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PROPOSAL FOR NEW CRITERIA AND NEW EQUATIONS TO GUARANTEE THE SELF-CLEANING OF SEWAGE PIPES

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Abstract: The sizing methodology for sanitary sewage collection systems uses fixed criteria to avoid sediment deposits at the bottom of free conduits at low flow rates, and these self-cleaning criteria have values that generally do not take into account the synergy of physical and hydraulic parameters in real operational situations, especially in partial separator, unitary and dry weather collection systems. This work therefore details new self-cleaning concepts that take into account the characteristics of the conduits, fluids and sediments, as well as the type of sediment transport in real operational situations. In addition, existing standards and practiced criteria were duly analyzed in order to mathematically model 829 existing and representative data extracted from specific laboratory and field tests for self-cleaning in the operation of sewage pipelines around the world, with different diameters, situations and materials. After statistical analysis and validation of the proposed model, new tensile stress values and new self-cleaning equations for design criteria are presented, together with a new methodology, in order to hydraulically dimension the sanitary sewers in initial flow situations. In this case, the minimum tractive stress values proposed are 1.0Pa for separator--type sewage systems, 1.5Pa for systems with time collection (collectors or interceptors) and 2.0Pa for unit or rainwater systems. Finally, it is recommended to use a new general self-cleaning equation containing the Froude number (Fr*) of the sediment, in order to then use both the minimum self-cleaning velocity (vn) and the minimum self-cleaning tensile stress (τn), under the actual operating conditions of the sanitary system.
Keywords: Collector, Sediment, Self-cleaning, Tractive stress, Sewage projects.

INTRODUCTION

Sewage collectors must carry the maximum design discharge at high flow rates and be free of sediment deposits at low flow rates, as this influences collector hydraulics.

Worldwide, a minimum flow velocity (0.3 to 1.0m/s) or a minimum tensile stress (1.0 to 12.6Pa) is adopted to keep suspended sediments moving and thus avoid deposition on the bottom (GUIMARÃES, 1975; ABNT, 1986; VONGVISESSOMJAI, TINGSANCHALI, & BABEL, 2010; AB. GHANI & AZAMATHULLA, 2011; AZAMATHULLA, AB. GHANI, & FEI, 2012; BSI, 2013; SAFARI, MOHAMMADI, & AB. GHANI, 2018; and MONTES, BERARDI, KAPELAN, & SALDARRIAGA, 2020).

The minimum value defines the slope of the conduit in order to guarantee the continuous transport of sediment at least once a day, because the accumulation of deposits reduces the hydraulic section of the conduit and increases its roughness, thus reducing the flow rate of sanitary, rainwater, unitary and dry weather collectors. In addition, they cause turbulence, septic conditions (bad odors and corrosion) and overflows (CAMP, 1946; ABNT, 1986; BSI, 2013 and EBTEHAJ & BONAKDARI, 2013), rendering the affected collector inoperable.

However, criteria that use a single value of velocity or tensile stress for self-cleaning are ineffective, because transport and sediment vary under local conditions. Thus, the self-cleaning must contain parameters of the transported material (sediment and waste), flow characteristics and type of movement inside the collectors (GAY, PRUS-CHACINSKI, NOVAK, & NALLURI, 1979; AZAMATHULLA, AB. GHANI, &FEI, 2012; SAFARI, AKSOY, UNAL, & MOHAMMADI, 2017; SAFARI, MOHAMMADI, GILANIZADEHDIZAJ, & SEYYEDI, 2017; and SAFARI, MOHAMMADI, & AB. GHANI, 2018).

OBJECTIVES

This work proposes changing the current design criteria for collectors and presenting new equations to guarantee self-cleaning, which include the characteristics of the sediments, the type of flow inside the collectors, for each type of system (rainwater, separator, unitary and dry weather), considering real operating conditions.

The main characteristics of the fluid being transported are: specific mass (ρ); kinematic viscosity (ν); hydraulic radius (R=A/P); hydraulic depth (Y=A/B); wetted area (A); width of the water surface (B); wetted perimeter (P); water height (y); hydraulic form factor (β).

