



# Unified classical formula for non-cohesive total-load sediment transport in marine coastal zones



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## ABSTRACT

This paper proposes the concept of a significant transport rate, in coastal environments that contains different spatial and temporal scales and multiple interacting forces (e.g., waves, tides, wave-current, and wind density currents) as well as, the complex physical processes of total-load sediment which is not easy to calculate for practical needs due to restricted range of applicability. The present study develops a unified classical formula for non-cohesive total-load sediment transport in marine coastal zones by using dimensional analysis and self-similarity concepts where a set of independent variables considered. A dataset of total-load collected at both field observation stations and from the laboratory flume conditions and the six well-known relevant formulas were used to evaluate the predictive capability of the proposed formula. Since the results show that, the new formula is in good agreement with both field and flume data sets measures, the authors are suggesting the use of it for the sediment-carrying capacity predictions of total-load sediment transport in marine coastal zones.

## 1. Introduction

Sediment transport is important in the fields of coastal environmental science, geomorphology, as well as hydraulic and coastal and harbor engineering. In recent years, the significance of sediment transport in the marine coastal environment and the coastal engineering studies has been widely recognized. The physical processes of the coastal environment sediment transport are complex, multi-scale, multi-dimensional processes having various effective parameters and hence is considered to be one of the most difficult problems in this field.

The total sediment transport pattern and the bed roughness are the two distinct characteristics that have been examined by Einstein (1950), Bagnold (1966), Engelund and Hansen (1967), Bijker (1971), Graf (1971), Vanoni (1975), and Yalin (1977) for the rivers and Sleath (1984), Nielsen (1992), Fredsøe and Deigaard (1992), Soulsby (1997), van Rijn (2007) and Khorram and Ergil (2010a) for the coastal regimes.

Over the last few decades, many theoretical or empirical and semi-empirical formulas have been developed for the use in coastal studies with reasonable accuracies to predict the sediment transport rates. The commonly used methods that are often applied to compute the total-load sediment transport in coastal waters were developed by Engelund and Hansen (1967), Ergil (2000), Khorram (2008), Khorram and Ergil

(2011b) and van Rijn (1984a, 1984b).

Calculating the total-load sediment transport is a challenge, due to the complexity of the hydro-dynamics and the variety of the governing phenomena. Indeed, it is very difficult to estimate sediment fluxes on beaches due to the combination of steady flows (currents) and oscillatory flows (wave dispersion, wave-current, and water depth). Moreover, the variations in mean water level (tide, set-up, and set-down), breaking wave effects (turbulence and undertow), and topographic influence (mean slope and bed forms) should all be integrated into the analysis as well. Generally the energies due to tides, waves, winds, and currents are constantly present in the coastal zones. Various methods, approaches, and even the dimensional and dimensionless parameters used in the literature create confusion among the researchers while selecting the best representative equation, since each equation has its own range of applicability and validity for a typically unique data set (Khorram and Jafari, 2010c).

The aim of this study is to develop a unified classical formula to estimate the non-cohesive total-load sediment transport amount in marine coastal environments that characterizes the currents, combined winds, waves and tides and the density-driven currents with better predictions and wider ranges. It is obvious that, there is large number of independent variables and parameters both in dimensional and dimensionless forms that are influencing the total-load transport mechanism. To determine the precision of the proposed formula, the

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wide range of measurements gathered from the relevant experimental and the case study data sets, the dimensional analysis and the self-similarity concept studies based on the number of independent variables are all harmonized.

## 2. Complete and incomplete self-similarity

Sediment transport is a complicated natural phenomenon that has a nonlinear character which can be described either the logarithmic or the power law. Self-similar solutions always correspond to the idealized problems in which the parameters of the problem having the dimensions of the independent variables (the characteristic length or the time) that are equal to zero or to infinity. In the non-idealized case, on the other hand, the ratios of the independent variables to these parameters are defined and hence forming the incomplete self-similarity. On the basis of the values and the nature of the similarity parameters, some hypotheses can be formulated in terms of either complete or incomplete manner in order to either reduce the number of independent variables or at least to retrieve some more practical relations (Barenblatt, 1996; Wang et al., 2002; Khorram and Ergil, 2010b, 2011a). Under such circumstances, the incomplete self-similarity argument has proven to be an efficient tool for computing total-load flow rates.

## 3. Sediment transport equation

The definition of the total-load transport rate is (van Rijn, 2013):

$$q_{tj} = \alpha_{bj} q_b + U_j h C \quad (1)$$

so, the sediment balance equation is given as:

$$\frac{\partial}{\partial t} \left( \frac{h C_t}{\beta_s} \right) + (1 - P_m) \frac{\partial \xi}{\partial t} + \frac{\partial (q_{tj})}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_s h \frac{\partial C}{\partial x_j} \right] \quad (2)$$

where  $C_t$  is the depth-averaged total-load sediment concentration obtained from  $C_t = q_t / (U_c h)$ , and  $\beta_t$  is the total-load correction factor related based on  $\beta_s$ , and  $u_b$  as defined (Wu, 2007):

$$\beta_t = \frac{1}{r_s / \beta_s + (1 - r_s) U_c / u_b} \quad (2')$$

where  $r_s$  is the fraction of suspended load within the total load.  $\beta_s$  and  $\beta_t$  accounts the time lag between the flow and the sediment transport. Since there is no analytical solution for  $\beta_t$ , for practical purposes, it must be calculated iteratively either by calculating it through interpolation from the pre-computed relevant tables or by setting constant values for certain range of field conditions.

