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## **Hydraulic performance degradation of a conduit section : case study of an ageing drainage system in Montreal**

Dégradation de la performance hydraulique d'un tronçon d'égout pluvial : Etude de cas dans un réseau à Montreal

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### **RESUME**

Le présent article propose un modèle théorique d'évaluation de la performance hydraulique d'un tronçon d'égout pluvial dont les paramètres hydrauliques se dégradent principalement par vieillissement. Il a été appliqué à une étude de cas à l'Île-des-Sœurs dans l'arrondissement de Verdun sur la rive sud dans la ville de Montréal. La section de la conduite en béton armé étudiée a été sélectionnée à cause des problèmes rapportés de débordement. La zone critique a été identifiée dans l'enveloppe des courbes représentant la variation de l'indicateur de surcharge, en fonction des paramètres hydrauliques tels que la rugosité et le rayon hydraulique. Des recherches continuent pour développer des courbes de dégradation temporelle des paramètres hydrauliques qui soient représentatives de la région de Montréal.

### **ABSTRACT**

The present paper proposes a model for estimating the hydraulic degradation of hydraulic parameters (roughness, hydraulic radius ...) induced by random and temporal factors. After analyzing these degradation parameters, the surcharge indicator was then analysed. The proposed model was applied to a case study on Nuns' Island in the Borough of Verdun, Montreal where a few flood problems have been reported in the last five years. A study involving a few specific drainage systems in the Montreal region is still needed to develop the hydraulic degradation curves that will be more representative of that region. Such curves will be helpful either in planning of interventions or in optimizing video inspections so that informed decisions can be made about conduits rehabilitation or replacement.

### **KEYWORDS**

Degradation, drainage system, hydraulic capacity, hydraulic performance, surcharge indicator.

## INTRODUCTION

An increase of drainage systems malfunctions and failures have been observed in Quebec for the last ten years. They are mostly characterized by the flooding of basements and roadways. The reasons for these malfunctions are multiple and complex: extremely heavy rainstorms, which have been occurring with greater frequency in the last 30 years, changes in the stormwater runoff coefficient due to the modification of the surface nature or simply the hydraulic performance decrease due to an ageing infrastructure. A recent study conducted in a region south-west of Montreal showed that the design rainfall is exceeded much more times than expected, putting the drainage system at a real flooding risk because of the decrease of the drainage systems' hydraulic performance (HP) (Daynou and Fuamba 2007). To date, the only way to detect this decrease has been costly video inspections carried out regularly by municipal authorities. Even though these inspections are a pertinent information tool for decision makers for cleaning, rehabilitating or replacing the drainage systems' conduits, their prohibitively high cost means the inspections are not always part of municipalities' annual budgets. Now, however, the strong possibility exists of developing a mathematical tool to assess the HP of the drainage systems' conduit sections, constituting a feasible and complementary approach accessible to municipal decision makers. Such a tool can be helpful either in planning of interventions or in optimizing video inspections so that informed decisions can be made about the cleaning, rehabilitation or replacement of these conduits. The present paper proposes this kind of mathematical tool for estimating the HP degradation of hydraulic parameters induced by temporal and random factors such as roughness and hydraulic radius.

## 1 STATE OF THE ART

Globally speaking, there are two types of sewer degradation: structural and hydraulic. The first type involves the structural state of the conduit (quality of materials, number of cracks and so on). Hydraulic degradation implies the breakdown of hydraulic parameters such as friction, hydraulic radius and conduit slope; this kind of degradation of an ageing drainage system becomes apparent when the conduits' hydraulic characteristics start decreasing. The resulting loss can be expressed by the gap between the current (now) and the initial (design) states of a sewer: the greater the gap, the higher the risk of conduit dysfunction. A correlation can be made between the two types of sewer degradation: the hydraulic capacity (HC) of the conduit section diminishes with the decrease of its structural state.

A few research studies have been conducted in the last decade about the structural degradation of conduits. Different predictive statistical and probabilistic models were developed as part of these studies in order to predict the conduit characteristics which vary over time. The objective of these studies was to plan future rehabilitation or replacement (Micevski *et al.* 2003, Baur et Herz 2002, Fenner 2000, Mailhot *et al.* 2000, Adam and Papa 2000 and Rotsum *et al.* 1999). The resulting and generally accepted approach to assessing the conduits' HP is to consider a global performance indicator which involves structural, hydraulic and environmental states (CERIU 2005, Bengassem 2001, and Deveau 2001). This indicator is selected on an arbitrary scale which varies between the full performance (indicator number 3) and the poor performance states (indicator number 0) of the conduits.

