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Computing Natural Gas Losses From Damaged Pipelines Using Analytical Discharge Equations and Network Modeling Software

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ABSTRACT

Assessing the discharged volume during third party digging damages with efficiency and acceptable accuracy is a challenge for multiple reasons. It involves complex physics phenomena, requires taking the right assumptions and has to be performed relatively quickly as the number of cases to compute each year is important. This paper summarizes the application of a comprehensive methodology used to perform this task.

The first part deals with the required field measurements needed to be obtained, the selection of an adequate physics equation as a function of the flow regime and the linkage between an analytical equation and a commercial CFD software to obtain a valid network pressure at the damage point.

In the second section, a validation attempt between computed results and field measurements is made using two different sets of data. First, for some very specific incidents where the pipeline damage is close to a gate station with SCADA recording, it is possible to obtain an hourly flow profile at the break. Second, simple configurations of pipe rupture have been replicated in laboratory and tested with air. For most of the cases, the described methodology shows a good match with experimental data with typical discharge coefficient values in the range of 0.61 to 0.92.

INTRODUCTION AND BACKGROUND

Gaz Metro « GM » is the main natural gas distributor in the province of Quebec on the east part of Canada. The territory is connected to the TCPL Mainline (figure 1) at the very end of the transmission system.

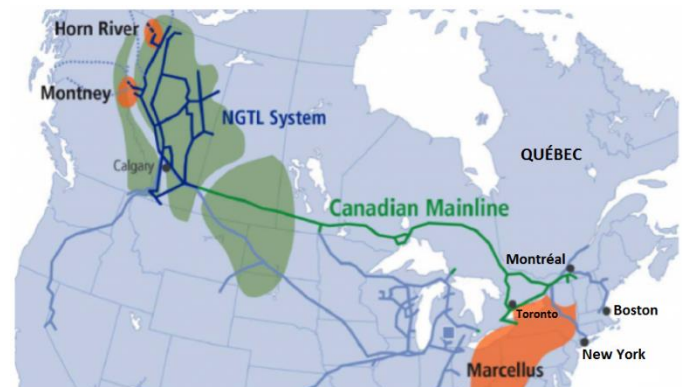


Figure 1 – TCPL NG Transmission Mainline to Quebec

GM distributes 97% of all natural gas in Quebec (figure 2) to over 200 000 customers located in more than 300 municipalities [1]. This can be achieved by an asset of 10 000 km of underground network pipeline with more than 90% being distribution mains and services, mostly small diameter plastic pipes. Along this distribution network, digging damages by third party represent by far the primary reason for unplanned emergency response and an important part of the total non-fugitive annual gas loss. Each year, 300 to 400 rupture cases are reported and analyzed.



Figure 2 – GM Natural gas system in Quebec

Historically, gas losses from third party damages have been computed for cost claims and annual balance of unaccounted volumes. However, since 2012 Quebec regulation asks the reporting of all estimated greenhouse gases “GHG”, first in an unofficial manner and lately (2015) with complete external verification as part of the cap-and-trade carbon market [2]. This new regulation has triggered the need to revise and adapt the methodology, documentation and record keeping used in any gas loss declaration. In addition to accurate numbers, the whole process and data have to be well documented and readily available in such a way that non-scientific staffs can understand and verify it during internal and external audits.

This paper is the result of the work performed during the past four years, which is mostly based on the different versions of the CEPEI Methodology Manual [2]. However, the approach has to be refined and adapted to the reality of the GM distribution system. For obvious reasons, it is desirable to obtain a more realistic flow rate, which can be noticeably smaller than the one predicted by theoretical equations.

Also, potentially the only weakness of the Methodology Manual [2] is the lack of experimental validation and field verification. For unknown reasons, few documented literature data on this topic are available. The validation section of this paper tries to fill a little this gap by comparing two types of data with the values computed by the analytical method.

As will be discussed in the next sections, a critical parameter in the overall methodology is the pressure inside the pipe at the damage point. Reference [2] summarizes the possible ways this can be obtained without giving any details on how this should be calculated.

It is important to understand that for low pressure distribution systems, the flow resulting from the damaged pipe directly affect the pressure in the vicinity of the break. As pressure in the system decreases, the flow at the break drops quickly until a steady state is reached. Regardless which analytical discharged equation is chosen, the results may differ significantly for small variations in the assumed pressure. For incidents that last multiple hours, the impact of the pressure on

the total discharged volume is even greater.

