North American Society for Trenchless Technology (NASTT)
NASTT's 2013 No-Dig Show

Sacramento, California
March 3-7, 2013

WM-T4-03

Examining Pipe Ramming Design – A Forensic Analysis of a High Risk Project

Christopher Price, Staheli Trenchless Consultants, Bothell, WA
Kimberlie Staheli, Staheli Trenchless Consultants, Bothell, WA

ABSTRACT: The amount of technical guidance on pipe ramming design is extremely limited. As such, Engineers either rely on contractors to design pipe rams or they must rely on rules-of-thumb and historical successes and failures to make determinations of wall thickness, shoe designs, and achievable crossing lengths. Often Engineers approach a project by over-designing casings and limiting drive lengths to ensure against failure. Successful pipe ramming projects rarely involve post-installation investigations; therefore, whether success is achieved through proper design or by over-design remains unclear.

This paper uses a case history of a pipe ramming project where 120-inch and 144-inch casings were driven to refusal prior to the completion of the ram. A forensic analysis of the project was performed to determine the cause of the failure. The findings of the analysis provided a valuable opportunity to improve upon current design standards.

This paper explores the state of the art of pipe ramming design standards. It further highlights lessons learned through forensic analysis to draw conclusions for recommended changes to design standards based on theory and practical experience.

1. INTRODUCTION

There is little design guidance available to engineers utilizing pipe ramming as a project solution. In general this gap has been effectively bridged with conservative designs based on rules-of-thumb and previous experience. However, as projects become more complex it is incumbent on designers to develop a comprehensive and economical design solution. To this end, key elements of pipe ramming design are illustrated using two case histories. Both pipe rams were contractor designed and exhibited identical modes of failure. An investigation was performed to determine the initial cause of failure to aid in developing a solution to successfully complete both crossings.

2. PIPE RAMMING CONSTRUCTION CASE HISTORY

Two road crossings were bid as a trenchless crossing with performance specification, allowing the contractor to design the trenchless project. Although at different locations, the crossings were to replace existing low capacity culverts in order to contain fish bearing streams beneath a roadway. Both crossings were approximately 300 feet in length; however the capacity requirement dictated one 120-inch casing and one 144-inch casing. The soil conditions for the crossings were nearly identical consisting of fill placed over the native glacial till soil deposits. This created a soil profile of relatively loose fill material consisting of sand, silt, wood and other fill debris overlying a dense to very dense glacial till. At both locations the streams flowed at the interface of the native glacial till and overlying fill contact which dictated the casing elevations.

The 144-inch casing installation advanced 135 feet before progress slowed in the last foot of installation and eventually resulted in refusal of forward movement. After removing the hammer and excavating the material inside the casing, deformation was observed for the leading 70 feet of the casing. The deformation of the pipe began at the bottom center of the pipe and continued to increase vertically until the bottom of the pipe met the crown as seen in Figure 1. Based on the 70-foot length of damaged pipe, the pipe started to deform when it was approximately 65 feet past the insertion ring. To investigate the cause of the initial deformation, a hole was cut in the bottom of the casing pipe at the initial point of deformation. Meanwhile, pipe installation work stopped at the first crossing and the Contractor shifted operations to the 120-inch crossing.

Figure 1. Invert Deformation of 144-inch Casing

When ramming the second crossing, although there was no indication of damage, ramming was stopped approximately 105 feet into the ram to excavate within the casing and verify that the pipe was not being damaged. Unfortunately, the excavation operation exposed a damaged pipe. Approximately 35 feet of pipe was deformed at the invert. The deformation of the pipe began at the bottom center of the pipe and continued to increase vertically until the bottom of the pipe met the crown of the pipe as seen in Figure 2. Based on the 35-foot length of damaged pipe, the pipe started to deform when the pipe was approximately 70 feet past the insertion ring. There was no wood or rock present in the soil removed in the damaged section of pipe that would be considered an obstruction. Though the pipe failure manifested in the same fashion as on the previous crossing, there was no obvious evidence for the cause of failure. A hole was cut in the bottom of the casing at the location where the deformation initiated in an attempt to find a source of the failure and all pipe installation work stopped until a repair plan was developed.

Figure 2. Casing Failure with Invert Deforming to the Crown of 144-inch Casing

Investigation at the initial points of failure consisted of cutting out sections of the deformed invert to expose the surrounding soil and to excavate the immediately surrounding material as seen in Figure 3.

