A Literature Review on the Sediment Transport Process in Shallow-Grade Culverts and Storm Sewers

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Abstract

Sedimentation of fine muddy material in culverts and storm sewers becomes an important issue in Texas coastal plain shallow-grade drain systems. It leads to a reduction inflow capacity with time and an associated high cost of cleaning. It may not be possible to maintain the required 2 feet per second along sewer in time. The objective of study is to conduct an extensive literature review, and field survey to implement physical experiment for quantifying the sediment transport process in shallow grade culverts and storm sewers. The previous studies indicate that culverts or sewers should be designed to transport fine grains as a suspended load and transport granular sediments as a bed load, and to erode the sediment deposition with high flow velocity to achieve self-cleaning. The suspended load, bed load and bed erosion sediment transport equations have been developed as the function of the sediment grain size, the sediment concentration, the slope of the culverts or sewers, the bed roughness. To quantify the sediment characteristics, three samples were collected from the culvert, the ditch and the sewer located in Orange County of southeast Texas. The sieve analysis indicates that d_{50} are greater than 0.5mm and d_{65} are greater than 1mm for all the samples. However, more fine particles are included in the sewer sump and ditch than that in the culvert. The ongoing study is to set up a physical model based on the key variables in the previous transport equation to study the transport process in shallow grade culverts and storm sewers.

1. Introduction

In the Texas coastal plain shallow grade system, the sedimentation of fine muddy material in storm sewers, and culverts is a significant problem. The first and most obvious is that it reduces the cross-sectional area and the conveyance of the culverts and sewer pipes. Secondly, the deposits can increase the bed roughness and further reduces the conveyance. As a whole, from the hydraulics point of view, sedimentation in the culverts and storm sewers cause the potential flooding of the roads and adjacent areas. In addition, the sewer system network causes environmental concern when the aerobic bacteria and fungi use hydrogen sulfide gas and secrete sulfuric acid [11, 14]. A single value of minimum velocity has been determined to design storm sewer for carrying sediment The design requirement in TxDOT hydraulic Design Manual (2009) set that the lower limit is to maintain the flowing full velocity 2ft/s in culverts/storm sewers at all the points in time to avoid deposition and the upper limit is fixed to prevent erosion of the pipe by grit transported in the storm water. This velocity is unrelated to

sediment characteristic and hydraulic behavior.
In TxDOT Beaumont district, driveway culverts are now installed by the property owners, and matching the flat slope of adjacent ditch caused siltation in the culverts and ditches. From 2011 to 2012, nine maintenance sections in the district spent approximately $700,000 on ditch and culvert cleaning (personal communication, John E. Sudela, Transportation engineer, TxDOT Beaumont district). However, the recent studies indicate that the minimum self-cleansing velocity should be developed as the function of sediment grain size and concentration, the slope of culvert or sewer and the bed roughness. The objective of this study is to conduct an extensive literature review and field survey to implement physical experiment for quantifying the sediment transport process in shallow grade culverts and storm sewers.

2. Method Development

A literature review has been conducted on the deposition in culverts and storm sewers with particular emphasis on methods currently used to quantify the potential for reduced capacity with time and space, to develop physical model for simulation sediment transport.

2.1 Sediment Transport in Culvert/ Storm Sewers

Flow in culvert and storm sewer systems range from open-channel to pressurized pipe flow depending on stream stage/inflow discharge. The study on the basic sediment transport mechanics in open-channel flows and transport of solid in pipeline system are necessary. Sediments transported by open channel flow are divided into two categories. Bed material load contains silt, sand, gravel, cobbles and boulders from the river bed and lower bank; and, wash load includes the materials which travel along the channel without deposition. The bed material load also divided into three sediment transport modes. Sediment transporting in suspension within water column is called suspended load and sediment contacting with channel bed is a bed load. The state between these two is saltation. Cleveland et al. [13] has developed a sediment transport database with an emphasis on bed load transport. However, the suspended load transport is the dominant mode in the coastal plain.

