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ON THE TOTAL LOAD SEDIMENT TRANSPORT OF URBAN WASTEWATER FLOWS

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ABSTRACT: The objective of the present work is to determine the total load of the urban wastewater flow and compare the results with the proposed relations by previous researchers for calculating the total load. For this goal, the gradation curves of sediment have been analyzed. Field experimental data has been collected at the entrance grit chamber of the wastewater treatment plant in Khomein city, Iran. A rectangular concrete channel was prepared. The channel demonstrates a length of 18m, a width and depth of 0.5 m, and a longitude slope of 0.1%. The goal of this setup is to collect and measure the deposited sediment from the wastewater flow. A long-period accumulation test was planned to study the development of the sediment characteristics over 10 days. According to our observation, the PSDs range from 0.075 mm to 31 mm, and the solid particles are in the size range of 0.30 mm to 2 mm. For this goal, continuous hydraulic conditions were set up: flow rate, Q = 14.7 L/s, and longitude slope, S_0 = 0.1% (0.001). Particle size distribution (PSD) was measured with use of gradation test. A total of 14 samples of the deposited material have been collected after 7 months at an interval of 15 days. Also, the mass rate of the total load of sediment transferred by the flow has been measured, and the results have been compared with 10 famous methods for calculating the total load by using d50. The results show that Ackers and White's method [1] estimates the total load with a relative error of 9.34%. So, this method can be used to estimate the total load of the flow with high accuracy. Also, the distribution of sediment particle size in the urban wastewater flow has been achieved, and the range of particle diameters is between 0.075 mm to 31 mm.

KEYWORD: Sediment Characteristics, Wastewater Flow, Gradation Curve, Total Load, Sediment Transport, Khomein City.

NOTATION

Q	Discharge (m^3/s)
U	Average Velocity (m/s)
L	Length of the channel (m)
B	Width of the channel (m)
H	Flow Depth (m)
A	Flow Area (m^2)

P	Wetted Perimeter (m)
R	Hydraulic Radius (m)
S_0	Longitudinal Slop of Channel Bed (%)
v	Fluid Viscosity (m^2/s)

1. INTRODUCTION

The accumulation of sediment in sewers is the source of several problems, such as hydraulic section reductions and premature overflows, odors and corrosion problems [3]. Operators use up a lot of financial and human resources to cleanse sewers where they are not self-cleansing and where sediment may accumulate. Then, to keep resources and improve sewer operation and maintenance, a better understanding of sediment accumulation, erosion, and transfer is essential [7,19,31]. Knowing about the characteristics and properties of sewer sediment permits the attainment of three aims: 1) to improve scientific knowledge on sediment and to develop sediment transport models; 2) to optimize the allotment of resources in cleansing sewers by decision models on the basis of sedimentation rates and to later check the competence of cleansing and 3) to estimate optimal locations of flushing gates for sediment scouring, e.g. [7,8,11]. The characterization of sediment has been produced in some research throughout the past decades. Some examples are the works of [3,9,10,13,18,21,31]. Further new studies were focused on the bed strength variances depending on the consolidation time and the aeration conditions [4,24,26,27,30]. In those works, it was concluded that the deposit strength is affected by the microbiological activity due to the organic matter and the oxygen content. Sediment attributes are connected to suspended or bed load transport rates in sewers [3]. Customary sediment transport models are established on river sand equations, while other parameters, like cohesiveness, are not taken into account [6]. Laboratory and field studies have been reported to confirm sediment transport equations in sewers, but only the physical characteristics of the sediment have been contained in the suggested models [29]. The presence of organic particles has also been studied in some laboratories, from them, it was concluded that bed shear stress and, therefore, the sediment transport rate are influenced by small organic fragments [5,25]. In combined sewers, upstream secondary pipes (diameters > 400 mm) should probably cause a solid output because of the particle sedimentation preferred by dry-weather flow situations [23]. The management of sewer sediment is a significant subject in urban regions with significant maintenance costs. For better understanding the transport processes of sediment in sewers, the particle sizes of the sediment have to be included in the models. And because of the high variability in particle size distribution in raw sewage, the determination of d50 is crucial. The objective of the present work is to determine the total load of the urban wastewater flow and compare the results with the proposed relations by previous researchers for calculating the total load. To do that, experimental work was carried out in a concrete rectangular channel fed with urban wastewater flow, and particle distribution sizes of the deposited sediments and their weights have been achieved.