In most cases, a commercial CFD software can be used to obtain the pressure profile around the break. However, extra care has to be taken since those software are primarily design to compute steady-state pressure drop inside pipes with velocity well below sonic conditions. As it may be correct to assume sub-sonic flow on small diameter and long service lines, there are many cases where this assumption will be invalid. For main lines close to a gate station with service lines damaged in the first few meters, the probabilities that flow will reach sonic velocity are high.

GM uses Synergi Gas as the main CFD modeling software since the last 20 years. Born out of the efforts of Dr. Stoner, it is a leading network analysis program for natural gas pipelines, distribution networks, and gas gathering fields since the 1970’s. The proposed methodology for computing gas losses take into account the specific characteristics of this software but it is expected to be easily adaptable to other product used in the industry.

ANALYTICAL METHOD

Damages in typical distribution system may result in a fully ruptured line or in a pipe puncture. Regardless of the size of the discharge diameter « d_1 » (figure 3), the type of damage has a direct impact on the magnitude of the discharged flow. However, most break configurations can be bonded between two limiting cases. First is a free flow from a fully ruptured line where the actual and the theoretical flow rates are roughly the same ($C_d \approx 1$). Second is a very small pipe puncture ($\beta = d_1/d_2 \approx 0$) where the flow is governed by the orifices and nozzles theory with the discharge coefficient heading to a limit value ($C_d \approx 0.6$).

Also, depending on the upstream conditions, both types of pipe damage may develop in either sonic or sub-sonic flow. Because discharged flow and system pressure are closely related, in most cases it is not possible to predict if sonic condition is reached or not. A first assumption has to be made and corrected later if system pressure drops below the limit value for sonic flow.

As for the physic of the discharge, free flow of fluid over a reasonably short distance may be considered isentropic because there is little heat transfer and friction effects are small [3]. The isentropic assumption can be applied to both sonic and sub-sonic cases.

The isentropic assumption yields to the two main equations (1) and (2) from reference [2]. However, both have been modified to include the discharge coefficient « C_d ». The C_d empirical parameter is defined in [4] as the ratio of the measured flow rate over the theoretical maximum flow rate. For a pipe puncture, C_d is expected to be less than 1 as the available area

of free flow will contract at the damage point. On the other hands, for a fully ruptured line the vena contracta area at the break is likely to be very similar to the pipe inside area. This will lead to an actual flow rate very close to the theoretical maximum flow rate and therefore $C_d \approx 1$.

Also, even if pressure levels on distribution systems are normally low (< 690 kPa or 100 psig), the compressibility factor « Z » can be easily added into (1) and (2) to broader the range of application to non-ideal gas scenarios. In this work, the Brill and Beggs [5] correlation has been used for that purpose.

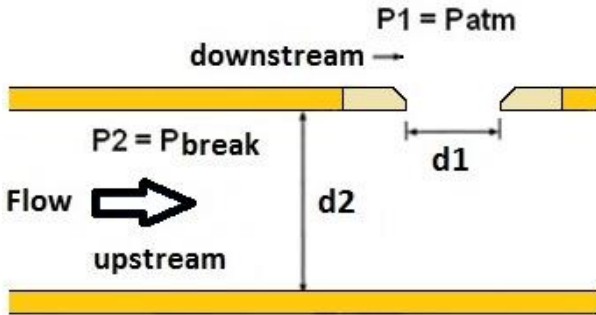


Figure 3 – Simplified break layout

For choked condition ($M = 1$), the mass flow rate in kg/s is:

$$\dot{m} = C_d * A_1 * P_2 \sqrt{\left(\frac{k * M_w}{Z_2 * R * T_2}\right)} * \frac{M}{\left(1 + \frac{k-1}{2} * M^2\right)^{\frac{k+1}{2 * (k-1)}}} \quad (1)$$

For sub-sonic condition ($M < 1$), the mass flow rate in kg/s is:

$$\dot{m} = C_d * A_1 * P_2 \sqrt{2 \left(\frac{k}{k-1}\right) \left(\frac{M_w}{Z_2 * R * T_2}\right) \left[\left(\frac{P_1}{P_2}\right)^{\frac{2}{k}} - \left(\frac{P_1}{P_2}\right)^{\frac{k+1}{k}}\right]} \quad (2)$$

where the Mach number « M » is defined as :

$$M = \sqrt{2 \left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] / (k-1)} \quad (3)$$

SOFTWARE COUPLING

With the CFD software, one way to simulate a line break is to add a valve component into the distribution system model where the damage has been reported. Exact field measurement to a reference point is required after the break has been secured.