Hydraulic simulation of a drainage system may also be used to evaluate the HP of a few conduits. Bengassem (2001) uses the XP-SWMM model to analyze the HP of a typical drainage system in a region north of Montreal. By simulating a conduit located downstream of the system and at the same time reducing its diameter value, the HP of the conduits located upstream in terms of water levels in manholes and the number

of surcharged conduits can be estimated. The drawback to the XP-SWMM model is that this approach rapidly becomes tedious, especially with an enormous number of surcharged conduits. It is also difficult to assign a surcharging responsibility to conduits because the real dysfunctional situation of the surcharged conduits can be masked. Analyzing the effects of low design conditions (specially on designed diameter) on a drainage system is easier because “surcharged conduits” can be localized exactly and analyzed for rehabilitation or replacement according to the degree of damage. This paper suggests an innovative analysis which relies on the prediction of the conduits’ hydraulic behaviour (degradation) by ageing since parameters from random phenomena are difficult to predict.

## **2 DEVELOPMENT OF THE MATHEMATICAL MODEL OF THE HP DEGRADATION**

The objective of the present study is to propose a dynamic model useful for making a prediction analysis on the HP degradation of the drainage system conduits. The model has three sections: input data section, calculations section and output results section. Input data to the model are hydraulic parameters. These parameters are of two types: the first type is formed by parameters describing the systems’ initial conditions related to the reference time ( $t_0$ ) and the second one by those describing the systems’ current modified conditions related to the actual time ( $t_a$ ). An algorithm based on Manning’s equation performs the prediction calculations. As output from the model, the extent of the conduit HP degradation will be provided in terms of indicator which is described in the following sections.

When the drainage systems’ HP deteriorates, the following hydraulic parameters are affected: hydraulic radius, roughness, conduit slope and discharge. An analysis of different factors affecting these hydraulic parameters reveals that factors are either temporal or random.

### **2.1 Temporal Factors**

A real correlation exists between these factors and the age and the surrounding environment (the catchment area morphology and geology) where the drainage system is located. Erosive wear and sedimentation are main examples of temporal factors. The erosion affects the Manning coefficient by increasing the roughness because fine particles are continuously being pulled out, thereby increasing the visibility of rough particles. Sediment particles from the catchment area’s continuous erosion will considerably reduce the hydraulic radius by decreasing the conduit diameter. Sedimentation transport will also affect the conduit’s slope when the deposit is not uniform. This is why municipal authorities need to plan periodical cleaning programs depending, of course, on their budget. Friction factor or roughness is one of the hydraulic parameters to be estimated in the design phase. Existing references show four friction states from perfect to poor (perfect, good, good enough, and poor) without mentioning the influence of age (Carlier 1986). However, this roughness value changes, usually increasing, because of both the ageing of the conduit material, which causes the erosion of fine particles, and some unexpected deformations of conduits caused by their ageing.

### **2.2 Random Factors**

These factors are non predictable, appearing anytime and affecting both the conduit structure and functionality. They may be generated by static loadings or chemical and human activities. Considerable static loadings on the top of conduits may, depending on the conduit type, cause cracking, fracturing, elongation, etc. A chemical effluent can aggressively accelerate the degradation of the conduits’ walls. During road or emergency response work, accidental human activities (i.e. the use of power shovels)

may damage the conduits' structures; thereby influencing the systems' HP. Construction work-sites beside road drains may also generate significant sediment transport towards the drainage system and reduce the conduits' diameters. Random factors cannot be modelled, but the HP degradation model will take into account the impact of random factors only when the latter can be quantified.

### 2.3 Formulation of the HP Degradation

The Manning equation (Eq. 1) is widely used for open channel flow, and considerable information is available on the selection of the Manning roughness coefficient ( $n$ ) values:

$$Q_{\max_0} = \frac{4\pi}{n_0} (Rh_0)^{8/3} S_0^{1/2} \quad 1$$

where  $Rh$  is the hydraulic radius and  $S$  the conduit longitudinal slope. The subscript 0 expresses the conduit reference (or design) state.