2.1.1 Sediment Transport Mechanics in Open Channel

The primary force exerted by flow on the particles is a drag force and the resisting force generated by particle weight and grain to grain contact of a particle with its adjacent particles [13]. The bed shear stress (τ_b) represents the average force exerted by flow on the bed per unit area. The important ratio in the mechanics of sediment transport is the ratio of drag and resisting force for horizontal and low slope channel. When the sediment bed is in motion, the equation 1 is used.

$$\tau^* = \frac{\tau_b}{(\rho_s - \rho)gd} \quad (1)$$

Where $\tau_b=\rho gRS$,

The equation 2 is used for definition of threshold of movement, when the sediment bed is stable.

$$\tau^*_{cr} = \frac{\tau_{b,cr}}{(\rho_s - \rho)gd} \quad (2)$$

Where τ_{cr}*= critical dimensionless shear stress or the Shields parameter [33, 9, 17, 16].
Brownlie [6] presented the equation 3 which was consistent with Shields Diagram [33] to calculate the value of τ_{cr}*.

$$\tau_{cr}^{*} = 0.22\left(\frac{\sqrt{\frac{\tau_b}{\rho}}}{\upsilon}d\right)^{-0.6} + 0.06\exp\left(-17.77\left(\frac{\sqrt{\frac{\tau_b}{\rho}}}{\upsilon}d\right)^{-0.06}\right) \quad (3)$$

The bed load changes into suspended load when the flow and turbulent stress become high enough to overcome the submerge weight on the particles. The equation 4 is a suitable estimator to determine that the suspend load or bed load will be dominant for particular flow and sediment size. This equation is developed by Hunter Rouse [32].

$$Z_R = \frac{w_s}{ku_*} \quad (4)$$

Julien [16] illustrated that 6.25< Z_R the sediment transport should be bed load; Z_R<1 pure suspended load; and 1<Z_R< 6.25 combined bed load and suspended load.

2.1.2 Solid Transport Mechanics in Pipeline System

The solid transport in pipeline system is divided into five different regimes [36, 12]. These regimes are: 1) homogeneous flows where all particles are distributed through pipeline system uniformly, 2) heterogeneous flows where the vertical suspended particle concentration is not uniform, 3) flow within pipeline which has a shapeable bed, 4) flows where a stationary bed exists and 5) a blocked pipe which is blocked by immobile deposited sediment. These regimes are function of flow velocity and particle size. Two important items that should be considered in pipeline systems are head loss and sediment concentration. The head loss is increased by increasing of sediment concentration. Head loss in pipeline with bed load (regime 3) is greater than the pipeline with suspended load [13]. Newitt et al. [27] proposed the equation 5 for calculating head loss in pipeline with bed load.

$$\frac{i_m - i}{c_v i} = 66\frac{SS_G gD}{V^2} \quad (5)$$

Laursen [19] demonstrated that i_m should be function of sediment concentration, pipeline size, sediment size and flow velocity. Graf et al. [15] utilized two dimensionless parameters to calculate total sediment transport load. The equation 6 is the best equation which is consistent with Graf's results for both pipeline and open channel.

$$\frac{C_v vR}{\sqrt{SS_G g d^3}} = 10.39\frac{SS_G d}{i_m R} \quad (6)$$

2.2 Sedimentation Consideration for Design of Culverts

Aggrading streams usually cause deposition although the degradation provides sufficient sediment supply to the inlet to where the deposition may occur [35]. In addition the sediment deposition in culvert could be a result of flood ceases or sufficient hydraulic changes. Gradient and friction are two prevalent hydraulic changes. The gradient influences on deposition when the culvert fills with sediment where the hydraulic gradient develops enough to prevent further deposition [35]. Deposition can also change friction of the culverts and bed form may be segment of this change [35]. Culverts are typically designed based on flow with specific return period. The culvert cross-sectional area should be greater than bankfull stream geometry to handle flow with return period. This increased cross-sectional area leads to velocity reduction and sediment deposition at low flow circumstance and sediment erosion at downstream [18]. The multicell culverts suggested by many researchers for imitating the natural stream flow and improvement of sediment and flow continuity over a range of flow conditions [18, 38]. Wargo et al. [38] carried out experiments on single and multicell culvert with moveable sediment and demonstrated the flow depths within multicell culvert were higher than those in the single cell and the scour depths are less at the same flow conditions. Muste et al. [26] invested the methods of increasing centerline velocity by using fillet on either side or inlet for flow contraction and acceleration. In summary, cross-sectional area is the most important parameter for design in term of sedimentation consideration.