2. MATERIALS AND METHODS

2.1. EXPERIMENTAL SETUP AND TEST PROCEDURES

To do the present research work, a rectangular concrete channel at the entrance of the wastewater treatment plant in Khomein city was prepared. That channel demonstrates a length of 18m, a width and depth of 0.5 m and a longitude slope of 0.1% (Figure 1). The goal of this setup is to collect and measure the deposited sediment from the wastewater flow. A pumping supply system presents the urban wastewater taken after the 500 mm screens put upstream of the grit chamber of the WWTP to the inlet of the pipeline (Figure 2).

Figure 1 Experimental setup for a rectangular concrete channel (upstream view)

Figure 2 The upstream screens

The tests have been conducted on samples of the wastewater collected from the inlet of a wastewater treatment plant located in Khomein city, Iran. All the tests have been conducted at the entrance of the WWTP, so the flow condition in the sewer can be represented. Details of the individual sewage treatment plants are listed in Table 1. A long period accumulation test was planned to study the development of the deposited mass and sediment characteristics during 10 days. For this goal, continuous hydraulic conditions were set up: flow rate, Q=14.7 L/s, and longitude slope, S_0=0.1% (0.001). Particle size distribution (PSD) was measured with the use of a gradation test. A series of 14 samples have been prepared for each test throughout the length of the channel after 10 days. The sampling procedure has been done according to the ASHHTO T88-70 standard (Standard method of test for particle size analysis of soils). All samples were assembled in a plastic container and mixed completely. Finally, a sample by weight of 2 kg was prepared and sent to the soil mechanics laboratory of Khomein for gradation testing (Figure 3). For each test, the sample has been dried in the oven for 24 hours at a temperature of 110^0C. Then, 1 kg of the sample is prepared for the gradation test using a laboratory weighting with an accuracy of 0.1 g. The series of the sieves include the sieve numbers of 1 ¼", 1", 3/4", 1/2", 1/4", 4, 5, 8, 10, 14, 18, 25, 35, 50, 70, 100 and 200. Table 2 includes a list of directed tests, periods during which they were performed and the sampling points.

Figure 3 The sediment sample prepared for gradation test (each sample has 2kg weight)

Table 1

Specification of the analyzed sewage treatment plant

Wastewater treatment plant	Location	Wastewater Treatment Plant Capacity, [m3/d]	Volume of Treated Wastewater per annum [thousand cubic m/year]
WWTP of Khomein	X=423085 Y=3723663	6600	2286

Table 2

Characteristics of the number of conducted tests and the period of the experimental works

Sample	Symbol	Number of conducted tests	Number of dry sample test	Number of wet sample test	Period of the experimental works	Sampling point
Wastewater Flow	R	14	7	7	07.05.2020-01.15.2021	Wastewater Treatment Plant inlet

3. RESULTS AND DISCUSSION

According to monitoring of the test site, distinctions in the size of particles recognized in the inflow from the wastewater treatment plant were concluded. In most cases, PSDs in the wastewater flow were multi-modal (Figure 4). In Figures 5 and 6, the distribution of particle sizes in the flow is shown. According to those figures, the distribution of sediment particles changes with changing weather conditions, and during wet weather conditions, the mean value of particle diameter (d50) is larger than the mean value of particle diameter during dry weather. In Figure 6, because of the large amount of data, the average values were computed with respect to all PSDs. Very high changeability of PSDs, derived from the procedure of transporting sewage to the wastewater treatment plant. Anyway, based on the results of the guided research, the authors were unable to draw conclusions regarding the effect of the sewage system on the distribution of particles in the wastewater. The majority of the solid particles are in sizes ranging from 0.30 mm to 2 mm. The size of the smallest particles recognized in the wastewater is less than 0.15 mm with the weight percentage of 2.6% that exists in all the samples. And the size of the biggest particles identified in the raw sewage is about 31mm with an average weight percentage of 0.75% that is rarely observed during the wet weather. One should mention that the examination of particle size distribution was done on the samples from the sewage treatment plant, where no chemical precipitation with metal salts was implemented. Figure 5 shows the distribution of particle sizes that have been measured in the form of bar diagrams. Because of the large amount of data, Figure 6 demonstrates the mean calculated values with respect to all PSDs.