According to literature on this subject, circular cross sections are able to handle maximum discharges once the water depth reaches approximately 94 % of the diameter of a typical conduit (Brière 2000). But when the roughness coefficient is considered variable with the water depth in the conduit, Chow (1959) showed that the maximum discharge can be observed at 97% of the diameter which is the same as full flow into the conduit. It is this case which is considered in the present study.

One knows that the conduit properties deteriorate due to temporal and random factors. Therefore, the Manning equation for the damaged conduit can be expressed as Eq. 2:

$$Q_{\max_d} = \frac{4\pi}{n_d} Rh_d^{8/3} \cdot S_d^{1/2} \quad 2$$

where the subscript  $d$  expresses the conduit damaged state.

### 2.4 Identification of the surcharge indicator

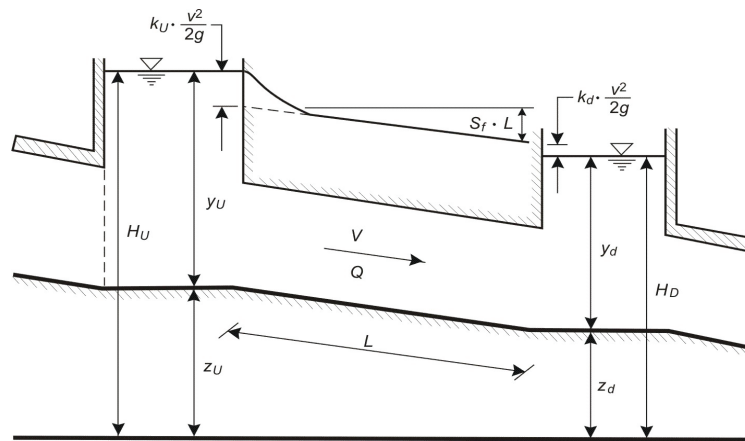


Figure 1: Full flow into a typical conduit

When the flow turns into full flow type in the typical conduit (as shown in Fig.1) because of the conduit's insufficient HC, one can estimate the extent of the pressurization stage by the calculation of friction head losses as expressed in Eq. 3.

Singular head losses due to manholes are assumed negligible for computation purposes.

$$\Delta H = \frac{f \cdot L}{128 \cdot \pi^2 \cdot g \cdot Rh_d^5} Q_{surcharge}^2 \quad 3$$

where  $f$  is the friction factor and  $L$  the conduit length.

By rewriting Eq. 1 (Manning equation) to express the conduit longitudinal slope which is equal to the conduit longitudinal head loss in uniform flows, one can obtain Eq. 4 which is expressed as:

$$S = \frac{n^2 \cdot Q^2}{16 \cdot \pi^2 \cdot Rh^{16/3}} \quad 4$$

When a flow from the open channel type turns into the full flow type for  $Q$  equals to  $Q_{surcharge}$ , the relationship between the Manning roughness coefficient  $n$  and the friction factor  $f$  (Eq. 5) can be obtained by equalizing Eqs. 3 and 4:

$$f = 197.74 \cdot Rh^{1/3} \cdot n \quad 5$$

If the reference level is the one shown in Fig. 1, and the water level in the downstream  $H_D$  and the total head losses through the conduit  $\Delta H$  are both known, then the water level in the upstream manhole  $H_U$  can be determined by Eq. 6:

$$H_U = \Delta H + H_D + L \cdot S \quad 6$$

The  $H_U$  calculations have to be started at the downstream end of the drainage system where the  $H_D$  is known (i.e. the river water level) and finish at the upstream end. Once the water level in the upstream manhole is determined, the  $I_S$  surcharge indicator can be defined to estimate the extent of the pressurization stage in comparison to the conduit land burial depth  $H_{LB}$ .  $I_S$  is therefore expressed by the ratio between the pressurization depth  $H_U$  and the conduit land burial depth  $H_{LB}$ . The latter is defined as the depth between the conduit crown and the soil surface. For the last conduit located at the downstream end of the drainage system where  $H_D = 0$ ,  $I_S$  can be expressed by Eq. 7:

$$I_S = \frac{H_U}{H_{LB} + L \cdot S} \quad 7$$

## 2.5 Dynamic Modelling of the Hydraulic Parameters

The main objective at this stage is to develop a statistical model of the temporal variation of the three hydraulic parameters: friction, hydraulic radius and sewer slope. A few of Montreal's ageing drainage systems have been selected according to both the range of construction dates (before 1965) and the sections that are dysfunctional. These investigations are continuing for now.