A valve instead of a pipe component has to be used because sonic condition is not tested in a pipe. As a result, velocity from large pressure drop may exceed the speed of sound in a pipe which is not possible. On the other hand, for valve facilities, depending on the value of the Mach number the

software will automatically choose between the sonic (4) and the sub-sonic (5) equation to compute the volumetric hourly flow rate « Q »:

$$Q = \frac{12 * C_g * P_2}{24} = \frac{C_g * P_2}{2} \quad (4)$$

$$Q = C_g * \sqrt{(P_2 - P_1) * P_1} \quad (5)$$

However, for discharge analysis the use of a valve component alone is useless because it is not possible to relate the C_g empirical parameter to the break characteristics. This is where equation (1) or (2) has to be brought in. For a sonic break, after re-arranging equation (1) on a volumetric hourly flow rate (m^3/h), the right-hand side can be equalized with the one of equation (4). When the C_g parameter is isolated (6), the break pressure « P_2 » on both side vanish and this gives a direct relationship between the break diameter d_1 and the valve coefficient C_g [6]. It is now possible to set-up a hydraulic model with this specific valve and obtain the pressure level at the break. Using this pressure P_2 with either equation (1) or (4), the exact same Q is obtained.

$$C_g = \frac{\pi * 3600}{2 * \rho_1} C_d d_1^2 \sqrt{\left(\frac{k * M_w}{Z_2 * R * T_2}\right)} \frac{M}{\left(1 + \frac{k-1}{2} * M^2\right)^{\frac{k+1}{2 * (k-1)}}} \quad (6)$$

The method required more steps when the break is supposed sub-sonic because P_2 doesn't vanish when equations (2) and (5) are equalized. An iterative approach has to be used. With a first estimate of P_2 , the C_g is obtained with equation (7). The CFD software computes a new value of P_2 which can be used to refine the estimate of C_g . When previous and new values of C_g or P_2 do not change by a great amount, the final discharged flow rate is obtained. This is normally achieved very quickly by only few iterations.

$$C_g = \frac{3600 * \pi}{4 * \rho_1} C_d d_1^2 P_2 \sqrt{\frac{\left(\frac{2 * M_w}{Z_2 * R * T_2}\right) \left(\frac{k}{k-1}\right) \left[\left(\frac{P_1}{P_2}\right)^{\frac{2}{k}} - \left(\frac{P_1}{P_2}\right)^{\frac{k+1}{k}}\right]}{\sqrt{(P_2 - P_1) * P_1}}} \quad (7)$$

The main advantage of this method is the possibility to use any analytical equation with the CFD software. The discharged flow is based on the chosen physics equation not on any hard coded values. The software computes only the network pressure based on the same hydraulic model used for design and planning. This gives a very accurate estimate of the pressure and reduces the discharged flow compared to the case where the system pressure has been fixed to an arbitrary maximum value.

VALIDATION

CASE 1: SCADA DATA

1.1 Damage at Berthier gate station

The first set of data is the result of a real third party digging incident during the summer of 2016 on GM distribution system. This case produces interesting data because the damage point is located nearby a city gate station where multiple scada parameters are recorded. The summer period is also an ideal time of the year because flows are low and more stables since air conditioning in Quebec is produced mostly by electricity.

The incident involved a fully ruptured 6'' PE pipe fed by one side at a nominal pressure of 400 kPa (58 psig). As can be seen on figure 4, rupture occur around 6:00 am and the rapid increase of flow causes the outlet pressure to decrease around 300 kPa. The normal maximum flow at this station is usually small and the gas regulators and the boiler are not sized for this added flow. For the same reason, gas temperature at the outlet of the station drops sharply to -5.9°C and return to normal only after the break has been secured around 11:25 am.

