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Sediment characteristics of urban wastewater flows

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ABSTRACT

Particle size of sediment is necessary to design and operation of sewer systems. In this regard, calculation of the effective particle diameter (EPD) to determine the particle Reynolds number (Re_i) is very important. The present research work focuses on the monitoring of non-cohesive sediments in urban wastewater flow and determination of the EPD considering dry and wet weather. For this goal, the gradation of sediment has been achieved and analyzed. A field experimental data has been collected at the entrance grit chamber of wastewater treatment plant of Khomeyn City, Iran. Also, the weights of deposited particles per second have been measured and the results compared with total load calculated by the Graf and Acaroglu method (1968) and the Einstein method (1950) by using d_{35}, d_{50}, d_{65} and d_{eff}. The results show that the methods estimate the weight of deposited sediment with more accuracy by using d_{eff}. Also, the gradation curve shows that the most particle sizes of the sediments in urban wastewater flow are between 0.075 to 31 mm and the averaged value of d_{50} for dry and wet weather condition are about 0.98 and 2.32 mm, respectively. The average value of d_{50} for all conditions is about 1.45 mm.

Keywords: Sediment characteristics; Wastewater; Effective particle diameter; Particle's Reynolds number; Graf and Acaroglu method; Einstein method

1. Introduction

The accumulation of sediments in sewers is the source of several problems such as hydraulic section reductions and premature overflows, odors and corrosion problems [1]. Operators use up a lot of financial and human resources to cleanse sewers where they are not self-cleansing and where sediments may accumulate. Then to keep resources and make better sewer operation and maintenance, a better understanding of sediments accumulation, erosion and transfer is essential [2–4]. Knowing about characteristics of sewer sediments permits the attainment of three aims: (1) to improve scientific knowledge on sediments 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 [4–6]. The description of sediments has been produced in several research works throughout the past decades and the examples are established in literature [1,7–14]. Further new studies were focused on the bed strength variances depending on the consolidation time and the aeration conditions [15–19]. In those works, it was concluded that the deposit strength is affected by the microbiological activity due to the organic matter and oxygen content. Sediment attributes are connected the suspended or bed load transport rates in sewers [1]. Customary sediment transport models are established on river sand equations while other parameters, like non cohesive sediment, are not taken into account [20]. Laboratory and field studies have been reported to confirm sediment transport equations in sewer systems, but just physical characteristics of sediments have been contained in the suggested models [21,22]. The attendance

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of organic particles has also been studied in some laboratories, and it was concluded that the bed shear stress and, therefore, the sediment transport rate are influenced by small organic fragments [23,24]. In combined sewers, upstream secondary pipes (diameters <400 mm) should probably cause in the solid output, because of the particle sedimentation preferred by the dry-weather flow situations [25]. The management of sewer sediments is a significant subject in urban areas with meaningful connected costs of maintenance. To understand the transport process of sediment in sewers, the particle size of the sediment has to be comprised in the models. And because of the high variability in particle-size distribution (PSD) of wastewater flows, determination of particle distribution is crucial. The objectives of present work are determining the particle size and weight of the deposited sediment and produce a gradation curve in the wastewater flows. In this regard, an experimental work was carried out in a concrete rectangular channel fed with real urban wastewater flow.

2. Material and methods

2.1. Experimental setup and test procedure

In present research work, a rectangular concrete channel has been used at the entrance of the wastewater treatment plant (WWTP) of Khomeyn City, Iran. It demonstrates a length of 25 m, a width and depth of 0.5 m and a longitude slope of 0.1% (Fig. 1). The locations of the city and WWTP and the catchment characteristics are shown in Figs. 2 and 3. The length of sewer network of Khomeyn City is about 200 km. The average discharge of wastewater flow entranced to the WWTP is about 130 L/s.

The goal of this setup is to collect and measure the deposited sediments of the wastewater flow. A pumping supply system set up in the entrance of the grit chamber for pumping the wastewater flow to the rectangular channel (Figs. 4 and 5).

