Proceedings of IPC 2006
International Pipeline Conference
September 25 – 29, 2006 Calgary, Alberta, Canada

IPC2006-10179

ESTABLISHING A SAFE WORKING PRESSURE DURING EXCAVATION OF A PIPELINE IN A ROCK DITCH

Samer Adeeb, David Horsley, Joe Zhou and Brad Sadoway
TransCanada Pipelines Limited, 450-1st Street S.W., Calgary, Alberta, T2P 5H1, Canada

ABSTRACT

In order to perform pipeline maintenance it is often necessary to excavate the pipeline. To ensure this is conducted safely, the expected condition of the pipeline and possible failure scenarios are considered in order to establish a safe operating pressure during the excavation and subsequent work. For pipelines that are laid in rocky terrain, consideration must be given to the possibility of a large rock impacting the pipeline. The purpose of this work is to describe the application of a numerical procedure to establish the safe working pressure during the excavation of a pipeline in a rocky terrain. A numerical procedure, developed previously [1] was shown to conservatively estimate a safe working pressure for the case of a rock falling on the pipeline. FEA was used to determine the relationship between the available kinetic energy of a falling rock and the energy to puncture the pipeline (as a function of internal pressure). The resulting puncture dimensions were then compared to the critical-crack-length to cause rupture. The safe pressure was obtained from the pressure where rupture first occurs, reduced by an appropriate safety factor. This paper describes the application of the numerical procedure described to cover a large range of pipe toughnesses and internal pressures.

Keywords: Pipeline integrity assessment, pipeline maintenance, mechanical damage, finite element analysis

INTRODUCTION

Many pipelines are used to transport pressurized flammable substances to supply the energy demand of modern society. While designers ensure that the pipeline is safe against failure due to internal pressure, statistics show that failures are often caused due to external mechanical interference. Approximately 50% of recorded pipeline failures in Europe and United States are due to third party damages [2], [3] and [4].

In an effort to understand the mechanical damage caused by a third party, researchers have studied the damage that can be caused by objects striking the pipe. Closed form solutions for the force causing puncture are established using numerical techniques [2], [5]. The energy required to puncture a pipe has also been experimentally investigated [6], [7], [8]. These efforts are directed towards finding a limit for the force and/or energy that will cause a hole or a crack in a pipe.

Third party damage can occur during regular maintenance operations. Thus, it is often necessary to reduce the internal pressure to reduce the risk of rupture due to the impact of an excavating tool. For pipelines in rocky terrain, there is a risk of a rock being dropped on the pipeline. This paper utilizes the numerical procedure established in [1] to examine the levels of pressure reduction needed to safely excavation pipes in rocky terrain. The established procedure was incorporated into software that may be used to calculate the safe dig pressure for a pipeline in rocky terrain. This paper gives an outline of the numerical procedure utilized and the resulting software.

METHODS

The assessment procedures developed in [1] requires solving two problems. The first is to determine the possibility of puncture due to a falling rock and the dimensions of the hole obtained. The second problem is determining whether the hole obtained will remain stable or will propagate in a catastrophic manner.

The amount of energy available for puncturing the pipe was estimated from discussions with field personnel on possible scenarios and rock types, shapes and sizes when handling rocks at dig sites. The overall procedure was based on assuming that the kinetic energy available of the falling rock will be totally absorbed as deformation energy of the pipe. Then, finite element analysis of pipe indentation was conducted and the deformation energy of the pipe was obtained by integrating the load-displacement curve of the indenter. In establishing the procedure in [1], two types of indenter tips were used: spherical and square. It was shown in [1] that the resulting puncture forces for the square indenter matched the results obtained by Brooker [9], and thus the procedure was verified. It was also shown that a round indenter is more likely to puncture the pipe than the square indenter whose length is equal to the diameter of the round indenter. Thus, in the current work, only the more severe round indenters were considered.

In order to assess the likelihood of catastrophic rupture initiated by the presence of the developed puncture, industry standard equations [10] were used based on the pipe dimensions, grade, toughness, and internal pressure.