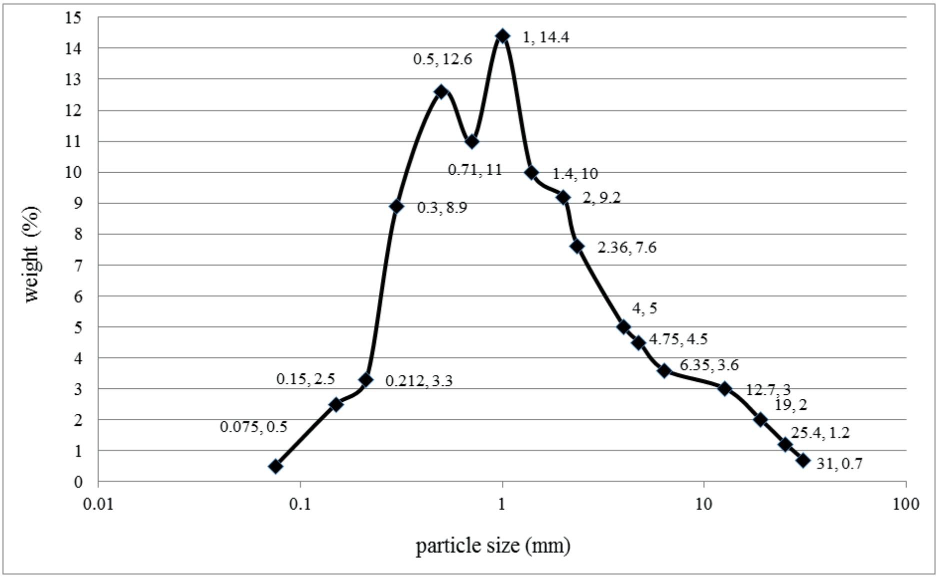

Figure 4 Percentage share of particles of diameter d_i in the total volume of the wastewater flow samples in all weather conditions collected from the WWTP of Khomein city

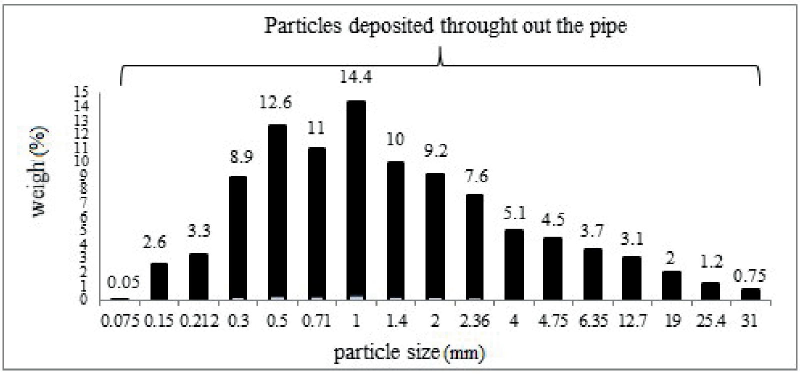

Figure 5 The measured particle size distribution in all weather conditions

The analysis of the earned PSDs for the wastewater allows us to draw attention to the fact that throughout the measurement range from 0.075mm to 31 mm, sections of the particles were deposited in the pipeline. Based on the analysis of the samples, most of the particles of a size exceeding 0.075mm were deposited in the grit chamber. All samples were also compared in terms of mean diameter (*d50*) values for sets of particles. Mean particle set diameters are specified directly, based on the gradation test. On the basis of PSDs, the values of mean diameter *d50* were determined. According to Figure 7, the average size of *d50* for the wastewater flow is about 1.45mm.

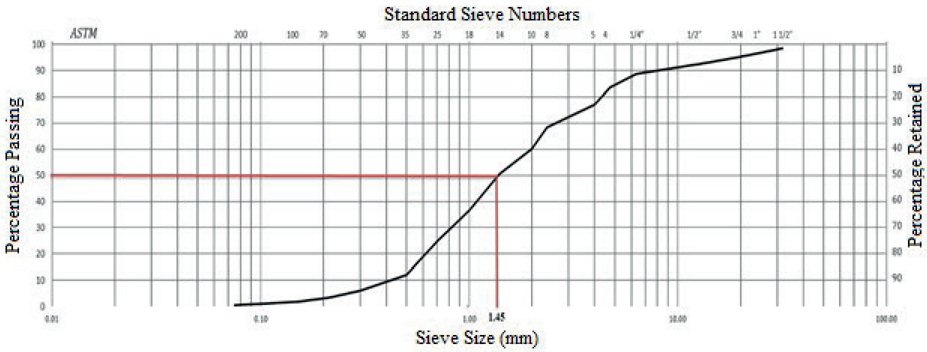

Figure 6 Gradation curve for the average particle size distributions of all samples

As it can be seen from Figure 6, *PSD*s included sand and gravel. And also, because the length of the pipe is equal to the length of the grit chamber of WWPT, it can be concluded that *PSD*s ranging from 0.075mm to 31mm can be deposited in the grit chamber.