## 3 A CASE STUDY

### 3.1 Description of the selected conduit section

One concrete conduit section has been chosen in the drainage system of Nuns' Island in the Borough of Verdun in south-east Montreal. The section had been reported "flooded" a couple of times according to the municipal managers in charge of this drainage system. 117.5 m. in length, it presents a concrete circular cross section of initial diameter of 1.650 m and a slope of 0.003 m/m. Its land burial depth up to the crown is 1.85 m. A series of visits to the selected conduit section were made to

determine the conduit's state of degradation. The conduit's internal walls were inspected from the manholes, deposited sediments measured and a sample picked up to be analysed in the Polytechnique materials laboratory. Observations indicated severe degradation of the conduit's internal walls. Observations from video inspections and photo series did not reveal any water infiltration and seepage losses; therefore, these two discharges were not considered. After the Chow study (1988), the damaged Verdun conduit section was given the worst value of the  $n$  coefficient of 0.02, which identifies a channel with a concrete invert and mortar wall. More investigations on velocity are needed to accurately estimate the current value of  $n$ . The value of 0.013 was used for  $n$  to show the conduit section's initial state.

No cleaning program has been carried out by the municipality since the construction of that drainage system; therefore, only a self-cleaning system could explain the gradual decrease in thickness of the sediments from when the system was constructed until now. The average thickness of the observed sediments was 17 cm. The size analysis per sieving conducted in the Polytechnique laboratory showed that the sediment sample was composed of 62% fine and medium sands and 34% cohesive clays. The remaining 4% corresponds to coarse sands. The important presence of cohesive clays testifies to a real consolidation state of the material and makes difficult to use the formulae and tables found in related literature about the limit flow and sedimentation velocities. Sedimentation is assumed uniform and it has contributed to the decrease of the hydraulic radius.

### 3.2 Analysis of the Conduit Hydraulic Degradation

The main problems presented by the selected conduit section are of two types: degradation of the internal wall and sedimentation which are visible from photos and video images. All possible and relevant combinations of the degradation of the hydraulic parameters implying the pressurization of the section were identified and analysed. The identified parameters are the roughness and the hydraulic radius. This approach was performed to determine the combinations responsible for inducing the extreme degradation stages which have been causing road flooding scenarios. The surcharge indicator  $I_s$  has been analysed in accordance with the roughness and the hydraulic changes. Table 1 shows how the surcharge indicator  $I_s$  values are changing with  $n$  and  $Rh$  whose extreme limits are critical cases causing flooding scenarios.

Table 1: Extreme values of the  $I_s$  surcharge indicator

$Rh$ (m)	$n = 0.013$	$n = 0.014$	$n = 0.015$	$n = 0.016$	$n = 0.017$	$n = 0.018$	$n = 0.019$	$n = 0.020$
0.41	0.19	0.19	0.20	0.21	0.22	0.23	0.25	0.27
0.40	0.19	0.20	0.21	0.22	0.24	0.26	0.28	0.31
0.39	0.20	0.21	0.22	0.24	0.26	0.29	0.32	0.35
0.38	0.21	0.22	0.24	0.26	0.29	0.33	0.36	0.41
0.37	0.22	0.24	0.27	0.30	0.33	0.38	0.42	0.48
0.36	0.24	0.27	0.30	0.34	0.39	0.44	0.50	0.56
0.35	0.27	0.30	0.35	0.40	0.46	0.52	0.59	0.67
0.34	0.30	0.35	0.41	0.47	0.54	0.62	0.71	0.81
0.33	0.35	0.41	0.49	0.57	0.65	0.75	0.86	0.98
0.32	0.42	0.50	0.59	0.69	0.80	0.92	1.05	1.20
0.31	0.51	0.60	0.71	0.84	0.98	1.13	1.29	1.47
0.30	0.62	0.74	0.88	1.03	1.20	1.39	1.59	1.80
0.29	0.77	0.92	1.09	1.28	1.49	1.72	1.97	2.23
0.28	0.96	1.15	1.37	1.60	1.86	2.14	2.45	2.77
0.27	1.21	1.45	1.72	2.02	2.34	2.69	3.06	3.46