Finite Element Analysis

The analysis conducted in this work was based on the estimated upper bound of a rock falling on the pipeline. A 0.5m diameter rock with a density of 2450 kg/m^3 (typical of granite) was assumed to fall from a height of 0.5m. Thus, the kinetic energy available to puncture the pipe is 12.57kJ. This kinetic energy is assumed to be totally used for the plastic deformation and the puncturing of a pipe. Finite element modeling was used to simulate a spherical indenter causing pipe indentation. As described in [1] the radius (R) of the spherical indenter took values between 50 and 100mm. The internal pressure of the pipe was varied between 0% to 70% of the internal pressure causing yield. The finite element modeling package ANSYS version 7.1, using 8-noded shell elements that support plasticity, was used to model the pipe. Due to symmetry, quarter models of the pipe and the indenter were used. The total length of the pipe analyzed was 5,000mm. The indenter was modelled with rigid elements that followed the degrees of freedom of a reference node. Symmetric boundary conditions were imposed on all edges of the quarter-model of the pipe. The bottom edge of the pipe was restrained from moving downwards simulating a rigid foundation. The reference node for the rigid indenter was restrained from moving in any direction except vertically to indent the pipe. The “geometric nonlinearities” option was chosen in ANSYS to include the rapid change in the contact area. As the model was repeated many times, a macro using the APDL ANSYS macro language was written to generate the model using the following as variables: Pipe outer diameter, pipe wall thickness, pipe internal pressure, radius of indenter, stress-strain curve. True stress-strain curves for the different pipe grades were obtained using minimum specified yield and tensile strength and a conservative estimate of uniform strain. The obtained curves were used to model the pipeline steel. Figure 1 shows the geometry and mesh of the model.

Obtaining the critical indenter size for a specified internal pressure

The load-displacement curve of the reference node of the indenter was obtained for each model. The deformation energy absorbed by the pipe was calculated by integrating the indenter force-deformation curve as described in [1]. For a certain value of the internal pressure, the indenter size was changed among four values. For each indenter size, the force causing puncture was obtained using a failure criterion, as described in [1]; when the maximum principal strain reaches 20% at any given point. As the indenter size increases, i.e. as the indenter becomes blunter, the force that is required to cause puncture increases (Figure 2)

For each indenter size, a quasi-static force versus displacement relationship was determined using FEA. The 12.57 kN of available kinetic energy is compared to the pipe deformation energy (from integrating the force-displacement curve) to determine the available quasi-static indenter force. Figure 3 shows load and energy versus displacement curves obtained for the reference node of an indenter for one size of indenter. Repeating this process for various indenter radii gives the relationship shown in Figure 4.

For any internal pressure, the available force may be compared to the force required to puncture the pipe. Figure 5 combines Figures 2 and 4 and was used to obtain the critical indenter radius for a specific pipeline pressure. The point of intersection of the two curves of Figure 2 and Figure 4 is considered a critical point (Figure 5). For indenters with larger radii, the available kinetic energy is insufficient to create enough force to puncture the pipe. The point of intersection of the two curves defines the critical indenter size with the available kinetic energy (12.57kJ) that causes puncture at the specified internal pressure.

Obtaining the relationship between the internal pressure and the critical indenter size

The whole process is repeated for different internal pressure values to obtain a curve, Figure 6, that relates the internal pressure with the critical indenter size. Figure 6 can be interpreted as follows: any point on the curve defines the bluntest indenter that can cause rupture under the specified available energy. For example, at an internal pressure of 0.4 of the pressure causing yield (P/Pyield = 0.4), any indenter with a size less than or equal to 59mm will puncture the pipe (with the given kinetic energy).

Obtaining the level of pressure reduction needed for a specified pipe

The maximum hole size that can be produced at P/Pyield = 0.4 will be related to the size of the indenter. The maximum hole or crack that is formed in the pipe due to puncture at a certain internal pressure is assumed in this work to be 90% of the diameter of the critical spherical indenter obtained from the previous analysis. The crack formed is compared with the NG-18 equation [10] that relates the internal pressure with the critical through wall crack size for a specified Charpy toughness. The safe working pressure is obtained by intersecting the mentioned two curves as shown in Figure 7.