Integrating the 3-D sediment transport equation over the suspended-load layer yields the governing advection diffusion equation for suspended load in tensor notation as (Wu, 2007):

$$\frac{\partial}{\partial t} \left( \frac{h C}{\beta_s} \right) + \frac{\partial (U_j h C)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_s h \frac{\partial C}{\partial x_j} \right] + P - D \quad (3)$$

where  $t$  is the time,  $x_j$  is the horizontal coordinate with subscript  $j = 1$  and  $2$ ,  $U_j$  is the depth-averaged current velocity in the  $j^{\text{th}}$  direction,  $h$  is the total water depth,  $C$  is the depth averaged suspended-load concentration,  $\beta_s$  is the suspended-load correction factor,  $\nu_s$  is the sediment diffusion coefficient,  $P$  and  $D$  are the entrainment and deposition rates of sediment at the interface between bed and suspended loads, respectively.

To the second term on the left-hand side of the Eq. (3) as suggested by Wu (2004), the non-equilibrium relationship for the bed changes is introduced:

$$(1 - p_m) \frac{\partial \xi}{\partial t} = \frac{1}{L_t} (q_t^* - q_t) \quad (4)$$

where  $q_t$  and  $q_t^*$  are the measured (actual) and the equilibrium total-

load transport rates respectively and  $L_t$  is the adaptation length (the characteristic distance) of the sediment motion used to adjust the non-equilibrium relationship. So the equilibrium of the coastal region total-load transport rate may be calculated from one of three widely used relevant empirical sediment transport formula Lund-CIRP Carmenen and Larson (2007), Watanabe (1987), and van Rijn (2007a, 2007b).

By ignoring the bed-slope effect on the bed-load transport direction and setting  $\alpha_{bj} = U_j / U_c$ , the total-load transport equation can be written as  $q_{tj} = U_j h C_t$ . Inserting this expression and Eq. (4) into Eq. (2) leads:

$$\frac{\partial}{\partial t} \left( \frac{h C_t}{\beta_t} \right) + \frac{\partial (U_j h C_t)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \nu_s h \frac{\partial (r_s C_t)}{\partial x_j} \right] + \alpha_t \omega_f (C_t^* - C_t) \quad (5)$$

where  $\omega_f$  is the sediment fall velocity,  $C_t^*$  is the depth averaged total-load concentration at the equilibrium state, and  $\alpha_t = U_c h / (L_t \omega_f)$  is the total-load adaptation coefficient.

Eq. (6) is used in this study for sediment transport calculation. It is closed by assuming  $r_s = C_*/C_t^*$ , in which  $C_*$  is the depth-averaged suspended-load concentration at the equilibrium state.

The fraction  $r_s$  is determined by the van Rijn sediment transport capacity equations. The advantage of this total-load formulation is that the suspended- and bed-load transport equations are combined into a single equation, and there is only one empirical parameter ( $\alpha_t$  or  $L_t$ ) to estimate.

## 4. Dimensional analysis for total-load flow rate prediction

The aim of this study is to obtain a unified classical formula for predicting the non-cohesive total-load sediment transport rate in marine coastal systems. To develop this formula, one of the most common ways is the use of dimensional analysis and Buckingham's Pi Theorem. The proposed influential parameters are:

$$\Phi_t = f(\theta_{cw,m}, D_*, R_h/d_s, G_s) \quad (6)$$

$$\Phi_t = \frac{q_t}{\sqrt{(G_s - 1) g d_s^3}} \quad (6a)$$

$$\theta = \frac{\tau_0}{(\gamma_s - \gamma) d_s} = \frac{\gamma R_h S_f}{(\gamma_s - \gamma) d_s} \quad (6b)$$

$$\theta_{cw} = (\theta_c^2 + \theta_w^2 + 2\theta_c \theta_w)^{0.5} \quad (6c)$$

$$\theta_{cn} = 0.5 f_c (U_c \sin^2 \theta) / [(s-1) g d_{50}] \quad (6d)$$

$$q_t = q_c + q_w [\sin(wt) + D \sin(2wt - p/2)] \quad (6e)$$

where  $q_t$  is the volumetric total-load sediment rate per unit width, and  $\Phi_t$  is the instantaneous dimensionless sediment transport rate (Khorram and Ergil 2011a, 2011c). The grain diameter  $d_{50}$  in this study is taken equal to the median grain size diameter, for practical purposes. The terms  $R_h/d_s$  and  $G_s$  are embedded in the Shields' parameter  $\theta_{cw,m}$ , where  $w$  correspond to the wave direction and  $n$  implies the normal direction. Taking  $\theta = f(\text{Re}_*)$ , one can generate a rather simple relationship:

$$\frac{q_t}{\sqrt{(G_s - 1) g d_s^3}} = f\left(\frac{\tau_0}{(\gamma_s - \gamma)}\right) \text{ or } \Phi_t = f(\theta_{cw,m}) \quad (7)$$

Therefore, it now becomes possible to apply the concept of incomplete self-similarity method proposed by Barenblatt (1996) to Eq. (4). Thus, the proposed equation can be expressed in the form of an asymptotic power law by an approximate relation method in the form of the intensity of the total-load rate since the function does not have a non-zero limit for sufficient small or large values:

$$\Phi_t = \alpha \theta_{cw,m}^\beta \quad (8)$$

where  $\alpha$  and  $\beta$  are the coefficients that are mainly depending on the granulometry.

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