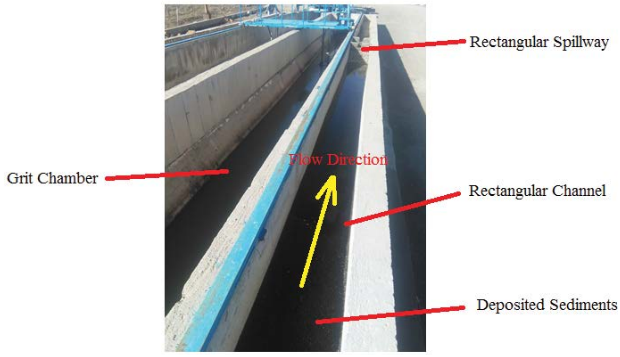

Fig. 1. Experimental setup of the rectangular concrete channel (upstream view).

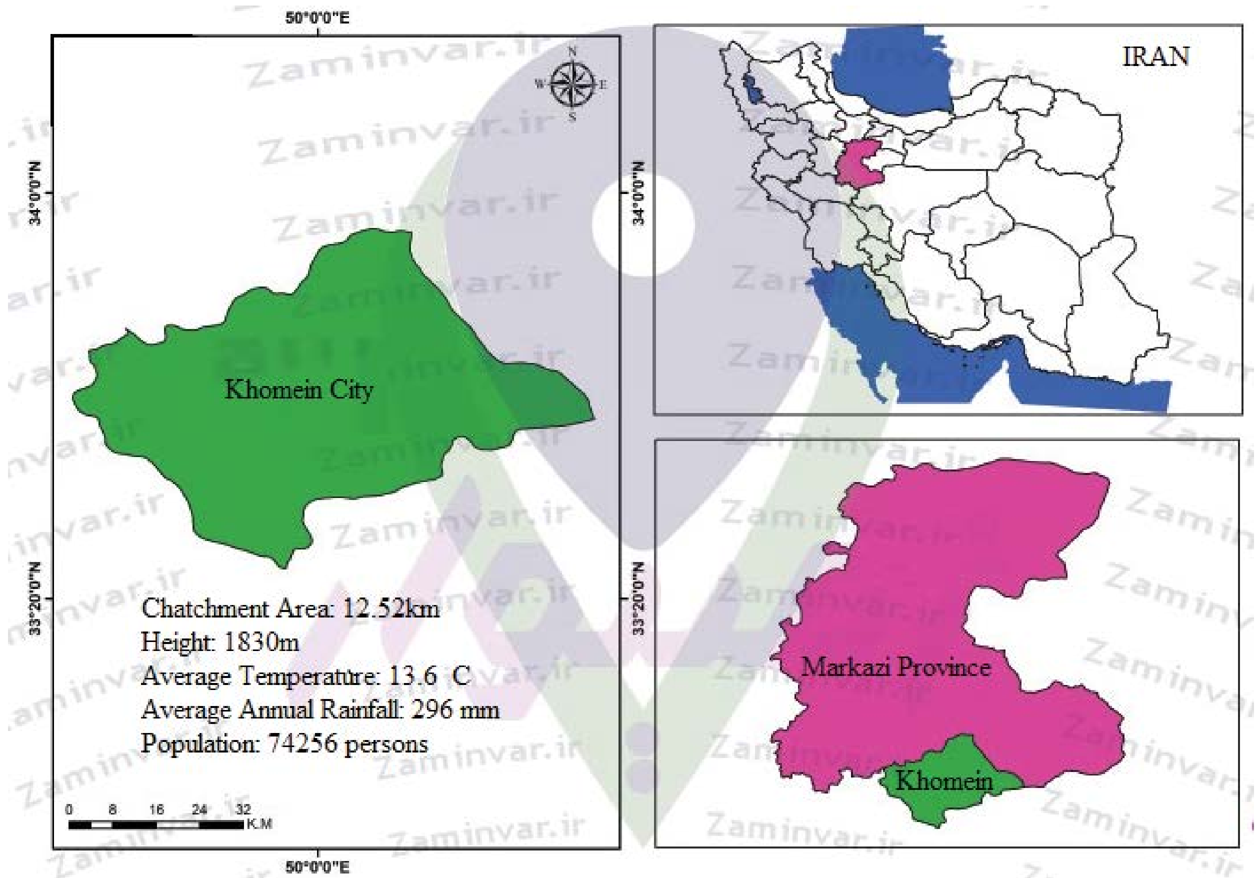

Fig. 2. Location of the catchment and its characteristics.