Utah Department of Transportation hydraulic manual of instruction roadway drainage, culverts suggests statistical assessment, simplistic assessment, complex assessment and tractive shear assessment under different design consideration. The statistical assessment is a rough estimate of future deposition and scour pattern. The assessment is not very accurate for the most culverts due to the unsteady flow. Simplistic assessment is more detailed approach based on extreme condition. The equation 7 and 8 for streams and culverts are presented below:

$$R_G = \frac{\left(\frac{q_s}{q}\right)_1}{\left(\frac{q_s}{q}\right)_2} \quad (7)$$

$$R_G = \left(\frac{V_1}{V_2}\right)^3 \left(\frac{n_1}{n_2}\right)^4 \left(\frac{y_2}{y_1}\right)^{5/3} \left[\frac{1-\frac{S_C}{S_1}}{1-\frac{S_c}{S_2}}\right] \quad (8)$$

Where q_s/q= ratio of sediment discharge to water discharge, $V_{1,2}$= average velocity in uniform flow, $n_{1,2}$= manning's n, $y_{1,2}$= average depth of uniform flow, $S_{1,2}$= slope of hydraulic grade line. The sediment transport ratio is used to determine deposition occurrence. When the sediment transport ratio is much greater than unity, all of the sediment transported by the stream is going to be deposited. The simplistic assessment is the common design method due to its simplicity and conservative assumption. The concept is developed based on DuBoy's formula and Manning's formula. The complex assessment requires the inflow and outflow hydrograph estimate. In this analysis the ability of the flow in order to remove the sediment is taken into account. The equation used to estimate sediment discharge for round culvert flowing full. In this assessment, fractions are routed through the site using finite time elements. The sediment discharge rate in volume per time through the culvert is a parameter to determine the deposition occurrence. If Q_{smax} is less than the sediment transport rate arriving at culvert, the deposition will occur in upstream.

$$Q_{smax} = 3.78 g^{0.5} d^{-1.02} S^{2.52} R^{1.52} A \quad (9)$$

The tractive shear assessment using morphology concept is a relatively subjective assessment which estimates a regime slope. In this assessment, the probable tractive shear is calculated based on mean annual discharge. The shear is determined by equation 10:

$$\tau = \gamma y S \quad (10)$$

If the τ is much greater than τ_c, the deposition won't occur. The tractive shear assessment predicts the deposition incidence by comparison between τ and τ_c. Should τ and τ_c be relatively close, the Complex Assessment may be justified [35].

2.3 Sedimentation Consideration for Design of Storm Sewers

Transport of sediment along the storm sewers divided into two phases: suspended load sediment, bed load sediment. The finer and lighter particles transported along the storm sewers in suspension. Crabtree [10] illustrated that the sizes of suspended particles in flow are 40μm and their settling velocity is less than 10mm/s. However, the heavier materials travel by rolling, sliding or saltating along the deposited bed as a bed load transport. Ashley et al. [2] indicated that the granular materials (2-10mm) are traveled as a pure bed load. The storm sewer should be designed to achieve self-cleansing performance to transport the finer particles in suspension, transport granular particles by sliding on the deposited bed and erode the cohesive material from bed. The storm sewers have been investigated in two terms of transport by many researchers. The cohesive materials should be eroded from bed to gain better self-cleansing performance. Laplace et al. [21] investigated on bed erosion in sewers in Marseille directly.

