

Regular Article

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An empirical formula development to predict suspended sediment load for Khour Al-Zubair port, South of Iraq

<https://doi.org/10.1515/eng-2022-0021>

received August 27, 2021; accepted September 05, 2021

Abstract: A new formula for determining the suspended sediment load in Khour Al-Zubair port has been proposed using dimensional analysis. Six cross-sections have been identified in Khour Al-Zubair port at Basrah province, South of Iraq for the purpose of conducting field measurements during the two tidal periods (Neap and Spring). The study involved taking field measurements of the hydraulic and fluid properties, and sediment sampling by section every 2 h to get effective parameters used for developing empirical formula. These parameters include the density of sediment (ρ_s), mean velocity (V), hydraulic radius (R_h), fall velocity of the particle (W_s), median grain size (d_{50}), the salinity of water (S), water level (W_L), the width of the estuary (B), specific gravity (G_s), maximum flow depth (D_{max}), and kinematics viscosity (ν). The formula was developed using the statistical analysis using the SPSS program and dimensional analysis method. A good agreement between the loads computed by the suggested formula and the observed data has been attained based on the correlation coefficient value ($R = 0.97$). The results showed that the average total suspended sediment loads by using the proposed formula is 1288285.464 tons/year.

Keywords: Khor Al-Zubair, π -theorem, suspended sediment concentrations, dimensional analysis

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1 Introduction

Harbors are considered to form the economic backbone of a country. Sea transport accounts for about 80% of global trade. To preserve harbor safety and the safety of sea vessels, it is essential to investigate the amounts of sediment loads. Sediments are sand, clay, silt, and other loose particles that settle at the bottom of a body of water [1].

There are two types of sediment particles included in the sediment transport periods: cohesive and non-cohesive sediments. Sediments can be classified into two types according to their cohesive force: (A) sediments with median particle size $d_{50} < 4 \mu\text{m}$, mud are classified as cohesive sediments. (B) Sediments of median particle size $d_{50} > 64 \mu\text{m}$ are weakly cohesive; these particles are classified as non-cohesive and range from mud through to sand.

Cohesive sediments, such as clay and small-particle mud, are often transported in the water column, as water currents easily suspend these sediments. Non-cohesive sediments, such as sand, are usually transported along the bottom by saltation, rolling, and sliding [2].

It is common to split the sediment transport modes into two parts: bedload and suspended load. The “suspended load” is the sediment carried by the water column as a suspension load. In contrast, the “bedload” consists of larger size particles transported within a thin layer on the stream’s bed [3]. Generally, the bedload transport rate of a stream is about 5–25% of that of suspension load [4].

There are many formulas for estimating sediment transport rates in the literature. But no universal equation can predict sediment transport for all sites, estuaries, rivers, etc. Many equations and formulas were derived from calculating sediment transport discharge, but these equations were derived according to the environment’s composition, the site’s morphology, and special hydraulic conditions.

Imara and Al-Hadethi [5] estimated an average suspended sediment concentration in the water column during the flow. The data were divided into two groups: The first group covered the fieldwork in the Tigris River at Sarai site and middle Euphrates canals. The second group was outside Iraq, which covered the Missouri River in Montana. This study was based on equation determined by Imara (1997) to analyze data measurement of the average suspended sediment concentration in the water column; the data were used from the first group in this analysis. A uniformity index was suggested to study the vertical distribution of the various kinds of sediment. A uniformity index is calculated for the Missouri river in the second group of data.

Khassaf and Addab [6] suggested an empirical formula to compute sediment loads in the Al-Meshkab regulator channel, Najaf city, Iraq. The hydraulic and sediment concentration measurements of the cross-section were taken on a daily basis. Eight dimensionless groups are used for developing the suggested formula, the proposed formula showed a good efficiency based on the comparison between the calculated and measured values.

The economic importance of Khor Al Zubair port requires establishing a specific formula that can calculate the sediment transport rate, it must be calculated based on the study area's local boundary and hydraulic parameters.

2 Study area

Khour Al-Zubair Port is the second largest port in Iraq, and it is located in Khor Al-Zubair estuary. There are 13 berths and piers in the port that are commercially used. The Khor Al-Zubair estuary extends to the effective limit of tidal influence. The tidal is at most semidiurnal. The tide becomes more progressive as it advances upstream of the Khor Al-Zubair. The depth of water ranges between 10 and 20 m of the navigational channel. The width of the Khor AL-Zubair canal varies from 1 to 2 km in the flooding (Figure 1) [7,8].

3 Data field measurements

The study involves six transect sections, three sections during a neap period, and three sections during the spring period. The first section is in the center of the port with coordinates (30°11'27.84" N and 47°53'30.45" E), while the remaining two are in north and south of the port with coordinates (30°13'5.73" N and 47°51'54.78" E) and (30°10'31.48" N and 47° 53' 51.73" E), respectively (Figure 2). During the two tidal periods (Neap and Spring), the total field measurements is equal to 36, representing the hydraulic and fluid properties, and sediment sampling by section every 2 h.



