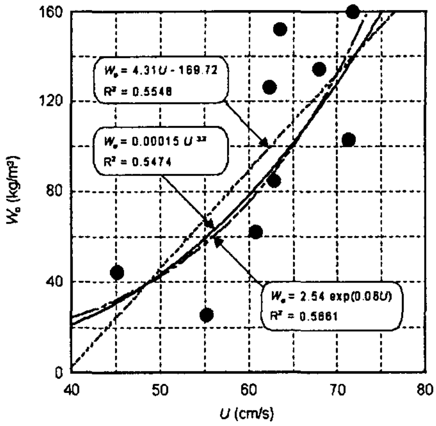

Fig. 3. Correlation between the rate of release of sediments due to grab (13m^3) dredging and section-mean current velocity at MP1.

Unless a pilot dredging for assessing the loss is planned, empirical relationships between the sediment losses due to dredging and related major parameters are useful until a reliable numerical model is developed. However, the empirical formulae should reasonably present the related phenomena.

Current effect on the rate of release of sediment caused by grab dredging in a macrotidal waterway has been well fitted by a power relationship.

However, the empirical formulae require lasting revisions based on field measurements for its reliable applicability.

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