2.3.1 Suspended Load Transport

The sewers should be designed to transport a minimum concentration of fine grain size particles. Many researchers represented the equations for suspended particles moving at limited deposition; Mack's [22] stated the equation, which is consistent with experimental results. This equation is valid beyond $\tau= 1.07\ N/m^2$. Ackers [3] developed the equation that the effective sediment bed width was reduced. Nalluri et al. [28] proposed a new design criterion for clean pipe (no deposition) with pipe diameter up to 1 m. Table 1 summarized the design methods which were represented by above researchers.

Table 1: Design Criteria for Self-Cleansing Storm Sewers in Term of Suspended Load Transport

Design Criteria	Remarks
$C_v = \dfrac{\lambda_0^3 V^5}{30.4(S_G-1)w_s^{1.5}A}$	Mack's (1982)
$C_v = J\left(w_e\dfrac{R}{A}\right)^{\alpha}\left(\dfrac{d}{R}\right)^{\beta}\lambda_0{}^{\gamma}\left(\dfrac{v}{\sqrt{g(S_G-1)R}} - K\lambda_0{}^{\delta}\left(\dfrac{d}{R}\right)^{\varepsilon}\right)^m$	Ackers (1991)
$\dfrac{v}{\sqrt{gd(s_G-1)}} = 3.08c_v^{0.21}D_{gr}^{-0.09}\left(\dfrac{R}{d}\right)^{0.53}\left(1.13\lambda_0^{0.98}c_v^{0.02}D_{gr}^{0.01}\right)^{-0.21}$	Nalluri and Ghani (1996)

Where, the various empirical coefficients (J, K, m, α, β, γ, δ, and ε) depend on the dimensionless grain size D_{gr} and the mobility parameter at the threshold of movement A_{gr}. The sediment size, specific gravity, sediment concentration and pipe diameter are important variables to influence the minimum velocity and gradient.

2.3.2Bed Load Transport

May [24] provides a method for circular pipe with deposited bed that is fit to laboratory data. Nalluri et al. [28] suggested an equation for pipe diameter more than 1 m which allows a limited depth of sediment. Ackers et al. [3] determined an equation based on the experimental results for preventing deposition in horizontal pipes. May [25] stated the equation for upward sloping and vertical pipe of inverted siphon that is consistent with the experimental results. Ota et al. [30] used dimensionless transport parameter $\emptyset = \frac{q_b}{d^{\frac{3}{2}}\sqrt{g(S_G\text{-}1)}}$ and dimensionless shear stress parameter $\tau^* = \frac{\tau}{\rho g(S_G\text{-}1)d}$ for studying of sediment transport over loose beds.

Volumetric sediment transport rate is a function of sediment concentration, hydraulic radius and flow velocity.

$$q_b = C_v RV \quad (11)$$

τ in the dimensionless parameter τ* is a complicated variable. It is related to τ_b where, the sidewall roughness is different form bed roughness. Also, it is related to τ'_b when bed forms construct. In the clean pipe, the mean shear stress is τ_0=ρgRS=ρV*. Azamathula et al. [5] generated a transport equation using Adaptive Neuro Fuzzy Inference System for bed load transport with a limiting velocity without deposition. Table 2 presents the design method for bed load transport.

Table 2: Design Criteria for Self-Cleansing Storm Sewers in Term of Bed Load Transport