It can be observed that a diminution of the hydraulic radius due to sediment deposits increases the  $I_s$  indicator, meaning the increase of the risk to overflow the upstream manhole. This tendency is exacerbated when the conduit internal wall is seriously damaged with increased values of  $n$ . In fact, the slight diminution of 8 cm of  $Rh$  can induce the upstream manhole overflow when the  $n$  conduit section equals to 0.020. Table 1 shows the critical stairs zone delimiting values responsible for the flooding scenarios. This critical delimiting zone can be visualized as the red vertical line in Fig. 2 where the variation of the  $I_s$  indicator is represented according to  $n$  and  $Rh$ . The line indicates that flooding scenarios can be prevented with the  $I_s$  values inferior to 1. Fig. 2 can also be used to test the HP of any conduit section assuming that its damaged conditions ( $n_d$ ,  $I_d$  and  $Rh_d$ ) are known. The graphs  $n = 0.013$  and 0.020 form envelop curves to be used for the prediction of the conduit section HP.

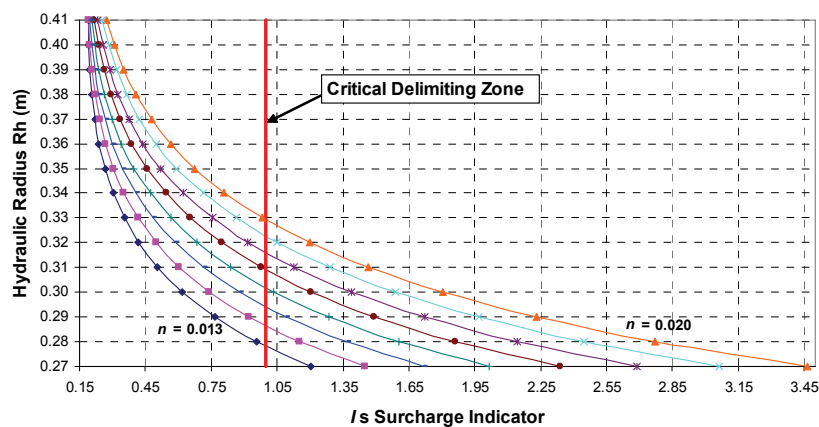


Figure 2: The  $I_s$  Surchage Indicator Graphic Representation

Regarding the current conduit state, it can be observed that the actual hydraulic radius of 0.37 m combined to  $n$  value of 0.020 gives a  $I_s$  value of 0.48 (see Table 1), meaning that the water depth at the upstream manhole cross section of the conduit is about 50% of its diameter. Table 2 shows that this level corresponds to a discharge value of 2.43 m<sup>3</sup>/s, instead of 4.99 m<sup>3</sup>/s expected at the design state.

Table 2: Discharge variation according to  $Rh_d$  and  $n_d$

$Rh$ (m)	$n = 0.013$	$n = 0.014$	$n = 0.015$	$n = 0.016$	$n = 0.017$	$n = 0.018$	$n = 0.019$	$n = 0.020$
0.41	4.99	4.63	4.32	4.05	3.82	3.60	3.41	3.24
0.40	4.60	4.27	3.98	3.73	3.52	3.32	3.15	2.99
0.39	4.30	3.99	3.72	3.49	3.29	3.10	2.94	2.79
0.38	4.01	3.72	3.47	3.26	3.07	2.90	2.74	2.61
0.37	3.73	3.47	3.24	3.03	2.86	2.70	2.55	2.43

#### 4 CONCLUSION AND RECOMMENDATIONS

A model able to predict the hydraulic degradation of a conduit section has just been proposed. It combines the conduit hydraulic parameters, i.e. hydraulic radius, slope and roughness, for the purpose of determining critical combinations which could surcharge the conduit section. The surcharge indicator has been identified to assess the conduit section HP. By taking into account the design and current conduit hydraulic parameters, the proposed model enables the evaluation of the conduit section HP by providing the indicator curves envelop. The proposed model was in fact



applied to a study case on Nuns' Island in the Borough of Verdun, Montreal where a few flood problems have been reported in the last five years. Investigations into the selected conduit section indicated sediment deposits and important degradation of the conduit's internal walls. The  $I_s$  surcharge indicator was then investigated. The model provided both the indicator  $I_s$  curves envelop and the critical delimiting zone, vital information to engineers aware of the drainage system surcharge. A study involving a few specific drainage systems in the Montreal region is still needed to develop the hydraulic degradation curves that are time and material dependent.

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