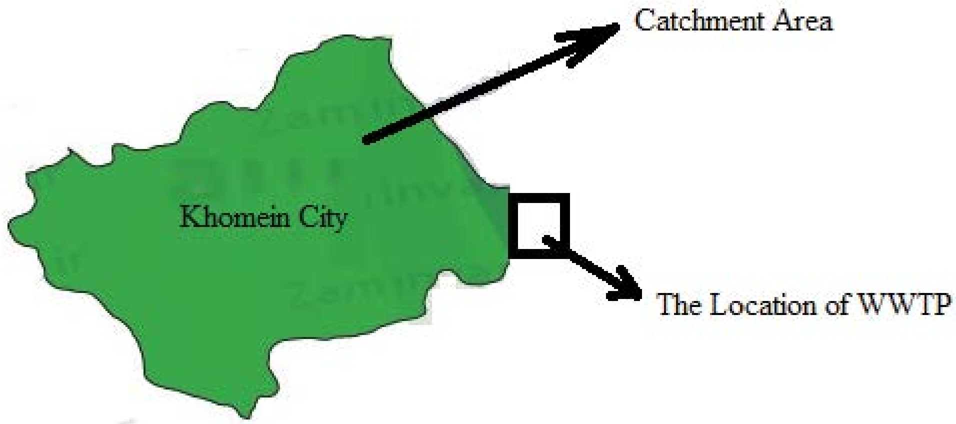

Fig. 3. Location of WWTP.

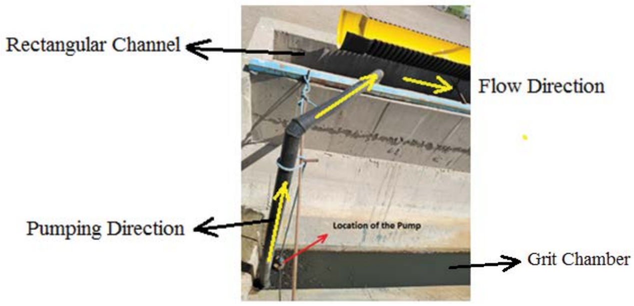

Fig. 4. Pumping supply system.

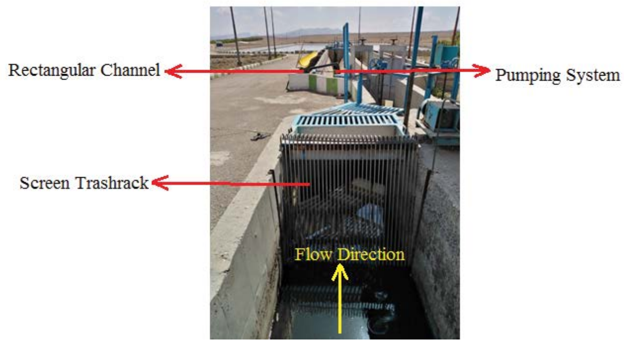

Fig. 5. Upstream screens.

The tests have been managed on samples of the deposited sediments collected from WWTP located at Khomeyn City, Iran. Details of the individual WWTP are listed in Table 1. A long period accumulation test was planned to study the development of deposited sediment characteristics during 10 d. For this goal, continuous hydraulic conditions were set up with the flow rate (Q) of 14.7 L/s and longitude slope of 0.1%.