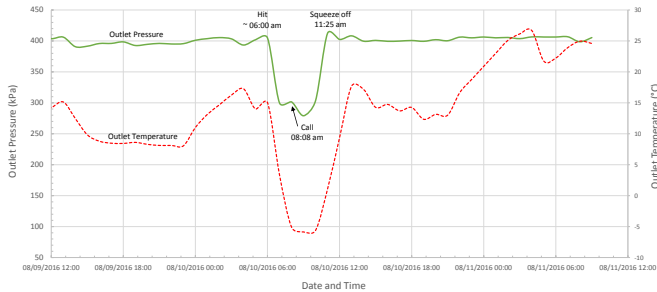


Figure 4 – Case 1.1 Event sequences

The value of the steady state flow at the damage point is estimated using figure 5 from the difference between the lowest value at 6:00 and the maximum steady flow between 8:00 and 10:00 am. Based on these values, flow at the rupture is around 5500 m³/h.

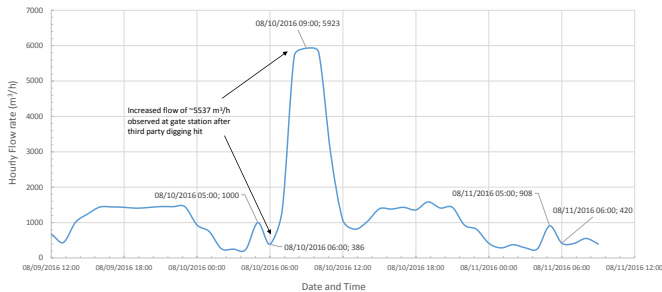


Figure 5 – Case 1.1 SCADA flow at gate station

This case has been reproduced with the CFD software based on pipe configuration from the GIS system. From figure 6, the color blue stands for 6'' and red for 4'' PE pipes. The total length from the gate station to the damage point is about 550 m.



Figure 6 – Case 1.1 CFD line break simulation

The large flow from the 6'' PE (158,7 mm inside diameter) ruptured pipe causes the pressure to drop quickly downstream of the gate station. In the vicinity of the break, pressure is well below 90 kPa. Therefore, the flow is assumed sub-sonic and equation (7) can be used with C_d equal to 1 (fully ruptured pipe with d₁=d₂ and β = 1).

Withing 3 iterations, the valve coefficient C_g converge to 292 m³/h / kPa at a break pressure of 4.1 kPa. Under these conditions, the computed discharged flow is 5976 m³/h.

1.2: Damage at Beauharnois gate station

The second set of data is also related to a third party digging incident, this time during the spring of 2014. The damage point is located at around 6 km of a city gate station where multiple scada parameters are recorded.

The nominal outlet pressure of this gate station is 1200 kPa (174 psig). The flow goes first into a 10'' steel pipe for 3.5 km and then into a regulating station where pressure is reduced to 400 kPa. This regulating station has ample capacity to maintain the nominal pressure of 400 kPa during the break, even if upstream pressure has decreased slightly to 1150 kPa. From this station to the damage point, the distribution network is built from sections of 8'' steel pipe (1.4 km), 6'' PE pipe (1.0 km) and 4'' PE pipe (0.1 km)

The fully ruptured pipe is a 4'' PE (93,5 mm inside diameter) fed by one side. The damage occurs around 13:00 with a very fast increase of flow measured at the gate station. As can be seen on figure 7, the outlet temperature drops to -0.8°C and returns to normal after the break has been secured around 17:17.

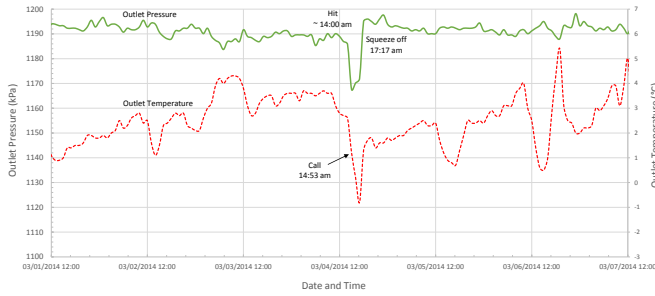


Figure 7 – Case 1.2 Event sequences

Using figure 8, the steady state flow at the break is estimated from the difference between the lowest value at 13:00 and the maximum steady flow at 16:00. Based on these values, flow at the break is estimated to be around 7000 m³/h.