AUTOMATING THE PROCEDURE

In order to generate Figures 2, 4 and 5, four finite element runs were conducted for a certain value of internal pressure. Those four runs were essential to generate smooth curves (Figure 5). The process was repeated for seven different values of the internal pressure, and thus there were 28 finite element runs in total to generate Figures 6 and 7 for a specified pipe diameter, wall thickness and grade. This process was repeated for the eleven different pipes shown in Table 1. The total number of finite element runs conducted to analyze the eleven pipes is 308. The resulting curves were stored and a program was written to generate curves such as Figure 7. Figure 8 shows the input needed for the program. The user has to choose the pipe from a drop down list. A value for the Charpy energy and a factor of safety are also left for the user to input. Upon execution, the program generates the NG-18 curve and the stored curve generated using the process described in the previous section. The finite element curve is shifted by the factor of safety specified as shown in Figure 9. The program calculates the intersection of the two curves and generates the acceptable dig pressure (Figure 9).

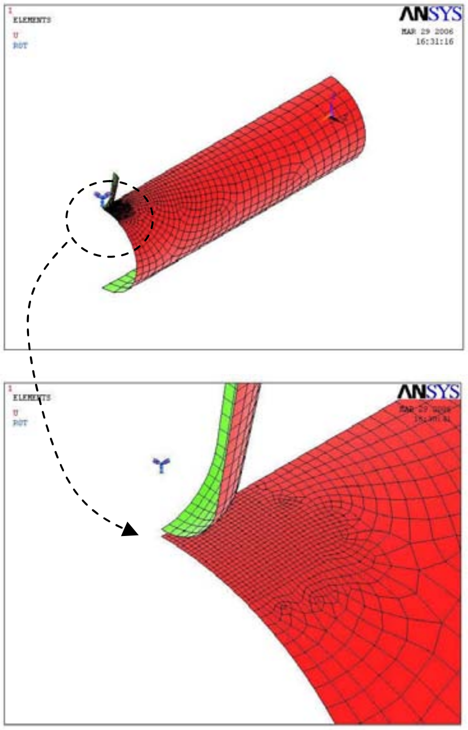

Figure 1. Geometry and mesh of the finite element model

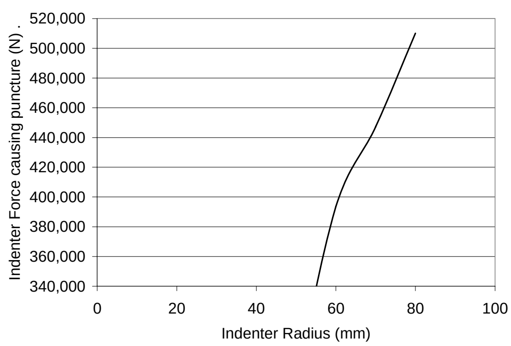

Figure 2. Typical relationship between the indenter size and the force causing puncture

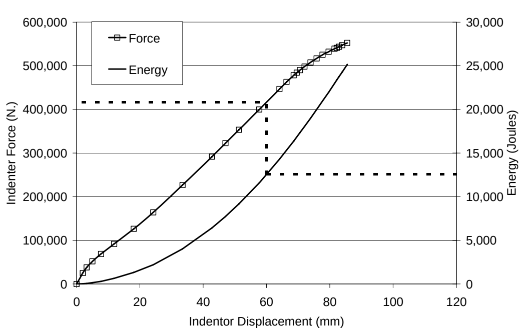

Figure 3. Obtaining the force equivalent to the available energy of 12.57kJ at a certain internal pressure