Sediment characteristics include the following parameters: specific mass (ρs); density (s=ρs/ρ); average size (d); volumetric concentration (Cv); width of deposited sediment (Wb); height of deposited sediment (ts); cross-sectional area with deposited sediment (As); perimeter of cross-sectional area with deposited sediment (Ps); dimensionless size (Dgr); sediment Reynolds number (Re*).

In relation to the conduit used and its interaction with the fluid being transported, we have: conduit diameter or base width (D or W); Darcy-Weisbach coefficient of friction (f); Manning's coefficient (n); hydraulic slope (S); total depth of fluid and sediment deposited (yt=y+ts); g=acceleration of gravity.

Figure 1 shows the typical cross-section of circular conduits, containing some of the physical quantities mentioned above.

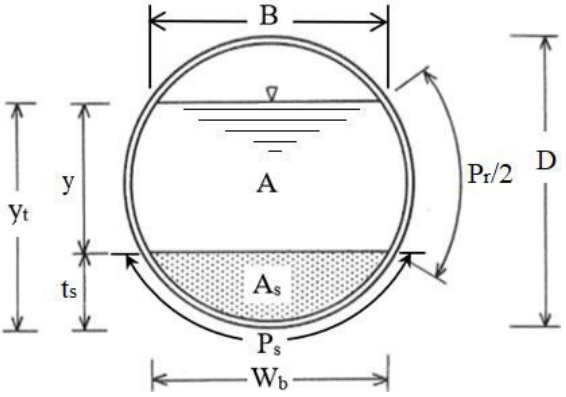

Figure 1: Typical cross-section of circular conduits with sediments deposited at the bottom (COELHO, 2022)

Finally, the type of sediment transport at the bottom of the conduit can be Incipient or Complete Movement (total drag of the bottom sediments). Transport for non-deposition of sediment can be of the following types: without deposits at the bottom of the conduit (Non-Deposition); or with Incipient Deposition in the conduit; or with deposits (Deposition) at the bottom of the conduit, where a small layer of sediment is allowed at the bottom, as shown in the cycle in Figure 2 (SAFARI, MOHAMMADI, & AB. GHANI, 2018).

METHODOLOGY USED

To support the proposal of new criteria and other self-cleaning formulas, we used data on minimum velocities (vn) and minimum tensile stresses (τn) for self-cleaning calculated or obtained from international research on the subject, including 829 experimental sediment transport data from eight groups of researchers in eleven tests with different materials.

In this case, there are 431 data points from self-cleaning experiments of the non-sediment deposition type without bottom deposits (Table 1) and 398 data points from the non-sediment deposition type with bottom deposits (Table 2). This type with deposits allows a maximum thickness sediment the bottom of larger diameter collectors, as long as it does

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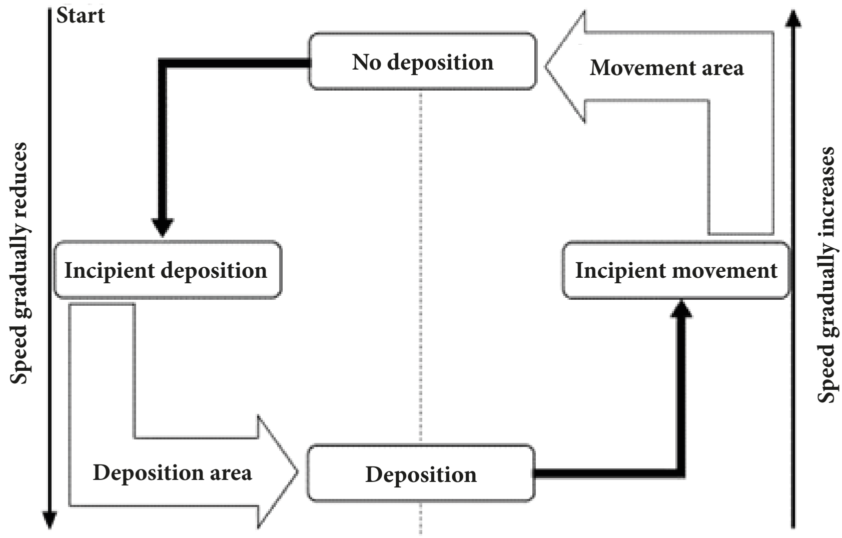