Three observations were made for both pipes at these locations.

1. There was no void space surrounding the pipe. The soil was in direct contact with the exterior pipe wall at all locations. There were no drag marks or voids created by displaced objects being pushed in advance of or being dragged along by the pipe.
2. The exterior material was dense glacial till consistent with that described in the boring logs, geotechnical investigation report, and in profiles provided with the contract documents.
3. No evidence of wood fragments, splinters, rock shards, or rock fragments, indicative of shearing through objects was found in the glacial soils. In addition, there was no evidence of displaced objects into the surrounding soil that would indicate the pipe rode over a large object causing deformation.

In both crossings, the leading cutting shoe failure had occurred and simply progressed to a point in which total collapse was achieved as the pipe was advanced. The mode of failure for both crossings was identical. The inverts of both pipes were deformed vertically upward beginning at the original point of failure and increasing linearly toward the leading edge of the pipe.

Figure 3. Exploratory Holes Cut into Casing Invert at Initial Point of Failure

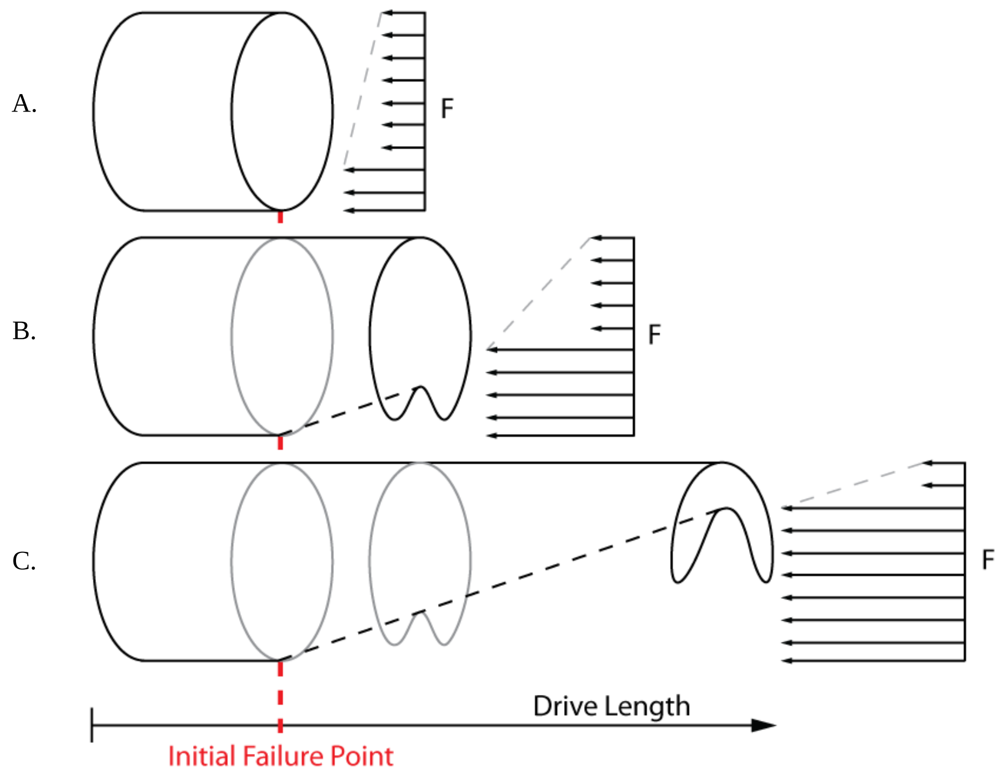

Figure 4. Illustration of Differential Stress on Leading Casing Pipe due to Dense Glacial Soils at Pipe Invert and Fill Soils at Pipe Crown

The casings failed due to inadequate design of the leading section of pipe. It is no coincidence that the modes of failure for both pipe crossings are identical, since the circumstances that initiated failure of the pipes were also identical. At both crossings, the pipes were rammed through a dense glacial till layer that was present at the bottom of the pipes with loose to medium dense fill soils at the crown. This created an unbalanced load distribution on the pipe with a stress concentration at the invert. Figure 4 shows the load distribution on the leading edge of the casing during ramming operations and illustrates the failure mode. Initially (at state (a) in Figure 4) the load is higher on the lower portion of the pipe due to the dense material at the invert. With inadequate stiffness, deformation propagated from the imbalanced loads caused by varying density soil strata. Once deformation initiates (state (b) in Figure 4), the discrepancy in the load distribution between the top and bottom of the pipe increases, due to the fact that the steel at the bottom portion of the casing is plowing, resulting in progressive deformation. This imbalance of load distribution continues until the casing is in total failure (state (c) in Figure 4). In order to ram the pipe successfully, it was necessary to design a leading pipe segment that was sufficiently stiff to withstand the unbalanced loads resulting from the geotechnical conditions present at the site.