3.1. COMPARISON THE MEASURED WEIGHTS OF SEDIMENT WITH TEN FAMOUS RELATIONSIPS

In this study, the unit weight of sediment has been measured in the flow, and the results have been compared with ten famous relations proposed before. However, river sediments are not so representative of sewer ones, but in this study, our goal is just compression. Previous formulas have been proposed to calculate the total load. Then, after finding the best formula, the necessary amendments can be applied. For doing that, a rectangular concrete channel with a length of 25 m, a width of 0.50 m, and a depth of 0.50 m has been used. To carry out this experiment, the wastewater flow was pumped in this channel for 420 seconds, and after that, the deposited sediment was collected and weighted in the laboratory. This experiment has been done 14 times, and the results are listed in Table 3.

Table 3

The measured weight of deposited sediment

Date	Weight of Sediment (kg)	Date	Weight of Sediment (kg)
07.05.2020	0.84	10.21.2020	0.74
07.21.2020	0.80	11.05.2020	0.97
08.05.2020	0.88	11.20.2020	0.94
08.21.2020	0.92	12.05.2020	1.08
09.05.2020	0.77	12.20.2020	1.14
09.21.2020	0.81	01.04.2021	1.17
10.06.2020	0.85	01.15.2021	1.12

According to Table 5, by using the arithmetic mean formula, the average weight of the sediment can be calculated using equation (1) as follows:

$$\bar{m} = \frac{1}{14}\sum_{i=1}^{12} m_i = \frac{1}{14} \times (13.02) = 0.93\ kg \qquad (1)$$

where, in the above equation, $\bar{m}$ is the average weight of sediment in kg and m_i is the weight of each sample in kg. And then, by dividing the average weight of sediment by the time of the experiment, the average weight of sediment per second can be calculated using equation (2) as follows:

$$\overline{M_t} = \frac{\bar{m}(kg)}{t(s)} = \frac{0.93\ kg}{420\ s} = 0.002\ \frac{kg}{s} \qquad (2)$$

where, in the above equation, $\overline{M_t}$ is the average weight of sediment per second and t is time in seconds. So, according to equation (2), the measured average weight of the sediment in the wastewater flow is equal to 0.002 kg/s. Then the measured data was compared with 10 famous total load methods for calculating total load by using d_{50}, as shown in Table 4. In this table, the negative sign of relative error shows that the relation estimated total load is less than the measured total load of the flow. As it can be seen in Table 4, the best for estimating the total load of the wastewater flow is Ackers and White's method, with a relative error of 9.34%. For more information about the equations, see [12]. The flow condition and all of the parameters have been used in the equations listed in Table 5.

Table 4

Comparison of the measured and calculated weight of sediment using d_{35}

Total Load Method	Relationship	Relative Error (%)
Einstein Method (1950),[12]	$W_T = \sum i_s G_{st}$	1300
Laursen's Method (1958), [14]	$\bar{C}_t = 0.01 \left(\frac{d_{50}}{h}\right)^{\frac{7}{6}} \left\lvert \frac{\tau_0'}{\tau_{0c}} - 1 \right\rvert f\left(\frac{u*}{w_s}\right)$	50
Engelund and Hansen's Method (1967), [20]	$q_t = 0.05U^2 \left(\frac{d_{50}}{\Delta g}\right)^{0.50} \theta^{1.5}$	35
Graf and Acaroglu's Method (1968), [15]	$q_t = \Phi_t (\Delta g d_{50}^3)^{0.50}$	60
Yang's Method (1972), [16]	$\bar{C}_t = \frac{10^{-6} \times 10^{M+N \log P_s}}{s}$	45
Ackers and White's Method (1973 and 1990), [1,2]	$q_t = KU d_{35} \left(\frac{U}{u*}\right)^n \left(\frac{F_{gr}}{A} - 1\right)^m$ 7	9.34
Molinas and Wu's Method (2001), [22]	$\bar{C}_t = \frac{10^{-6} \times \left(\frac{1430\,(0.86 + \Psi_s^{0.50})\Psi_s^{1.50}}{0.016 + \Psi_s}\right)}{s}$	-99.99
Karim and Kennedy's Method (1990), [17]	$q_t = \Phi_t (\Delta g d_{50}^3)^{0.50}$	-99.8
Yang and Lim's Method (2003), [34]	$g_t = k \frac{s\tau_0}{\Delta w_s} (u_*^2 - u_{*c}^2)$	761
Sinnakaudan et al.'s Method (2006), [28]	$\bar{C}_t = 1.811 \times 10^{-4} \frac{(\Delta g d_{50}^3)^{0.50}}{UR} \left(\frac{U S_0}{w_s}\right)^{0.293} \left(\frac{R}{d_{50}}\right)$	470

Table 5

The flow condition and used parameters in the proposed total load methods.