At the start of each test, the outlet of channel blocked and the pumping flow started until the channel filled. The time of pumping flow was 420 s in each test and then let the sediments deposited completely after 1 d. Thus, the outlet of channel opened for pouring the wastewater flow from the channel. After that, let the deposited sediments become dry for at least 2 d (Fig. 6). The deposited sediments, therefore, collected and sent to the soil mechanics laboratory of Khomeyn for determining their weights. PSD was measured with use of gradation test. For grading test, a series of 14 samples have been prepared in each 10 d and sent to the laboratory. The sampling procedure has been done according to the ASHHTO T88-70 standard. All samples assembled in a plastic container and mixed completely. Finally, a sample by weight of 2 kg prepared and sent to the soil mechanics laboratory of Khomeyn for doing gradation test (Figs. 7 and 8). For each test, a sample has been dried at the oven for 24 h at a temperature of 110°C. Then 1 kg of the sample prepared for gradation test using a laboratory weighting with the accuracy of 0.1 g. A series of the sieves including sieve numbers of 1¼″, 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 direct tests, periods during which they were performed and the sampling points.

Table 1
Specification of the analyzed sewage treatment plant

Sewage treatment plant	WWTP of Khomeyn
Location	X = 423,085; Y = 3,723,663
Sewage treatment plant capacity, m^3/d	6,600
Volume of treated sewage per annum, thousand m^3/y	2,286

3. Results and discussion

According to the monitoring of test site, distinctions in the size of particles recognized on the inflow from the WWTP were concluded. In most cases PSDs in raw sewage were multi-modal (Fig. 9). In Figs. 9 and 10, the distribution of particle sizes in the flow has been shown. According to these figures, the distribution of sediment particles changes by changing in weather condition and during wet weather condition the mean value of particle diameter (d_{50}) is larger than that of dry weather. In Fig. 11, because of the large amount of data the average values computed with respect to all PSDs. Very high changeability of PSDs, derived from the procedure of transporting the flow to the WWTP. Nevertheless, based on the results given by the guided research, the authors were unable to draw conclusions regarding the effect of sewer system on the distribution of particles display in the flow. The highest portion in the wastewater flow had particles of a size ranging from 0.30 to 2 mm. The size of smallest particles recognized in the flow is less than 0.15 mm with the weight percentage of 2.6% that exist in all samples. And the size of biggest particles identified in the raw sewage is about 31 mm with the average weight percentage of 0.75% that observed during the wet weather condition, occasionally. One should mention that the examination of PSD was done on the samples from the WWTP to which no chemical precipitation with metal salts was implemented. The domains of the size of particles verified in the selected samples of the flow where demonstrates in Table 3. Fig. 11 shows the distribution particle sizes have been measured, in the form of bar diagrams.

The analysis of the earned PSDs for raw wastewater allows us to attention that throughout the measurement range from 0.075 mm to 31 mm section of the particles deposited in the pipeline. Based on the analysis of samples, most of the particles of a size outdoing 0.075 mm were deposited in the grit chamber. All samples were also compared in the aspect of d_{50} values for sets of particles. Mean particle set diameters specified directly basing on the gradation test.

On the basis of PSDs, the values of d_{50} were determined. The analysis of d_{50} for the earned result sets displayed that the d_{50} of deposit particles in the flow is included within the range of 0.80 to 2.90 mm particle sizes (Table 4). According to Table 4 and Fig. 12, the average size of d_{35}, d_{50}, d_{65} and d_{eff}, for the wastewater flow is about 0.98, 1.45, 2.21 and 2.9 mm, respectively.

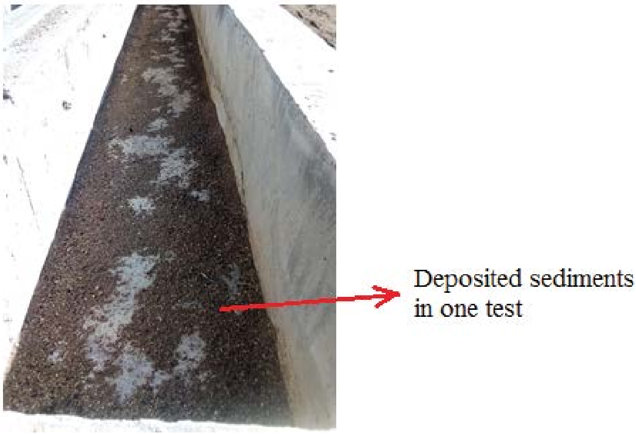

Fig. 6. Deposited sediments in the channel in one test to determine the weight of deposition.