Design Criteria	Remarks
$C_v = \eta(\frac{W_b}{D})(\frac{D^2}{A})(\frac{\Gamma\lambda_g v^2}{8g(S_G-1)D})$	May (1993)
$\frac{v}{\sqrt{gd(s_G-1)}} = 1.18c_v^{0.16}(\frac{w_b}{y_0})^{-0.18}(\frac{R}{D})^{-0.34}(-0.0014c_v^{-0.04}\left(\frac{w_b}{y_0}\right)^{0.34}(\frac{R}{d})^{0.24}D_{gr}^{0.54})^{-0.31}$	Nalluri and Ghani (1996)
$C_v = 0.0303\left(\frac{d_{50}}{D}\right)^{0.6}\left(\frac{D^2}{A}\right)\left(1-\frac{V_T}{V}\right)^4[\frac{V^2}{g(S_G-1)D}]^{\frac{3}{2}}$ $V_T = 0.125\sqrt{g(S_G-1)d_{50}}(\frac{y_0}{d_{50}})^{0.47}$	Ackers, Butler and May(1996)
$C_v = (0.0303-0.0169sin\theta)(\frac{4}{\pi})\left(\frac{d_{50}}{D}\right)^{0.6}\times\left(1-\frac{\sigma V_T}{V}\right)^4[\frac{V^2}{g(S_G-1)Dcos\theta}]^{\frac{3}{2}}$ $V_T = 0.125\sqrt{g(S_G-1)d_{50}}(\frac{D}{d_{50}})^{0.47}$ $\sigma = \sqrt{\frac{sin\theta+\mu cos\theta}{\mu}}$	May (2003)
$\frac{v}{\sqrt{gd(S_G-1)}} = 0.785\xi^{-0.614}c_v^{0.277}\left(\frac{R}{d}\right)^{0.227}\left(\frac{k}{d}\right)^{0.409}(\sqrt{\frac{\lambda_0}{8}})^{-1.227}$	Ota and Nalluri (2003)
$\frac{V}{\sqrt{g(S_G-1)d}} = 0.22D_{gr}^{-0.27}C_v^{0.16}(\frac{d_{50}}{R})^{-0.29}(0.851D_{gr}^{0.03}C_v^{0.04}\lambda_0^{-0.51})^{-0.51}$	Azamathula et al. (2011)

In case of bed load movement, the minimum self-cleansing velocity can be influenced by pipe diameter, sediment size, specific gravity, flow depth, sediment roughness, sediment width bed and sediment concentration. The most significant variable is sediment concentration for large size pipes, and the particle diameter is a less important variable [8].

2.3.3 Bed Erosion

Butler et al. [7] presented the criteria based on aspects of sediment mobility and deposition. In the first criterion, the erosion was defined in term of minimum bed shear stress and in other criterion, the transportation was described in term of minimum shear stress τ_c which keeps particles in suspension. Lynse [20] suggested the minimum shear stress should be 4 N/m^2 for self-cleansing. Yao [39] demonstrated the shear stress at the invert pipe is always greater than average shear stress and declared that the flat bottom region is a critical place for sediment deposition and should be focused more in future. Also, proposed the shear stress value between 1 N/m^2 and 2 N/m^2 should be suitable for sanitary sewers. Butler et al. [7] represented the design criteria based on the potential flow to erode and transport sediments. This design criterion was defined in terms of the required full-bore flow in the sewers. Wotherspoon [37] developed a model to determine the threshold of sediment erosion based on the equation developed by Mehta and Parthenaides [23].

$$\frac{\rho_d}{\bar{\rho}} = \xi \left[\frac{\acute{z}}{H}\right]^{-\xi} \quad (12)$$

Where ρ_d= sediment bed density at depth z.

Erosion of cohesive particles from deposited bed is the third movement criteria to gain self-cleansing. The cohesive materials increase the value of shear stress that flow needs to erode the deposited bed. Skipworth et al. [34] developed a model for predicting erosion in a pipe.

$$E = M\left[\frac{\tau_b - \tau_c}{\tau_c}\right] \quad (13)$$

Butler et al. [8] suggested the equation 14 to determine the minimum bore velocity for eroding the cohesive particles from bed.

$$V_f = \sqrt{\frac{8\tau_b}{p\lambda_b}} \qquad \lambda_b \approx \frac{1}{4\,[\log \frac{k_b}{3.7D}]^2} \quad (14)$$

The important variable for bed erosion is a bed shear stress. The bed shear stress is a function of hydraulic radius and channel slope.

3. Sediment Characteristics Study

It was appreciated that the minimum self-cleansing velocity depends upon sediment characteristics and size. To quantify the sediment characteristics, three samples were collected from the culvert, ditch and sewer located in Orange County of Southeast Texas. Sieve analysis was carried out to determine grain size distribution for three samples.