Figure 2: Types of sediment transport according to fluid velocity (SAFARI, MOHAMMADI, & AB. GHANI, 2018 adapted by COELHO, 2022)

not significantly affect the hydraulic movement (according to SAFARI, MOHAMMADI, & AB. GHANI, 2018; MONTES, BERARDI, KAPELAN, & SALDARRIAGA, 2020; SAFARI, MOHAMMADI, GILANIZADEHDIZAJ, & SEYYEDI, 2017; AB. GHANI, 1993; MAY, 1993 and VONGVISESSOMJAI, TINGSANCHALI, & BABEL, 2010).

Researchers	Year	Data
Ab. Ghani	1993	110
May	1993	27
Mayerle	1988	211
Montes *et al.*	2020	44
Safari *et al.*	2017	12
Vongvisessomjai et al.	2010	27

Table 1: Modeled data for self-cleaning criteria type no sediment deposition without bottom deposits

Researchers	Year	Data
Ab. Ghani	1993	26
El-Zaemey	1991	290
May	1993	67
Perrusquía	1992	10
Perrusquía	1993	5

Table 2: Modeled data for self-cleaning criteria of the non-sediment deposition type with bottom deposits

This data was inserted into the main existing models and the new proposed models of self-cleaning in conduits, which use dimensionless parameters to predict sediment transport, by calculating the dimensionless Froude number of the sediment particle movement (Fr*), according to Equation 1, e, then the self-cleaning velocity (vn) or the minimum tensile stress (τn), according to Equation 2 and Equation 3, respectively. In addition, there are equations for the Reynolds number of the sediment (Equation 4), the dimensionless size of the sediment (Equation Equation 65), the hydraulic form factor () and the coefficient of friction (Equation 7) in the conduit (EBTEHAJ, BONAKDARI, & SHARIFI, 2016; SAFARI, MOHAMMADI, & AB. GHANI, 2018; and MONTES, BERARDI, KAPELAN, & SALDARRIAGA, 2020).

$$Fr^* = c0(Re^*)^{c1} C^{c2} D_{gr}^{(c3)} (d/D)^{(c4)} (d/R)^{(c5)} (D^2/A)^{(c6)} (B/R)^{(c7)} (y/P)^{(c8)} (y/D)^{(c9)} (d/y)^{(c10)} (ts/y)^{(c11)} (ts/d)^{(c12)} (Wb/y)^{(c13)} \beta^{(c14)} f^{(c15)} S^{(c16)}$$

Equation 1

Being:

$$Fr^* = vn[gd(s-1)]^{-0,5} \rightarrow vn = Fr^*[gd(s-1)]^{0,5}$$

Equation 2

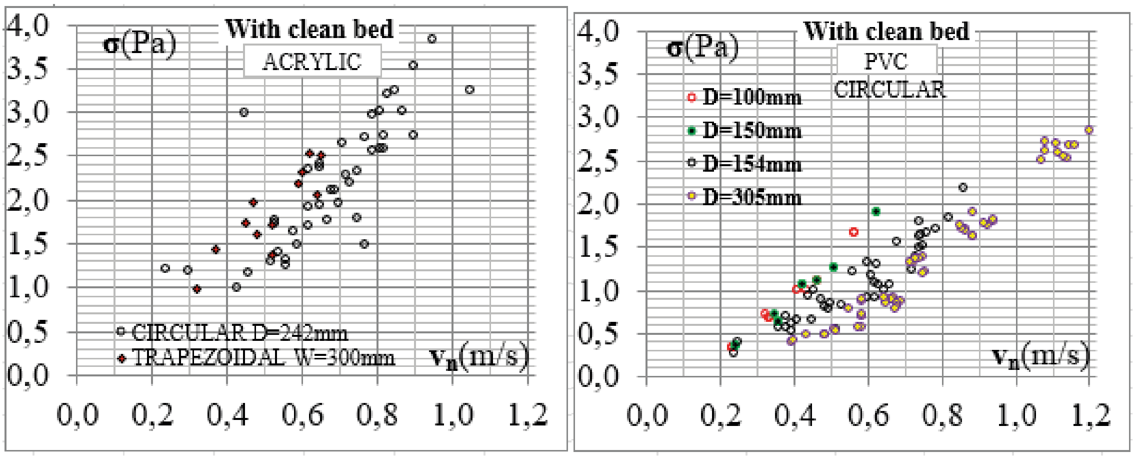

Figure 3: Minimum self-cleaning velocities and respective tensile stresses for acrylic and PVC collectors, considering no deposition of sediment at the bottom of the pipe.