Fig. 7. Deposited sediments in the channel after 10 d to determine the gradation curve.

3.1. Effective particle diameter

The effective or average hydraulic equivalent particle diameter d_{eff} was based on the applied sieve method in which

Table 2
Characteristics of the number of conducted tests and the period of the experimental works

Sample	Wastewater flow
Symbol	R
Number of conducted tests	14
Period of experimental work	04.25.2020–12.10.2020
Sampling point	Sewage treatment plant inlet (after screens)

Fig. 8. Sediment sample prepared for gradation tests.

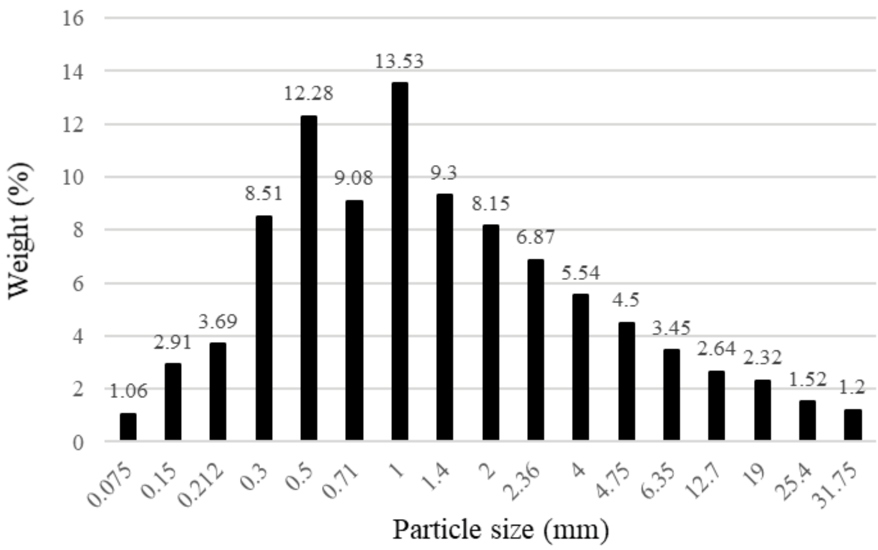

Fig. 9. Measured PSD in dry weather condition.

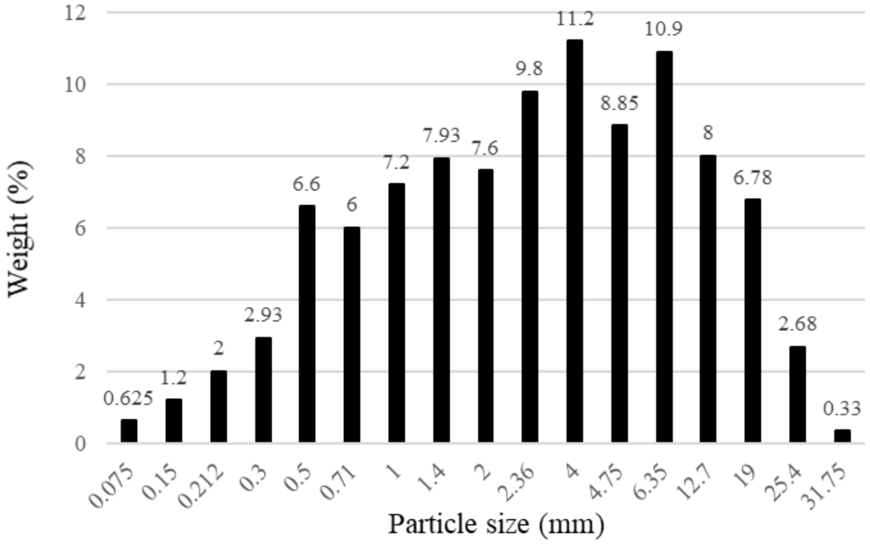

Fig. 10. Measured PSD in wet weather condition.

particles were divided over the slides of sieves and calculated according to the appropriate geometric mean for the sieves as Eq. (1):

$$d_{\text{eff}} = \sum_{i=1}^{17} d_{s.i} w_i \tag{1}$$

where d_s is particle size, w is the weight of each particle in percent and superscript i is the number of sieves that in this study is equal to 17. So, it is possible to calculate the effective particle diameter (EPD) by using Eq. (1) and Fig. 12, which it gives 2.9 mm.