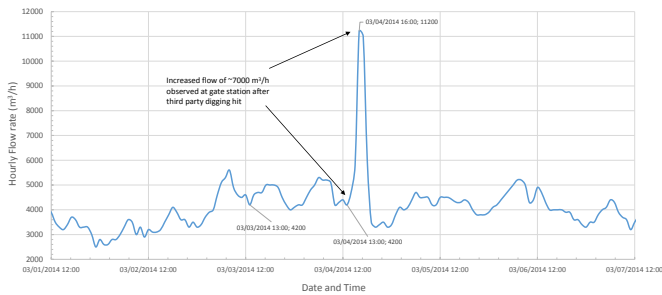


Figure 8 – Case 1.2 SCADA flow at gate station

From figure 9, the color brown stands for 8” steel, blue is for 6” PE and red for 4” PE. The total length from the regulating station to the damage point is close to 2.5 km.

The flow from the 4” ruptured pipe causes the pressure to drop quickly in the vicinity of the break to less than 90 kPa. Therefore, the flow is sub-sonic and equation (7) is used with C_d equal to 1 (fully ruptured pipe).

Withing 3 iterations, the valve coefficient C_g converge to 132 m³/h / kPa at a break pressure of 33.8 kPa. Under these conditions, the computed discharged flow is 7701 m³/h.

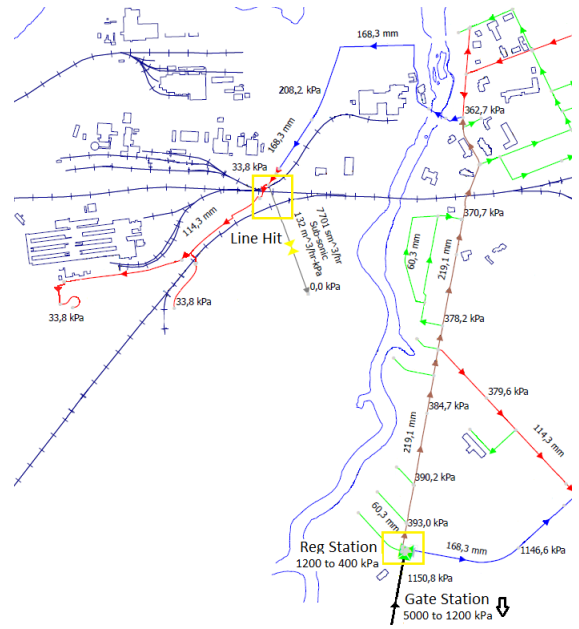


Figure 9 – Case 1.2 CFD line break simulation

CASE 2: EXPERIMENTAL TESTING

As mentioned before, pipe punctures represent a significant part in the total reported third party dig-in incident. This type of rupture generally produces smaller flows that are more difficult to isolate from normal variations recorded by the Scada system. For that reason, a small scale experimental set-up as been made to measure the flow under realistic network conditions as described on figure 10.

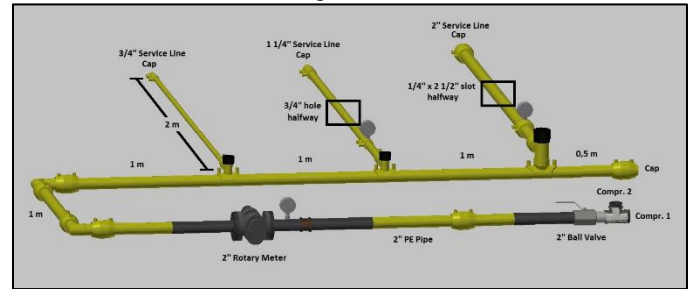


Figure 10 – Experimental setup

The inlet ball valve is connected to two air compressors that are switched on or off to obtain multiple data points. A 2” Romet R-55 rotary meter has been used to measure the uncorrected flow. This flow was later corrected based on the pressure read on the transmitter mounted at the inlet of the meter. The main U shape is made of fused 2” PE pipes where 1 1/4” and 2” service lines have been tied-in one after the other. Both of these service lines are capped at the end.

As can be seen on figure 11, a circular hole of 20.5 mm has been drilled halfway along the 1 1/4” service line. In the case of the 2” service line, a rectangular opening of 60.0 mm by

6.5 mm has also been cut halfway. The corresponding hydraulic diameter of the rectangular opening is 22.3 mm. Both opening surfaces are similar but with very different shapes. Finally, a pressure transmitter has been installed on both service lines at 0.5 m from the main pipe

Note that each service lines has been tested individually not simultaneous. Results from this experiment are presented in the next section.