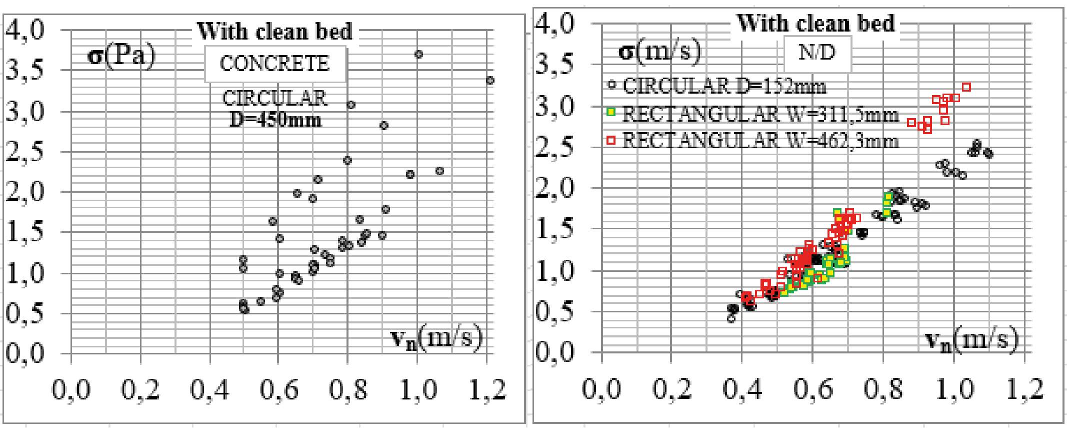

Figure 4: Minimum self-cleaning speeds and respective tensile stresses for concrete and general collectors (N/A), considering no sediment deposition at the bottom of the conduit.

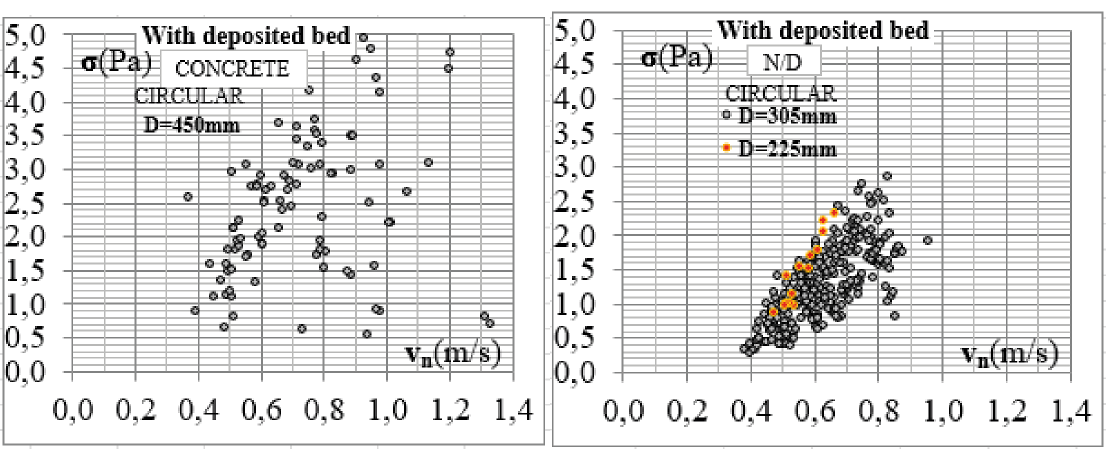

Figure 5: Minimum self-cleaning speeds and respective tensile stresses for concrete collectors and in general (N/A), considering the non-deposition of sediment type with deposits at the bottom of the conduit