Figure 1: Study area location [9].



Figure 2: Transect sections locations.

3.1 Hydraulic and geometric data measurements

The Acoustic Doppler Current Profiler (ADCP) technology was used to measure water velocity, discharge, area of cross-sections, top width, and water level during two periods (Spring and Neap) with a 2 h record on a complete tidal cycle. The field measurements were carried out during the season from October to December. ADCP Rio Grande 600 kHz and WinRiver II software version 2.04 were used for this purpose [10]. WinRiver II program showed sections as a velocity contour graph as in Figure 3.

3.2 Water-level data

The water level data are measured by installing a HOBO water level (100 feet) data recorder at Khour Al-Zubair

port [11]. HOBO device relies on converting water column pressure into measurements of water level height. The device was placed inside a pipe of more than 9 m to maintain the device’s safety from the tidal heights. The device was calibrated, and its level was attributed to a known point on the pier 7.09 m for the lowest low water (LLW).

3.3 Suspended sediment concentrations

Water of Khour Al-Zubair port contains many suspended sediments due to its location within the Khour Al-Zubair estuary. The suspended sediment concentration temporally varies a lot within each tidal period. The number and location of sampling verticals should be selected by the desired level of measurement precision. Sediment suspended in streams can be sampled in several ways.

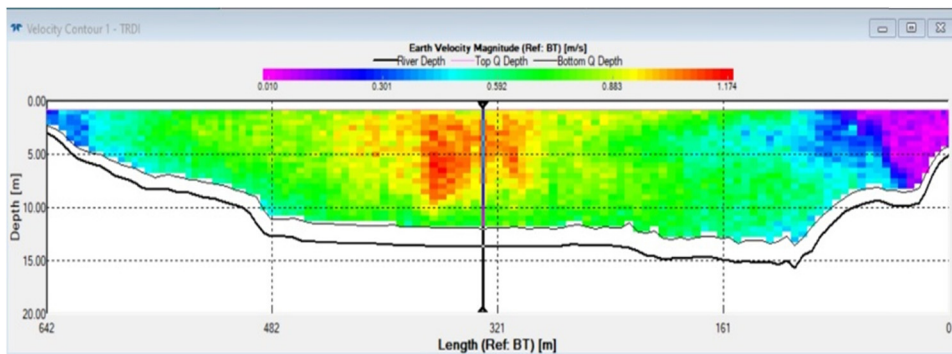


Figure 3: Velocity contour graph for center port transect.

According to the recommendations of the Inter-agency Committee on Water Resources, the number and sites of the required vertical sampling were determined [12]. At each transect in this study, sample verticals were chosen at $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of the streamflow width, and the cross-section of the flow was divided into three equal parts of nearly equal discharge. At three depths of $0.8D$, $0.6D$, and $0.2D$, three samples were obtained at each vertical every 2 h along the tidal period, where D denotes the depth from the water's surface [12]. A water sample is drawn from each station using a sampling device called the Nansen bottle made in Tsurumi Yokohama, Japan, no. 94595 (9-1978). The suspended load concentration is subsequently determined in the laboratory [13].

3.4 Water temperature and salinity measurement

The temperature and salinity of water are required to compute most reaction coefficients in the hydrodynamic properties. So, the temporal variation in temperature and salinity must be specified. A sample of water was drawn from each station using the Nansen bottle every 2 h along the tidal period, and the temperature and salinity of water were measured by the Multimeter MM 40 device [14].

3.5 Bed materials sampling

The Van Veen grab instrument was used for sediment sampling to obtain information about the bed material. Bed samples were collected from 23 October to 25 October 2020, where three-bed material samples were taken for each section in the study reach. Van Veen grab is an essential bed surface sampling tool. It is made of stainless steel and used for taking samples from the bottom of the estuaries, rivers, lakes, etc. [15].

4 Laboratory works

The laboratory work is needed to find sediment concentration at tidal cycle (Spring and Neap) and to construct the grain size distribution curve of the bed material, samples were drawn from each section for sieve analysis and hydrometer test.

4.1 Sediment concentration measurement

Following the collection of suspended sediment samples, the samples were filtered using the Glass filtration system with vacuum, and Millipore membrane filter (filter paper), with $0.45\ \mu\text{m}$ pore size. The suspended sediment concentration is calculated by using equation (1) [16,17].

$$\text{SSC} = \frac{M}{V}, \quad (1)$$

where SSC is the suspended sediment concentration (ppm, mg/L, or kg/m^3), M is the mass of the sediment (mg), and V is the volume of water (L).