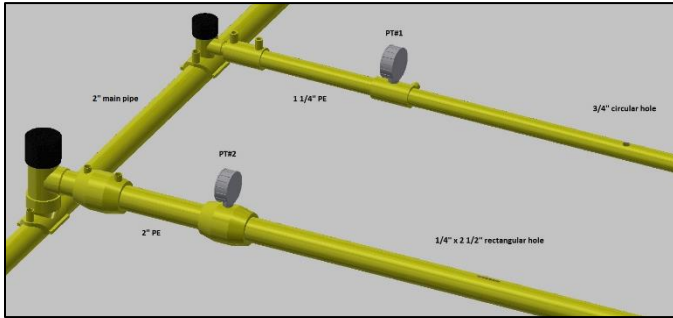


Figure 11 – Damages close-up

RESULTS AND DISCUSSION

The results obtained for cases 1.1 and 1.2 are summarized in table 1. Both are typical examples of fully ruptured main line from excavating without proper locate documents. Based on these results, two important observations can be made.

Table 1: Results for SCADA data with fully ruptured line

Config (-)	P break ⁽¹⁾ (kPa)	Qexp ⁽²⁾ (m ³ /h)	Qmax ⁽³⁾ (m ³ /h)	C _d ⁽⁴⁾ (-)
1.1	4,1	5500	5976	0,92
1.2	33.8	7000	7701	0,91

Notes for table 1:

(1) Computed by CFD, (2) From Scada, (3) Computed with C_d=1 in eq#5 and CFD, (4) Qexp / Qmax

First is that even for fully ruptured main line very close to a gate station, the flow regime is very likely to be sub-sonic. In both cases, pressure calculated at the break by CFD is well below 90 kPa. This increases the importance to model sub-sonic flow adequately by using the more complex equations (2) and (7).

Second, by using the CFD software and equation (7), the resulting theoretical maximum flow rates (C_d=1) are very close to what has been observed on the Scada system. By doing the ratio of the actual and maximum flow rates, an averaged theoretical C_d value of 0,915 is obtained. This confirms the initial hypothesis that for fully ruptured pipe, the

C_d value should be close to 1. More results need to be analyzed to confirm that a C_d value closer to 0.915 rather than 1 should be used. Even if the difference seems small, using a C_d of 1 in both cases overpredict the discharged volumes by 8 to 9% with direct impact on the annual GHG reporting.

The next groups of results (tables 2 and 3) have been produced by the experimental set-up described in the previous section. The objective was mainly to study the common situation where the flow is discharged from a pipe puncture. Again, all cases are in the sub-sonic category.

Based on these results, the discharge coefficient seems influenced a little by the velocity of approach and far more by the β ratio. With the 1 1/4" service line, when flow increases by 37% on average by putting the second compressor online, C_d rises only by 0,03 on average. The variation for the 2" service line is even smaller (0.02) for more than 50% flow increase.

The trend for the variation of C_d with the β ratio is more direct.

For low values of β (smaller pipe punctures), C_d is going down to the traditional accepted value of 0.61. On the other hand, when β is increased, break configuration will look more like a fully ruptured pipe with a C_d moving up to 1. This is observed on tables 2 and 3 when the calculated C_d are moving up (0.63 to 0.76 on average) when β is increased from 0.44 to 0.65.

Unfortunately, it is not possible to assess if the opening geometry (circle or rectangle) also influences the variation of C_d since both cases involve different β ratio.

Table 2: Results for 1 1/4" line with circular hole (β=0.65)

Config (-)	Compr ⁽¹⁾ (#)	PT ⁽²⁾ (kPa)	Qexp ⁽³⁾ (m ³ /h)	Qmax ⁽⁴⁾ (m ³ /h)	C _d ⁽⁵⁾ (-)
2.1.1	1	7.7	237	318	0.74
2.1.1	1	7.7	242	318	0.76
2.1.1	1	7.7	232	318	0.73
2.1.2	2	13.2	323	419	0.77
2.1.2	2	12.9	319	414	0.77
2.1.2	2	12.8	330	412	0.80

Table 3: Results for 2" line with rectangular hole (β=0.44)