Par. / Est.	D mm	d mm	s -	S %	Cv ppm	Y mm	R mm	vn ms-1	ts mm	Wb mm	A m²	P m	B m	n=ns m-1/3s	σ N/m²
Minimum	100	0,15	2,49	0,04	1	0,63	11,2	0,24	5	45	0,000	0,025	0,000	0,004	0,26
1st Quartile	242	0,73	2,56	0,18	70	59,0	42,0	0,54	47	220	0,010	0,265	0,152	0,010	0,91
2nd Quartile	305	2,00	2,59	0,25	160	82,0	55,0	0,63	77	265	0,018	0,363	0,279	0,011	1,28
3rd Quartile	312	4,20	2,63	0,38	326	125,0	71,0	0,75	95	298	0,030	0,538	0,312	0,013	1,80
Maximum	462	8,74	2,79	1,00	7.211	450,0	136	1,33	130	407	0,159	1,414	0,462	0,031	9,35
Median	305	2,00	2,59	0,25	160	82,0	55,0	0,63	77	265	0,018	0,363	0,279	0,011	1,28
Average	304	2,79	2,59	0,29	271	106,4	58,7	0,65	76	265	0,029	0,408	0,273	0,011	1,47

Table 3: Sample data and results of the experiments carried out by the researchers

Stat. / Par.	D²/A	B/R	y/P	y/D	d/R	d/y	ts/y	Wb/y	β
Minimum	1,27	0,00	0,025	0,003	0,004	0,001	0,000	0,000	0,00
1st Quartile	2,56	4,05	0,216	0,210	0,012	0,008	0,000	0,000	1,51
2nd Quartile	4,36	4,92	0,265	0,318	0,036	0,028	0,000	0,000	1,72
3rd Quartile	7,20	5,49	0,318	0,498	0,086	0,065	0,606	2,157	1,92
Maximum	5.679,79	28,09	0,361	1,000	0,416	0,616	3,000	7,450	5,62
Median	4,36	4,92	0,265	0,318	0,036	0,028	0,000	0,000	1,72
Average	85,13	4,94	0,245	0,344	0,059	0,068	0,361	1,253	1,87

Table 4: Range of dimensionless fluid parameters calculated from sample data

Stat. Par.	s	d/D	Cv	Dgr	ts/d	f	S	Re*	Fr*
Minimum	2,49	0,0005	0,000001	3,46	0,000	0,003	0,00041	47,4	1,26
1st Quartile	2,56	0,0020	0,000070	16,85	0,000	0,018	0,00183	514,7	2,46
2nd Quartile	2,59	0,0066	0,000160	45,21	0,000	0,024	0,00251	1.162,2	3,72
3rd Quartile	2,63	0,0168	0,000326	95,76	26,552	0,033	0,00380	2.632,0	5,61
Maximum	2,79	0,0575	0,007211	197,56	226,415	0,193	0,01000	10.001,5	13,53
Median	2,59	0,0066	0,000160	45,21	0,000	0,024	0,00251	1.162,2	3,72
Average	2,59	0,0110	0,000271	63,71	27,489	0,027	0,00286	1.844,9	4,33

Table 5: Range of dimensionless sediment and conduit parameters calculated from sample data

$\tau n=vn^2\rho$ **Equation 2**

$Re^*=vndv^{-1}$ **Equation 3**

$Dgr=[gd^3(s-1)v^{-}$ **Equation 4**

$^2]^{1/3}$ **Equation 5**

$\beta=(P/B)^{0,5}[1,31(B/Y)^{-0,49}]^{-1}$ **Equation 6**

$f=8gn^2R^{-1/3}$ **Equation 7**

The coefficients c0 to c16 are generally obtained experimentally or from computer models. In this work, the coefficients were adjusted in genetic algorithm models or multiple linear regression or non-linear regression.

RESULTS OBTAINED OR EXPECTED

The statistical results of the parameters used to establish new self-cleaning criteria for collectors, as well as the new equations proposed, are shown in Table 3, Table 4 and Table 5.