3.1 Sieve Analysis

The samples were weighted and spread on tray. Afterward, the trays placed in the oven at 105ºc for a day. The sieves used are no 4, 16, 50, 100, 140, 200 and the pan at the bottom. The stack of sieves was vibrated in 10 minutes then amount retained on each sieve was weighted. The size distribution graphs were shown on the logarithmic scale. The figure 1 illustrates the cumulative grain size distribution for three samples.

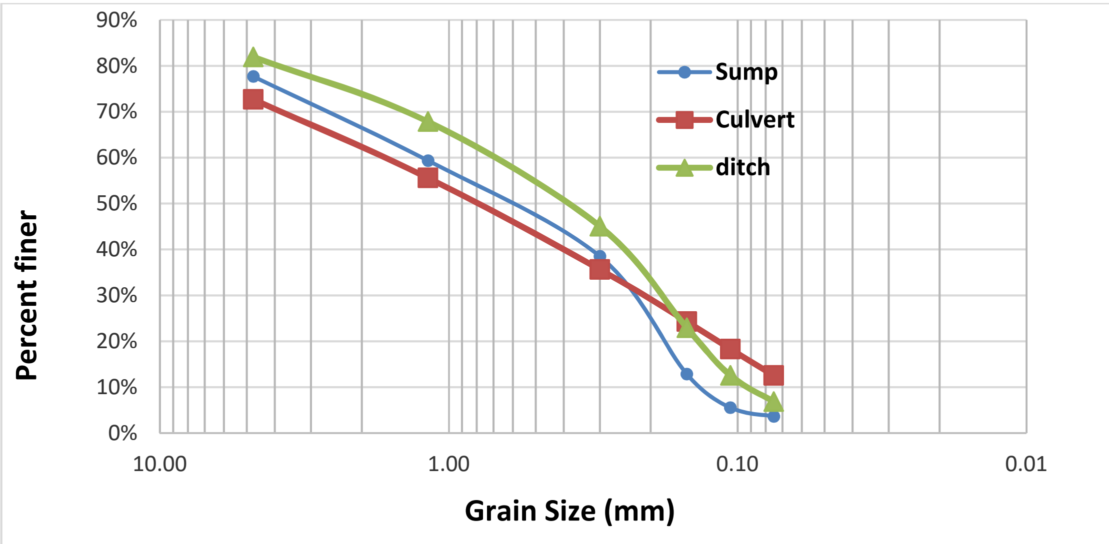

Figure 1. Cumulative grain size distribution

3.1.1 Results and discussion

The Figure 1 shows that the size distribution graphs of three samples are similar to each other's. However, sample median and sample mode have a different value for each site (the results are consistent with Almedeij's results [4]. Ota [29] proposed the use of d_{65} for predicting n Manning and use of d_{50} for calculating transport velocity. The sample median (d_{50}) for sump, culvert and ditch are 0.8, 0.9 and 0.62mm respectively. In addition d_{65} is greater than 1mm for each sample. The sample collected from culvert containing the highest proportion of gravels (figure 2). The few studies were carried out on the impact of cohesive materials on the minimum self-cleansing. The effect of cohesive and organic material should be studied more in future.

Figure 2. Grain size distribution from culvert

The average of sample median is 0.77mm that was used to compare Ackers' equation with Ota's equation for different pipe diameters in term of bed load transport. The assumptions for solving the equations are a circular sewer in half-full condition (ξ(ratio of bed and mean shear stresses)=1.05) with C_v (sediment concentration) = 100ppm, S_G (Specific gravity) =2.65, K (bed roughness for concrete pipe) =0.7mm and n_0 (Manning value)=0.0116 whenever manning equation is preferred. The comparison diagrams were shown on figure 3. Figure 3 depicts these equations are not consistent with each other. The difference between Ackers' equation and Ota's equation is light for smaller diameters and they become significant for lager sewers. Therefore, sediment transport in storm sewer should be studied more in future. Likewise, it displays the Acker's equations is more conservative than Ota's.