The standard gradation test shows a high changeability of the PSDs in the wastewater flow. This is because, the samples of the flow gathered at the same position at long intervals, almost different distribution of particles incident in the deposited sediments were monitored. This demonstrates the existence of seasonal changes in the distribution of particle sizes in the flow. To control PSDs that earned in the samples were bimodal. The coarse particle sizes included practically the entire measurement domain from 0.075 to 31 mm. And, as it can be seen from Fig. 10, PSDs contain sand and gravel. And also, because of the length of the channel equals the length of grit chamber of WWTP, it can be concluded that the PSDs ranging from 0.075 to 31 mm can be deposited in the grit chamber. The particles of diameter of 1 mm are the highest percentage shares in the flow. As it can be seen from Table 4, the size of d_{50} is different for all samples and its value in wet weather

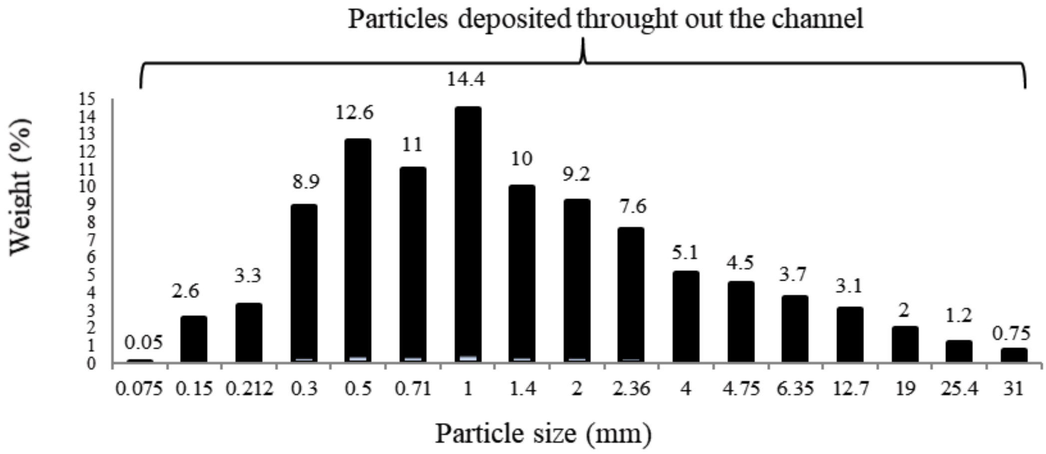

Fig. 11. Measured PSD in all weather conditions.

Table 3
Borderline particle sizes (in mm) verified in selected samples of the raw sewage

Date	WWTP of Khomeyn	
	min	max
07.05.2020	0.15	6.35
07.21.2020	0.15	12.7
08.05.2020	0.15	12.7
08.21.2020	0.15	12.7
09.05.2020	0.15	12.7
09.21.2020	0.15	12.7
10.06.2020	0.15	12.7
10.21.2020	0.15	19
11.05.2020	0.15	19
11.20.2020	0.15	12.7
12.05.2020	0.15	12.7
12.20.2020	0.15	25.4
01.04.2021	0.15	31
01.15.2021	0.15	31

are greater than that of the dry weather condition, that it shows the effect of weather type on the distribution size of particles. Herein, the mean value of d_{50} is about 0.98 and 2.32 mm in dry and wet weather conditions, respectively.

One of the most popular and frequently used models for describing homogeneous liquid–solid fluidized suspensions is the model developed by the study of Richardson and Zaki [26] as the following equation.

$$\mathrm{Re}_t = \frac{\rho_l d_p v_t}{\eta} \tag{2}$$

where Re_t is the Reynolds number of particle, ρ_l is the density of liquid phase, d_p is EPD, v_t is the terminal velocity and η is the dynamic viscosity of fluid.