The values of minimum self-cleaning velocities (vn) and their respective minimum self-cleaning tensile stresses (σ=τn) are shown below (Figure 3, Figure 4 and Figure 5), identified by the type of collector material tested (acrylic, PVC or concrete), the shape (circular, trapezoidal or rectangular) and the diameter (100 to 450mm) or base width (300 to 462.3mm) of the collector.

With regard to the results of the sediment's Froude number (Fr*), this varies directly proportionally with the sediment's Reynolds number (Re*) and with the self-cleaning velocity (vn) in the sewage collector. However, the Froude number (Fr*) decreases exponentially with the diameter of the sediment (d) present in the sewage. Figure 6 illustrates these behaviors.

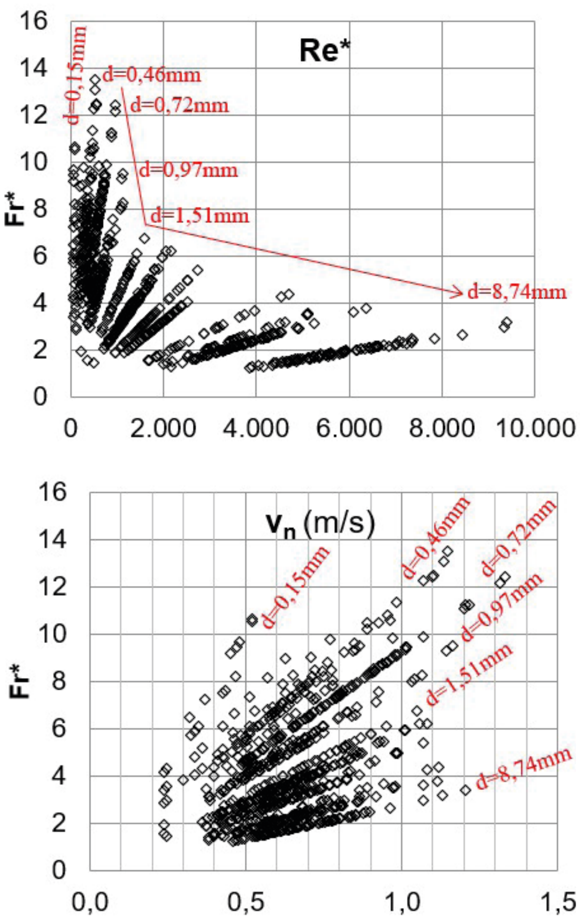

Figure 6: Behavior of the Froude number of the sediment (Fr*) with the Reynolds number of the sediment (Re*) and with the minimum self-cleaning velocity (vn) of the collector

ANALYSIS AND DISCUSSION OF RESULTS

In Brazil, ABNT standards NBR 14486, 9649 and 12207 (ABNT, 1986; 2000; 2016) set minimum tensile stress values of 0.6Pa (PVC collectors), 1.0Pa (collectors in general) and 1.5Pa (dry-weather collectors or dry-weather interceptors, or unitary).

According to Figure 3, for sediment transport without bottom deposits, most of the collectors made of materials considered internally smooth (acrylic, which is for laboratory tests, and PVC) had tensile stresses above 0.6Pa. While the concrete collectors (and in general) had self-cleaning tensile stresses well above 1.0Pa and above 1.5Pa in most of the tests, as shown in Figure 4.

In the tests considering a layer of sediment deposited at the bottom of the collector, the values were higher than 1.5Pa for concrete collectors, for the most part, and between 0.5 and 3.0Pa for collectors in general (see Figure 5). In practice, the values even exceeded 2.0Pa, especially in larger diameter pipes.

After inserting the data into the genetic algorithm generated by the **GeneXproTools** program (GEPSOFT, 2024), the 845 model (Equation 8) was obtained for the Froude number of the sediment (Fr*), using 553 data to train the model and 276 data to validate the model, which achieved the highest accuracy (R^2=0.97 and RMSE=705, see validation of the equation in Figure 7).