Config (-)	Compr ⁽¹⁾ (#)	PT ⁽²⁾ (kPa)	Qexp ⁽³⁾ (m ³ /h)	Qmax ⁽⁴⁾ (m ³ /h)	C _d ⁽⁵⁾ (-)
2.2.1	1	2.5	241	393	0.61
2.2.1	1	2.5	253	393	0.64
2.2.1	1	2.5	241	393	0.61
2.2.2	2	5.6	385	591	0.65

2.2.2	2	5.5	381	583	0.65
2.2.2	2	5.4	360	580	0.62

Notes for tables 2 and 3:

(1) For 1 or 2 compressors running, (2) Pressure at 0.5 m from the break, (3) Corrected flow from the meter (4) Computed with $C_d=1$ in eq#5 and CFD, (5) Q_{exp} / Q_{max}

With the very limiting data generated from cases 1.1 to 2.2, the value of the discharge coefficient seems strongly correlated to the β ratio (figure 12). This is in accordance with nozzle and orifice theory and with the more complex formula for C_d in reference [4]. This leads to an important observation, if the discharge equations from reference [2] are used as it, which mean without the introduction of the discharge coefficient, it is equivalent to the case where $C_d=1$. As shown in this paper, this may increase the discharge volumes by at least 8% for fully ruptured pipes and between 24% and 37% for pipe punctures.

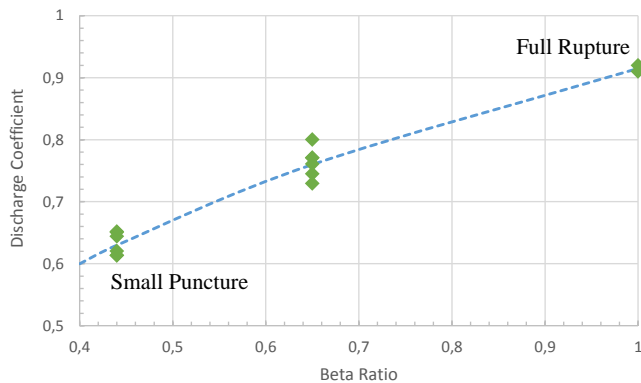


Figure 12 – Discharge coefficient as a function of the beta ratio

CONCLUSIONS

This paper summarizes a straightforward methodology to compute the steady-state discharge flow rate from damages on natural gas distribution system. This methodology is valid under sonic and sub-sonic conditions for either a fully ruptured or punctured pipe.

The use of a CFD software in combination with the adequate analytical discharge equation prove to be a very powerful tool to compute quickly and accurately the discharged volumes during a third party dig-in incident. The results presented in this paper show that in more cases, the pressure in the vicinity of the break is low. Using only a limiting value of the network pressure without the CFD software calculations, chances are high that discharged volumes will be greatly overpredicted.

In the same way, the use of the analytical equation without a correcting factor, in this case the discharge coefficient C_d , will also lead to significant overpredictions. As it may be acceptable in the cases of fully ruptured pipes (+9%), for

smaller opening damages the discrepancy between the actual and the calculated flow rates can be in the range of +37%.

In the future, additional experimental work shall be performed with more rupture configurations for both sonic and sub-sonic flow regime. This will help to better characterize the discharge flow encountered during the operation of a gas distribution pipeline. It will also improve the accuracy of the analytical equations and will lead in most cases to a decreased in computed volumes.

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NOMENCLATURE

Symbol	Definition	Units
\dot{m}	Mass flow rate at rupture	kg/s
Q	Volumetric flow rate at rupture	m^3/h
C	Flow coefficient	-
C_d	Discharge coefficient	-
A	Rupture surface	m^2
d_1	Rupture diameter	m
d_2	Pipe inside diameter	m
P_1	Atmospheric pressure	Pa
P_2	Rupture upstream pressure	Pa
k	NG specific heat ratio	-
M_w	NG molecular weight	kg/kmol
Z_2	NG compressibility factor at P_2	-
R	Universal gas constant	$Pa \cdot m^3 / kg \cdot mol \cdot K$
T_1	Rupture downstream temperature	K

T_2	Rupture upstream temperature	K
ρ_1	NG density at P_1 and T_1	kg/m^3
M	Mach number	-
β	Rupture/pipe diameter ratio d_1 / d_2	-
C_g	CFD valve constant	$(\text{m}^3/\text{h}) / \text{Pa}$

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