The rate of suspended sediment load can be estimated by multiplying the suspended sediment concentration with the water discharge using equation (2):

$$Q_s = \text{SSC} \times Q, \quad (2)$$

where Q_s is the suspended sediments discharge (mg/s or kg/s), and Q is water discharge (m^3/s).

4.2 Specific gravity and particle size distribution of bed materials

The test procedure listed in ASTM D854-2 [18] was followed to determine the bed materials' specific gravity. The average specific gravity value for all transects was 2.71. The grain size distribution was analyzed by using the gradation curve. The test was performed in two stages: sieve analysis for coarse-grained soils (gravels and sands) and hydrometer analysis for fine-grained soils (silts and clays) according to ASTM D422 [19]. Figure 4 shows the distribution curve of bed material size for the section (Port Center), and also shows that the soil is often mud (silts and clays) with a typical d_{50} grain size of about $2\ \mu\text{m}$.

5 Results and discussion

5.1 Empirical formula development

Dimensional analysis is a good way to deal with physical quantities and transform them into dimensionless quantities. Dimensional analysis reduces the number of variables

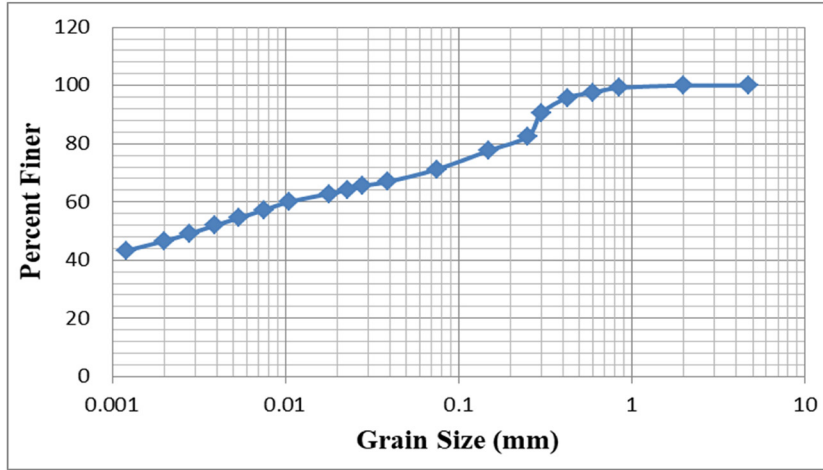


Figure 4: Grain size distribution curve for Port Center.

in a fluid phenomenon by combining some variables to form non-dimensional parameters [20]. The method is extremely generic and mathematically straightforward. Buckingham’s π -theorem is one of the essential and effective dimensional analysis.

Buckingham’s π -theorem was suggested by Buckingham in 1914 and called Buckingham’s π -theorem [21]. Variables used in field and laboratory investigations, as well as their relationships, are indicated in equation (3):

$$F(Q_s, d_{50}, W_s, \rho_s, B, R_h, V, \rho_w, D_{max}, \nu, S, W_L) = \text{constant.} \quad (3)$$

The repeating variables are selected (R_h, V, ρ_s), i.e., the first variable represent the hydraulic property, the

second represent the fluid property, and the third represent the sediment characteristics. The results of the analysis are given by equation (4):

$$\frac{Q_s}{\rho_s \nu R_h^2} = F\left(\frac{W_s}{V}\right)\left(\frac{d_{50}}{R_h}\right)\left(\frac{S}{\rho_s}\right)\left(\frac{W_L}{R_h}\right)\left(\frac{B}{R_h} G_s\right)\left(\frac{V D_{mas}}{\nu}\right). \quad (4)$$

The final form of the equation has been determined by conducting the regression analysis with the help of the SPSS program on the observed data. During the two tidal periods (Neap and Spring), 24 different sections were selected to derive the proposed formula. In contrast, 12 sections were used for verification of this formula. The regression analysis was performed, and the following formula was extracted:

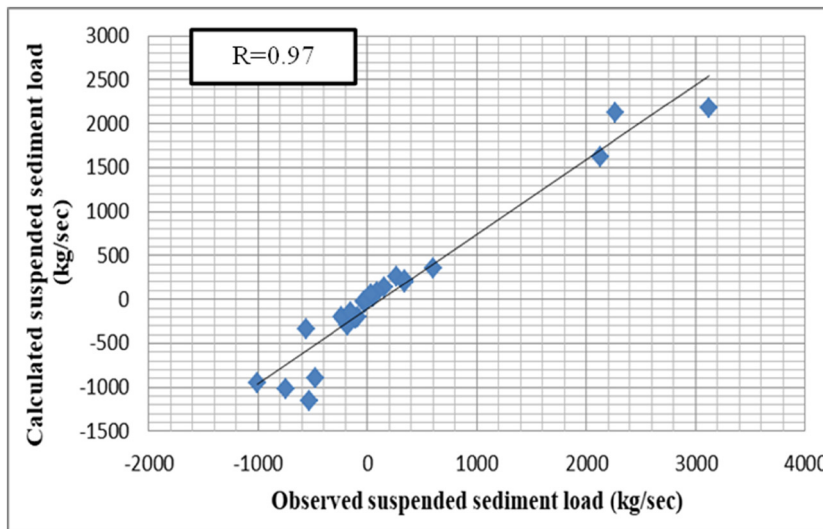


Figure 5: Scatter plot of observed and calculated suspended sediment load.