This general equation (Equation 8) proposed by the author of this work used the dimensionless parameters d/R, f and S and is valid for sediment transport the non-sediment deposition type, with movement **without** deposits at the bottom or **with** deposits at the bottom of the sewer. From this equation, the minimum self-cleaning velocity (vn) and the minimum self-cleaning tensile stress (τn) are calculated, according to the formulas presented above.

$$Fr^{*}=[1+2305{,}2Sf^{-1}(d/R)^{-1}]^{1/5}+[0{,}079Sf^{-1}(d/R)^{-1}]^{5/3}+e^{[2(d/R)-f]}+(d/R)^{1/5}\ln(S) \qquad \text{Equation 8}$$

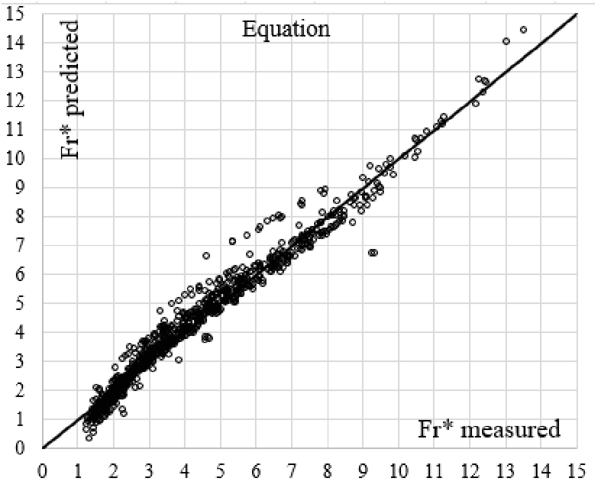

Figure 7: Validation of General Equation 1 for the Froude number of the sediment (Fr*) with the self-cleaning data measured in the experiments studied

CONCLUSIONS / RECOMMENDATIONS

According to the results presented here, it can be seen that the minimum value criteria standardized in Brazil are deficient, especially when using collector pipes with lower roughness such as PVC. It can therefore be inferred that they do not cover real operational situations, considering the field, laboratory and pilot-scale tests studied.

Therefore, the ABNT NBR 14486 standard **should not** be used for sizing PVC collectors with regard to the minimum tensile stress of 0.6Pa, as the values should be at least 1.0Pa for the separator type network, in accordance with ABNT NBR 9649.

On the other hand, when there are dry-weather catchments/interceptors contributing to the collector or interceptor, their sizing should consider at least 1.5Pa of tensile stress, in accordance with the NBR ABNT 12207 interceptor standard, because they have larger quantities of sediment transported and with larger dimensions, compared to the sediment transported in separator systems.

This minimum value of 1.5Pa is mainly valid for sizing dry-weather collectors, which are widely used in Brazil today, and for **any diameter** (or dimensions).

On the other hand, for unitary (and rainwater) systems or those with deposits at the bottom of the collector, which have higher sediment inputs, the tensile stress values should be above 2.0Pa. In this case, for diameters DN 400mm or greater, the principle of a fixed layer sediment deposits can be used, occupying a maximum of 1% of the cross section (as suggested by COELHO and AZEVEDO, 2022).

However, if this fixed criteria methodology is considered, the ideal would be to adopt minimum tensile stresses of 2.0Pa for sewage systems, regardless of type, material and diameter.

As the criteria are in practice variable, according to the results obtained in the researchers' tests, a new equation is proposed for any type of system (pluvial, unitary, separator and with dry weather catchments), based on the Froude number of the sediment, presented by the author of this article (Equation 8), to define sediment transport and thus calculate its minimum velocity (Equation 2) and self-cleaning tensile stress (Equation 3), considering the parameters presented in this work.

However, the project is expected to be close to the real operational and more sustainable conditions of sewage collectors, including interceptors and **dry weather collectors**, which are included in the sanitation concession contracts of various municipalities in Brazil. This will prevent routine clogging and overflows from collectors that are undersized according to current criteria, thereby reducing pollution of water bodies and the inherent operating costs.

REFERENCES

1. ABNT. NBR 9649 - *Projeto de redes coletoras de esgoto sanitário*, Associação Brasileira de Normas Técnicas, 1986.

2. ABNT. NBR 14486 – *Sistemas enterrados para condução de esgoto sanitário - Projeto de redes coletoras com tubos de PVC*, Associação Brasileira de Normas Técnicas, 2000.