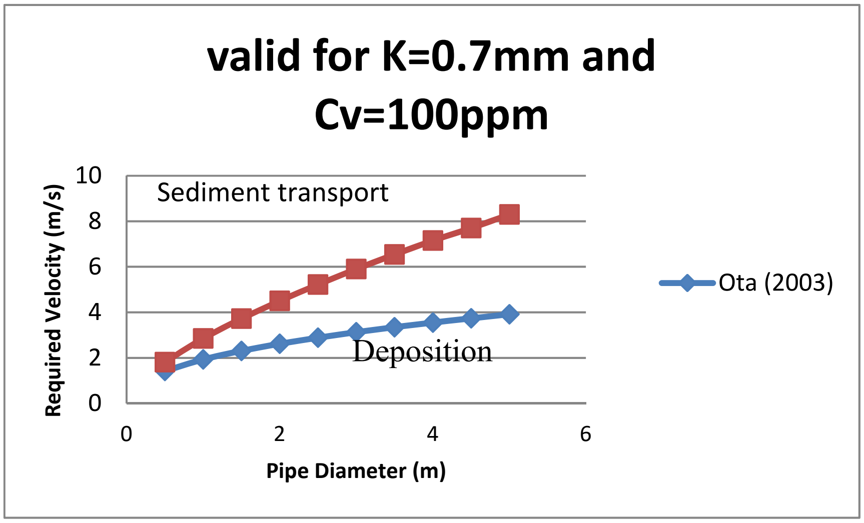

Figure 3. Comparison between Ota and Ackers Equations

4. Physical Model Design

We will be investigating the effects of sediment concentration, particle size and particle characteristics on the sediment transportation in shallow grade culverts or storm sewers. Based on U.K. data, sediment concentration varies from 10mg/L to 1000 mg/L. Based on experimental data the particle size (sample median) varies from 0.62 mm to 0.9 mm and the specific gravity ranges from 2.0 to 2.65. These dimensionless parameters $\emptyset = \frac{q_b}{d^{\frac{3}{2}}\sqrt{g(S_G-1)}}$ and $\tau^* = \frac{\tau}{\rho g(S_G-1)d}$ developed by Mayerle and y/D will be used to design physical model.

The ratio of bed shear stress and mean shear stress is function of y/D. Thus, the dimensionless shear stress parameter is correlated to the ratio of flow depth and pipe diameter.

Pipe size and slope, flow depth, sediment size, sediment concentration and discharge influence on dimensionless parameters. Table 3 indicates different kind of tests for quantifying sediment transport.

Table 3: Physical Experiment Condition

Transport mode	Pipe slope	Sediment size (d_{50})	Discharge	Pipe size	W_b (mm)	K (mm)	Sediment concentration (mg/L)
Suspended load	0.5%	0.4mm	25ml/s	1ft	*	*	100
	1%	0.7mm	75ml/s	1ft	*	*	200
	2%	1mm	125ml/s	1ft	*	*	500
Bed load	0.5%	0.4mm	25ml/s	1ft	constant	1	100
	1%	0.7mm	75ml/s	1ft	constant	1	200
	2%	1mm	125ml/s	1ft	constant	1	500
Bed erosion	0.5%	0.4mm	25ml/s	1ft	constant	1	100
	1%	0.7mm	75ml/s	1ft	constant	1	200
	2%	1mm	125ml/s	1ft	constant	1	500

84 experiments should be carried out for each transport mode based on table 3.Ota et al. [31] suggested using compensated dimensionless bed shear stress ($\psi(\frac{d}{k})^{2/3}$) and dimensionless particle velocity ($\frac{V_s}{\sqrt{gd(S_G-1)}}$) due to good correlation.

The concept of minimum velocity and gradient at limited deposition has been generated from the literature review. The idea focuses on trying to keep sediment from deposition. The experiments will be carried out in EM2 model (Figure 4) with an inserted culvert/pipe to simulate sediment transport in culvert or storm sewer. The EM2 geo-model is a complex modeling system sharing many of variables and behaviors of real world rivers. We will be investigating the role of turbulence in keeping particle in suspension and the effect of turbulence on re-suspending deposited particles by using key dimensionless variables.