As it can be seen from Eq. (2), the value of EPD is very important to calculate Re_t. In addition, determination of the EPD in urban wastewater flow is a crucial because of the existence of a wide range of solid particle diameters. Therefore, in this study using a sieve analysis the EPD of the urban wastewater flow has been determined with a high accuracy and it can be used in Eq. (2).

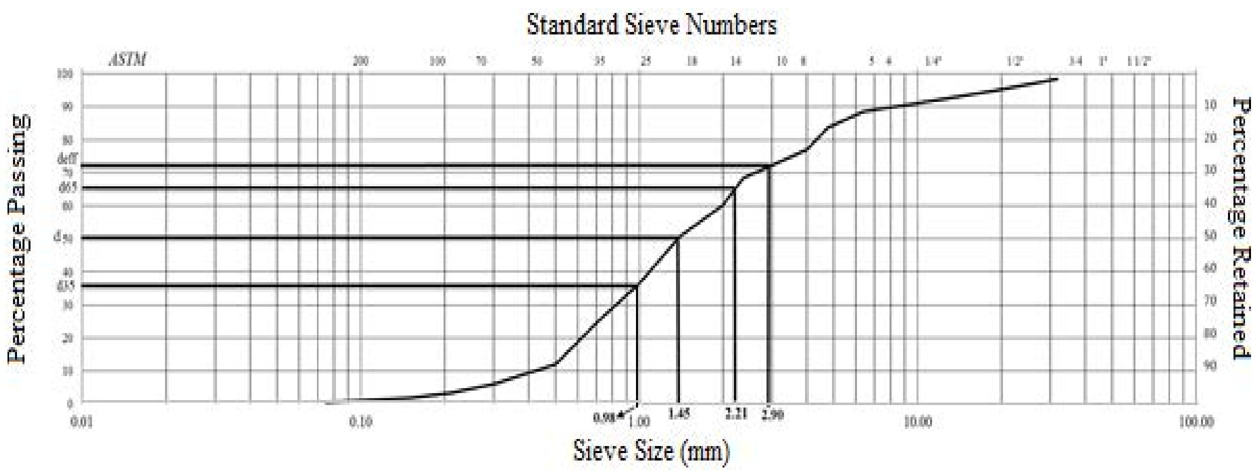

Fig. 12. Gradation curve for the average PSDs of all samples.

3.2. Comparison the measured weights of sediments with total load Einstein method

In this study, the unit weight per second of the sediments have been measured in the flow according to Eqs. (3) and (4). The results are listed in Table 5.

According to Table 5, the average weight of the sediment can be calculated using Eq. (3) as follows.

$$\bar{m} = \frac{1}{14}\sum_{i=1}^{12} m_i = \frac{1}{14}\times(13.02) = 0.93\text{ kg} \tag{3}$$

where in Eq. (3): $\bar{m}$ is the average weight of sediments in kg and m_i is the weight of each sample in kg.

And then by dividing the average weight of sediment to the time of doing the experiment, the average weight of sediment in per second can be calculated using Eq. (4) as follows:

$$\overline{M_t} = \frac{\bar{m}(\text{kg})}{t(s)} = \frac{0.93\text{ kg}}{420\ s} = 0.002\frac{\text{kg}}{s} \tag{4}$$

where $\overline{M_t}$ is the average weight of sediment in kg/s, and t is time in s.

Table 4
Mean diameters of the sediment (d_{50}) in the wastewater flow collected from the WWTP

Date	WWTP of Khomeyn
	d50 (mm)
07.05.2020	0.90
07.21.2020	0.88
08.05.2020	1.10
08.21.2020	0.84
09.05.2020	0.80
09.21.2020	1.30
10.06.2020	1.40
10.21.2020	1.30
11.05.2020	1.60
11.20.2020	1.50
12.05.2020	1.90
12.20.2020	1.80
01.04.2021	2.90
01.15.2021	2.20