3. ABNT. NBR 12207 - *Projeto de interceptores de esgoto sanitário*, Associação Brasileira de Normas Técnicas, 2016.

4. AB. GHANI, A. *Sediment Transport in Sewers*, 362p. Newcastle Upon Tyne, UK: PhD thesis. Univ. of Newcastle Upon Tyne, 1993.

5. AB. GHANI, A., & AZAMATHULLA, H. *Gene-Expression Programming for Sediment Transport in Sewer Pipe Systems*. *Journal of Pipeline Systems Engineering and Practice*, 2 (3), pp.102–106, 2011.

6. AZAMATHULLA, H., AB. GHANI, A., & FEI, S. *ANFIS-based approach for predicting sediment transport in clean sewer*. *Applied Soft Computing*, 12 (3), pp.1227–1230, 2012.

7. BSI. BS EN 752:08 – *Drain and sewer systems outside buildings*. British Standards Institution. UK, 2013.

8. CAMP, T. *Design of Sewers to Facilitate Flow*. *Sewage Works Journal*, 18 (1), pp.3-16, 1946.

9. COELHO, F. M. *Coletor Sanitário: Nova Metodologia de Dimensionamento de Coletores de Esgoto*. São Paulo: Editora Dialética, 332p, 2022.

10. COELHO, F. M., & AZEVEDO, J. P. S. de. *Design Criteria for Roughness Values under Real Sewer System Operating Conditions*. *Journal of Pipeline Systems Engineering and Practice*, 13 (3), https://doi.org/10.1061/(ASCE)PS.1949-1204.0000654, 2022.

11. EBTEHAJ, I., & BONAKDARI, H. *Evaluation of Sediment Transport in Sewer using Artificial Neural Network*. *Eng. Applic. of Comput. Fluid Mechanics*, 7 (3), pp.382–392, 2013.

12. EBTEHAJ, I., BONAKDARI, H., & SHARIFI, A. *Bed Load Sediment Transport in Sewers at Limit of Deposition*. *Scientia Iranica, Transactions A: Civil Engineering*, 23 (3), pp.907-917, 2016.

13. GAY, J., PRUS-CHACINSKI, M., NOVAK, P., & NALLURI, C. *Discussion of Sewer design for no- sediment deposition*. *Proc. of the Institution of Civil Engineers*, 67-Part2(1), pp.251-252, 1979.

14. GEPSOFT. *GeneXproTools*. https://genexprotools.com, 2024.

15. GUIMARÃES, C. *Critérios Convencionais de Projetos*. CC. 2/75: *Redes de Esgotos Sanitários*. CETESB/ABES/BNH, 1975.

16. MAY, R. *Sediment transport in pipes and sewers with deposited beds*. UK: Report SR320. HR Wallingford Limited, 1993.

17. MONTES, C., BERARDI, L., KAPELAN, Z., & SALDARRIAGA, J. *Predicting bedload sediment transport of noncohesive material in sewer pipes using evolutionary polynomial regression – multi- objective genetic algorithm strategy*. *Urban Water Journal*, 2020.

18. SAFARI, M. J., AKSOY, H., UNAL, N. E., & MOHAMMADI, M. *Non-deposition self-cleansing design criteria for drainage systems*. *Journal of Hydro-environment Research*, 14 (1), pp. 76-84, 2017.

19. SAFARI, M. J., MOHAMMADI, M., & AB. GHANI, A. *Experimental Studies of Self-Cleansing Drainage System Design: A Review*. *Journal of Pipeline Systems Engineering and Practice*, 9 (4), 2018.

20. SAFARI, M. J., MOHAMMADI, M., GILANIZADEHDIZA J, G., & SEYYEDI, H. *A General Self-Cleansing Model for Drainage System Design*. Pipelines 2017. Phoenix, USA, 2017.

21. VONGVISESSOMJAI, N., TINGSANCHALI, T., & BABEL, M. S. *Non-deposition design criteria for sewers with part full flow*. *Urban Water Journal*, 7 (1), pp.61-77, 2010.