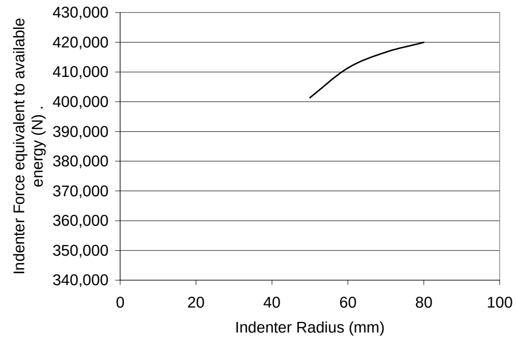

Figure 4. The relationship between the available quasi-static equivalent force and the indenter size

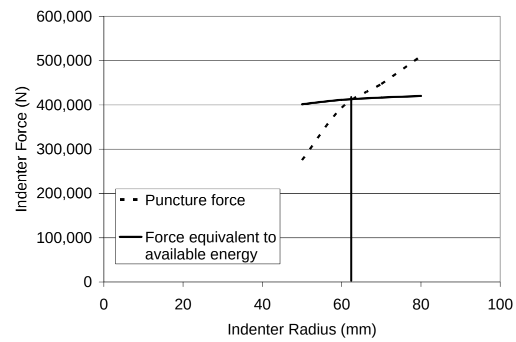

Figure 5. Obtaining the critical indenter size by comparing the available force and the force to puncture (at the internal pressure specified)

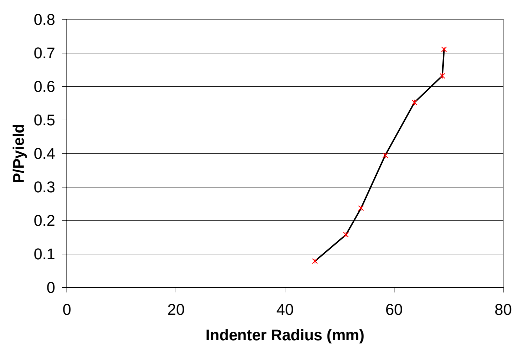

Figure 6. The relationship between the internal pressure and the critical indenter size for the available kinetic energy

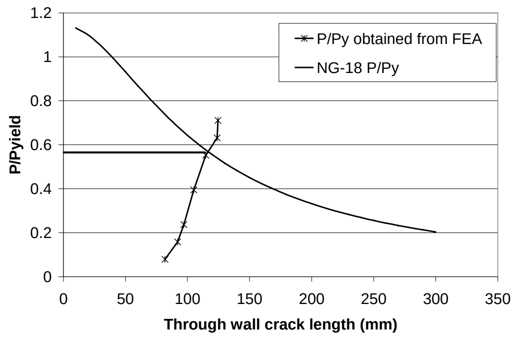

Figure 7. Safe working pressure is obtained by intersecting the NG-18 equation with the obtained curve (curve from Figure 6 by replacing the indenter size with an assumed crack size of 90% of the diameter of the indenter)

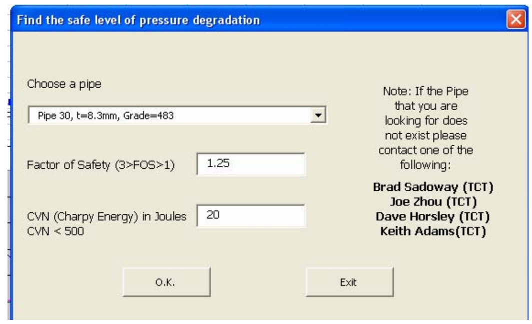

Figure 8. Input to the software

Report:			
OD (mm)	762		
t (mm)	8.3		
Grade	483		
CVN (Joules)	20		
Py (MPa)	10.64		
Acceptable dig pressure (MPa)	**4.84**	**at S/Sy %**	**45.53**
FOS used	1.25		