According to Eq. (4), the measured average weight of sediment in the wastewater flow is equal to 0.002 kg/s. Then, by comparing the measured data with Graf and Acaroglu method [27] and Einstein method [28] by using d_{35}, d_{50}, d_{65} and d_{eff} for calculating the total load sediment as follows.

$$q_t = \Phi_t\left(\Delta g d_i^3\right)^{0.50} \quad \text{Graf and Acaroglu method}[27] \tag{5}$$

$$W_T = \sum i_s G_{\text{st}} \quad \text{Einstein method}[28] \tag{6}$$

where in Eq. (6): W_T is the total load in N/s, $i_s G_{\text{st}}$ is the total load in N/s per width of the section for each particle [29]. Table 6 gives a comparison of the measured and calculated weight of sediment in the flow. As it can be seen in Table 6, the total load of sediments has been calculated by using d_{eff} which is more accurate than the other three particle diameters. So, it can be said that d_{eff} is suitable for using in both proposed methods. In Table 6, the negative sign of relative error shows that the relation estimated the total load is less than the measured total load of the flow.

4. Conclusion

The phenomena and procedures that happen with the sedimentation in wastewater flow are described by high

Table 5
Measured weight of deposited sediments

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

Table 6
Comparison of the measured and calculated weight of sediment in the flow

Total load method	Relationship	Relative error (%)			
		d_{35}	d_{50}	d_{65}	d_{eff}
Einstein method (1950)	$W_T = \sum i_{\text{st}} G_{\text{st}}$	1,635	1,300	1,730	700
Graf and Acaroglu method (1968)	$q_t = \Phi_t\left(\Delta g d_i^3\right)^{0.50}$	185	60	25	–4.25

intricacy. For increasing the accuracy, knowing about PSDs is significant, indeed. Also, it is essential to improve new research methods for analyzing them in both qualitative and quantitative points of views. In present study, an important attempt has been provided to measure the weights and analyzed the PSD of sediments in urban wastewater flows. In this regards, the gradation curve of the particles and the EPDs of urban wastewater sediment have been determined with a high accuracy and it can help the other researchers to determine Re_t of the fluid. Also, this study presents a good sight of solid particle distribution in urban wastewater flows that can be used for future studies in regards of sediment transport by the flow.

The test results demonstrate that:

- According to Fig. 12, there is a high changeability of the PSDs in wastewater flows. The PSDs are included sand and gravel particles.
- The PSDs deposited in the pipe ranging from 0.075 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 average value of d_{35}, d_{50}, d_{65} and d_{eff} for the wastewater flow equals 0.98, 1.45, 2.21 and 2.90 mm, respectively. The d_{50} values in wet weather are greater than that of dry weather condition, and it shows the effect of weather type on the size range of d_{50}.
- The mean value of d_{50} is about 0.98 and 2.32 mm in dry and wet weather conditions, respectively.
- The total load of the sediments has been measured and it is equal to 0.002 kg/s.
- The weight of sediments in the fluid flow compared with the calculated weight of total load sediment by using the Graf and Acaroglu method and the Einstein one. The results show that the calculation of total load by using d_{eff} are more accurate than the other three particle diameters.
- The Graf and Acaroglu method may estimates the total load of the flow with a high accuracy by using d_{eff} with a relative error of 4.25%. And this method can be recommended for calculating the total load sediment for the wastewater flows.
- The particles of diameter of 1 mm give the highest percentage (14.4%) shares in the fluid flow.

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Symbols

d_p	—	Effective particle diameter
d_{50}	—	Mean particle diameter
d_s	—	Particle diameter
EPD	—	Effective particle diameter
i	—	Number of sieves
i_sG_{st}	—	Total load of sediment;
m_i	—	Weight of each sample
$\bar{m}$	—	Average weight of sediment, kg
$\overline{M_t}$	—	Average weight of sediment per second, kg/s
PSD	—	Particle-size distribution
Re_t	—	Particles' Reynolds number, –
t	—	Time, s
v_t	—	Terminal velocity, m/s
W_T	—	Total weight of sediments per second
WWTP	—	Wastewater treatment plant
η	—	Dynamic viscosity, m^2/s
ρ_l	—	Density of liquid phase, kg_m

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