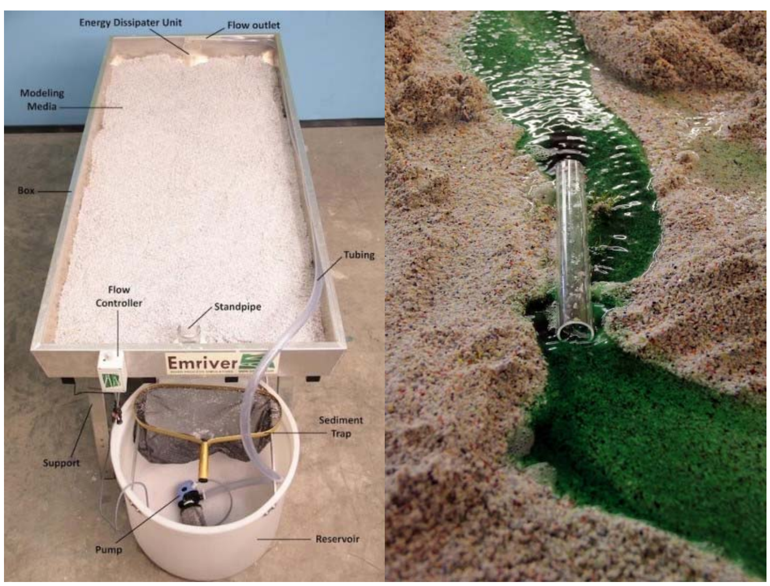

Figure 4. The sketch of the experiment facility and inserted culvert (www.emriver.com)

5. Summary and Conclusion

The review of historical studies illustrates that the single value of minimum self-cleansing velocity could not meet the criteria for transporting sediment at limited deposition. Furthermore, it may not possible to keep the minimum velocity along culverts and sewers. Therefore, the minimum self-cleansing should be developed as a function of the sediment characteristics, sediment size and hydraulic behaviors in order to have a proper self-cleansing performance. The cumulative grain size distribution graphs were approximately similar to each other based on this study. However, the sample median (d_{50}) and sample mode vary locally within each site. Each equation in literature captures different parameters and hydraulic characteristics. Comparison between Ota's equation and Ackers' one in term of bed load transport in the same condition shows that Ota's Criteria is more conservative than Ackers'. Additional studies to capture all parameters and accurate results are needed in order to have an optimized required velocity.

6. Notation

A= flow cross-sectional area, equivalent full flowing
C_v= sediment concentration
d=d_{50}= grain diameter
D= pipeline diameter
Dgr= dimensionless sediment size= $(d(S_G-1)g/(v_2))^{1/3}$
E= erosion rate at bed shear stress
g= acceleration due to gravity
H= total bed depth
i and i_m= gradient of the piezo metric head line for a pure fluid and mixture respectively
k= Von Karman constant, bed roughness size
M= erosion rate when $\tau_b=2\tau_c$
n= manning
q_b= volumetric sediment transport rate per unit width
Q_{max}= sediment transport rate
R= hydraulic radius
R_G= sediment transport ratio
S= slope channel
S_c= critical slope at which sediment of given size begin to move
SS_G= submerged specific gravity
S_G= sediment specific gravity
V= cross-sectional average velocity
V_s= fastest particle velocity of sediment of diameter d
V*= mean shear velocity
w_s= particle settling velocity
w_e= effective width of sediment bed
w_b= sediment bed width
y= depth of flow
Z= bed depth (below surface)
Γ= transition coefficient for particle Reynold number

η= sediment transport parameter
λ_0= Darcy-Wesibach friction factor
λ_g= friction factor corresponding to the grain shear factor
λ_b= friction factor corresponding to the sediment bed
ξ= coefficient from Mehta and Parthenaides
τ_b= bed shear stress
τ_{bcr}=critical bed shear stress
τ^*=dimensionless bed shear stress
τ_{cr}^*= critical dimensionless shear stress
ρ= fluid density
$\overline{\rho}$= average bed dry density
ρ_d= sediment bed density
γ= unit weigh of water
θ= angle of pipe to horizontal positive upward
μ= effective friction coefficient between sediment particles and wall of pipe

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