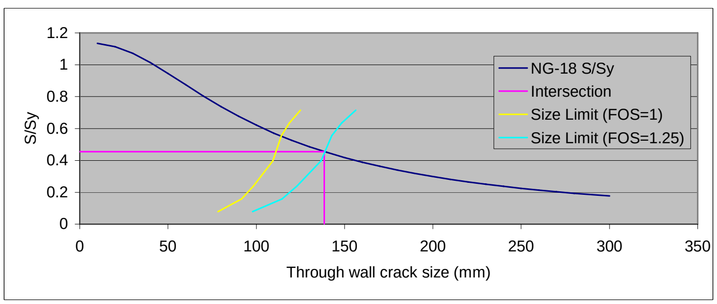

Figure 9. Calculating the safe working pressure

Table 1. Different pipes analyzed

NPS (inches)	Wall thickness (mm)	Grade (MPa)
18	6.35	414
20	6.5	414
24	6.68	483
24	6.4	414
26	7.92	359
30	8.3	483
30	9.53	359
34	10.31	359
36	9.14	448
42	11.4	483
48	12	550

CONCLUSIONS

This work describes how a numerical procedure to establish a safe working pressure for a pipeline in a rock ditch area [1] was developed. The total kinetic energy of a falling rock is assumed to be consumed in the plastic deformation leading to the puncture of the pipe. Using finite element analysis, the value of the critical indenter size (with a given kinetic energy) that would cause puncturing of the pipe was obtained for different values of the internal pressure. A through wall crack whose length was assumed to be 90% of the diameter of the spherical indenter was assumed to be formed upon puncture. The curve generated between the through wall crack formed and the internal pressure was compared with the NG-18 equation curve for through wall critical crack sizes that would lead to rupture. The point of intersection of the two curves was assumed to be the point of the safe working pressure.

It should be noted here that there is a high level of conservatism in the described procedure. The available kinetic energy is assumed to be totally consumed by the plastic deformation leading to puncturing the pipe, without any account for the energy dissipated in friction, sound and/or rebound of the indenter. Another source of conservatism is the assumption that failure will occur at the onset of the principal strain reaching a value of 20% at any point. Failure is predicted to occur a little beyond that point when the average stress on a large area under the indenter would reach the ultimate stress of the pipe material. A third level of conservatism is the choice that a through wall crack of a size of 90% of the diameter of the indenter would develop. It is expected that the punctured hole is not as critical as a through wall crack that is used for the NG-18 equations. The conservative assumptions used here are due to the limited information available and to increase the level of safety for the working crew.

REFERENCES

[1] Adeeb, S.M. and Horsley, D. (2006). A Numerical Procedure to Establish a Safe Working Pressure During Excavation of a Pipeline in a Rock Ditch. *International Journal of Pressure Vessels and Piping,* (Paper accepted for publication)

[2] Brooker, D. C. (2003). Numerical modelling of pipeline puncture under excavator loading. Part II: parametric study. *International Journal of Pressure Vessels and Piping* 80: 727-735.

[3] Bolt, R. (2001). Database reflects recent trends. *Oil Gas Journal* 48-54.

[4] Jones, D.; Kramer, G.; Gideon, D. and Eiber, R. (1986). An analysis of reportable incidents for natural gas transmission and gathering lines 1970 through June 1984. Battelle Columbus Division.

[5] Driver, R. and Zimmerman, T. (1998). A limit states approach to the design of pipelines for mechanical damage. *17th International Conference on Offshore mechanical and Arctic Engineering.*

[6] Palmer, A.; Neilson, A. and Sivadasan, S. (2003). Impact resistance of pipelines and the loss-of-containment limit state. *The Journal of Pipeline Integrity* 2(4): 231-240.

[7] Nielson, A. J.; Howe, W. D. and Garton, G. P. (1987). Impact resistance of mild steel pipes: an experimental study. *Unclassified report AEEWR 2125. UK Atomic Energy Authority, Winfrith.*

[8] Stronge, W. J. Impact and perforation of cylindrical shells by blunt missiles. Metal forming and impact mechanics: *William Johnson Commemorative Volume, Pergamon Press*, 289-302.

[9] Brooker, D. C. (2003). Numerical modelling of pipeline puncture under excavator loading. Part II: parametric study. *International Journal of Pressure Vessels and Piping* 80: 727-735.

[10] Eiber, R. J.; Bubenik, T. A. and Maxey, W. A. (1993). NG-18 Report 208 - Fracture control technology for natural gas pipelines. *Pipeline Research Committee of the American Gas Association*.