Conditions and Parameters	Symbol	Value
Discharge (m^3/s)	Q	0.0147
Average Velocity (m/s)	U	0.06
Length of the channel (m)	L	25
Width of the channel (m)	B	0.50
Flow Depth (m)	H	0.50
Flow Area (m^2)	A	0.25
Wetted Perimeter (m)	P	1.50
Hydraulic Radius (m)	R	0.17
Longitudinal Slop of Channel Bed (%)	S_0	0.10
Fluid Viscosity (m^2/s)	v	0.000001
Mean Particle Diameter (m)	d_{50}	0.00145
35% Passing Percentage of Particles (m)	d_{35}	0.00098
Particle Density (kg/m^3)	ρ	2650
Gravity (m/s^2)	g	9.81
Time (s)	t	420
Relative Density (Dimensionless)	s	2.65
Difference of Relative Density (Dimensionless)	Δ	1.65
Bed Shear Stress (pa)	τ_0	1.66
Shear Velocity (m/s)	$u*$	0.040
Shields Parameter (Dimensionless)	Θ	0.07
Shear Reynolds Number (Dimensionless)	$R*$	58
Particle Parameter (Dimensionless)	$D*$	36.60
Threshold Shields Parameter (Dimensionless)	Θ_c	0.037
Threshold Bed Shear Stress (pa)	τ_{0c}	0.87
Threshold Shear Velocity (m/s)	u_{*c}	0.029
Terminal Fall Velocity (m/s)	w_s	0.145
Threshold Average Velocity (m/s)	U_{cr}	0.32
Bead Shear Stress due to Particle Roughness (Pa)	τ_0'	0.009

Total Load Transport Intensity used in Graf and Acaroglu's Method	Φ_t	0.011
Mobility Number (Dimensionless)	F_{gr}	0.027
Particles Reynolds Number (Dimensionless)	Re	261
Relative of Fall Velocity to Shear Velocity (Dimensionless)	w_s^+	3.50
M parameter in Yang's Method (Dimensionless)	M	4.99
N parameter in Yang's Method	N	0.98
P_s parameter in Yang's Method	P_s	0.0018
A- parameter in Ackers and White's Method	A	0.178
n- parameter in Ackers and White's Method	n	0.126
m- parameter in Ackers and White's Method	m	1.86
K- parameter in Ackers and White's Method	K	0.032
Stream Power (Dimensionless)	Ψ_s	2.90×10^{-5}
$f(u^*/w_s)$ Function	$f(u^*/w_s)$	8
Total Load Transport Intensity (Dimensionless) used in Karim and Kennedy's Method	Φ_t	1.36×10^{-5}
Densimetric Froud Number (Dimensionless)	F_d	0.392
K parameters used in Yang and Lim's Method (Dimensionless)	k	12.50

4. COCLUSIONS

The phenomena and procedures that happen with the sedimentation in raw wastewater flow are described with high intricacy. For that, knowing about particle size distribution is significant. Also, it is essential to improve new research methods for analyzing them from both a qualitative and quantitative point of view. In this research, an important attempt has been made for the first time to measure and analyze the particle size distribution of particles deposited in raw sewage. Also, this study presents a good view of solid particle distribution in urban wastewater flow that can be used for future studies with regard to sediment transport by the flow. Besides, the total load of the wastewater flow has been determined, and the result has been compared with 10 famous relations proposed before. The test results demonstrate that:

- There is a high changeability of the *PSDs* in wastewater flow. The *PSDs* include sand and gravel.
- The *PSDs* deposited in the pipe ranged from 0.075 mm to 31 mm. So, the minimum particle size that can be deposited in the grit chamber of the WWTP is about 0.15 mm.
- The mean value of d_{50} for the wastewater flow is about 1.45 mm.
- The weight of sediment in the flow has been measured, and it is equal to 0.002 kg/s. The result was compared with the calculated total load using 10 famous methods for calculating total load. The results show that Ackers and White's method [1] estimates the total load of the wastewater flow with high accuracy and a relative error of 9.34%. So, this method can be used to estimate the total load of the flow with acceptable accuracy.
- Particles of diameter of 1mm explained for the highest percentage (14.4%) exist in the wastewater flow.

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