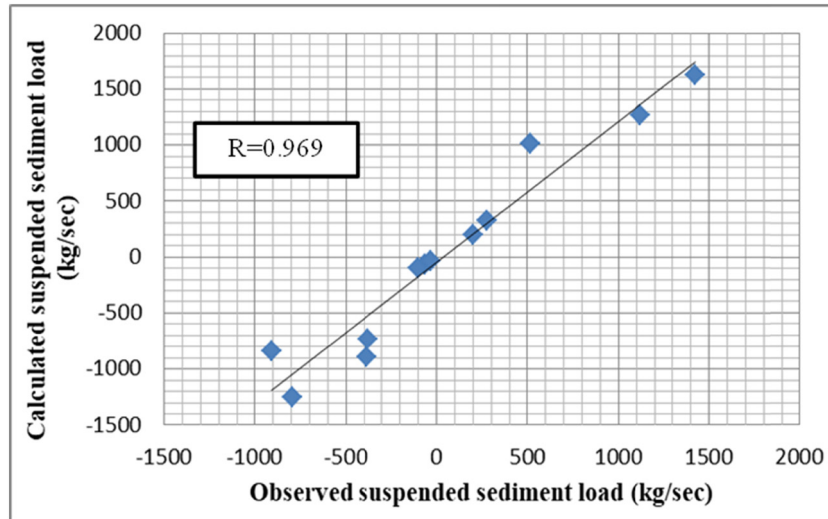


Figure 6: Scatter plot of observed and calculated suspended sediment load for verification stage.

$$Q_s = 1.2883 \times 10^{-4} \rho_s \nu R_h^2 \left(\frac{W_s}{V} \right)^{-0.032} \left(\frac{d_{50}}{R_h} \right)^{0.374} \times \left(\frac{S}{\rho_s} \right)^{0.554} \left(\frac{W_L}{R_h} \right)^{-0.172} \left(\frac{B}{R_h G_s} \right)^{0.421} \left(\frac{VD_{\max}}{\nu} \right)^{0.582}, \quad (5)$$

where Q_s is the suspended sediment load (kg/s), ρ_s is the density of sediment (kg/m³), V is the mean velocity (m/s), R_h is the hydraulic radius (m), W_s is the fall velocity of the particle (m/s), d_{50} is the median grain size (m), S is the salinity of water (kg/m³), W_L is the water level (m), B is the width of the estuary (m), G_s is the specific gravity, D_{\max} is the maximum flow depth (m), and ν is the kinematics viscosity (m²/s).

The applicability of the empirical equation for estimating the suspended sediment transport rate in Khour Al Zubair port was examined by comparing the calculated values with the observed values. Figure 5 illustrates a well-accepted relationship between the calculated and the measured values of sediment load for 24 sections with the correlation coefficient of $R = 0.97$. Moreover, the suspended sediment load with a negative value means that the load is opposite to the direction due to the tidal phenomenon.

5.2 Verification of the proposed formula

There is a need to verify the performance of the proposed formula by comparing the calculated results against another set of measured data. The proposed

formula used the remaining 12 sections of the measured sediment discharge for verification. The verification of the new formula is represented in Figure 6. It was a good similarity between observed and calculated sediment transport rates with a correlation coefficient $R = 0.969$. The results showed that the average total suspended sediment loads by using the proposed formula is 1288285.464 tons/year.

6 Conclusion

Sediment sample particle size distribution illustrated that the bed material of the port is often mud (silts and clays) with a typical d_{50} grain size of about 2 μ m. A new formula for sediment transport was proposed in this study by using Buckingham's π -theorem. The applicability of the empirical equation was examined by comparing the calculated values with the observed values for 24 sections, while the verification process is performed using another set of measured data (12 sections). There is a good matching between the observed and the calculated sediment transport rates with a correlation coefficient of $R = 0.969$. The average total suspended sediment loads by using the proposed formula is 1,288,285.464 tons/year.

Acknowledgements: The authors are grateful to the Marine Science Center/University of Basrah and General Company for Ports of Iraqi for helping with field measurements.

Funding information: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: The measured data that support the findings of this study are available from the corresponding author [Ahmed A. Dakheel], upon reasonable request.

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