Stiffness of the casing and cutting shoe is the most important design element of a pipe ramming project and often determines its success, especially in dense soil formations. The cutting shoe provides stiffness to the leading edge of the first pipe section as well as provides an impact surface that protects the casing from point loading. There are many cutting shoe designs; however the important aspects are the leading bevel angle/direction, and the placement and circumferential coverage of the banding. Each of these aspects is described in detail below. Figure 5 is an illustration of a pipe ramming set up that shows a typical cutting shoe to protect the leading edge of the steel pipe.

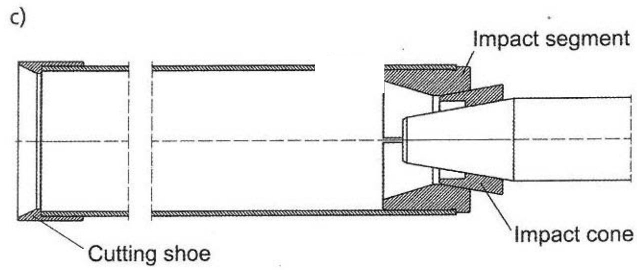

Figure 5. Pipe Ramming Setup (Stein, 2005)

Pipe Ramming Design

In the history of pipe ramming, smaller diameter and/or short crossings are common. In the states pipe ramming is a relatively young technology for the installation of large diameter steel pipes. As such, there is yet to be an ASTM or ASCE standard governing design and installation. However, pipe ramming has been used for a much longer time in Europe, and European standards, such as German Standard ATV-A161E, govern the design and installation of pipe ramming. This standard covers topics such as design of the pipe wall thickness and provides recommendations for the stiffness of the leading edge of the first pipe which is determined by the thickness of the inner and outer steel reinforcing bands and is based on the density of the soil through which the pipe will be rammed.

In the United States, pipe ramming manufacturers, such as TT Technologies, provide guidance on minimum hammer size and pipe wall thickness for given pipe diameters and driving lengths. In addition, the North American Society for Trenchless Technology publishes a "New Installation Methods Good Practices Guidelines" which covers pipe ramming practices. The textbook Trenchless Technology for the Installation of Cables and Pipelines by Stein (2005) also covers pipe ramming technology and gives guidance on design theory and proper application.

Cutting Shoe Design

The cutting shoe is a thickened leading edge that is either fabricated as a separate component that is later attached or a built-up portion of the casing lead edge. Prefabricated cutting shoes are commonly fabricated from higher strength steels than the casing, as a cost effective means of providing adequate strength while reducing necessary thickness or in difficult ground conditions where increased durability is required.

In certain ground conditions, face pressure may increase as the soil plug is formed within the casing, creating a zone of compacted soil as the casing and soil plug are advanced. In purely homogeneous soils with consistent density over the vertical face, the internal stress of the cutting shoe is also uniform. However, if large density differentials are encountered across the shoe, in the form of soil variations, wood, cobbles, or boulders, the internal stresses may vary dramatically. Care must be taken to design a cutting shoe that will survive such conditions. Hardened steel, increased wall thickness, and overall geometry are all parameters used to counter high internal stresses in the cutting shoe.

The increased thickness of the cutting shoe over the casing wall provides three distinct advantages. It creates an overcut to reduce skin friction, it reduces internal stresses with the increased cross sectional area, and it increases the stiffness against deformation. Even small deformation of the cutting shoe can lead to a progressive failure as the ideal round cylinder collapses into a closed wedge. Flexural stiffness is the product of the physical properties of the material, i.e., the elastic modulus, and the geometric arrangement of said material, known as the second moment of inertia. It is the casing geometry that has a possibility of deviating from the ideal design value while performing a pipe ram installation.

A given cylinder of constant cross section and radius has a constant second moment of inertia, I. However, if loading during installation causes deformation of the cross section to an elliptical shape (with the long axis in the horizontal) the moment of inertia decreases about the horizontal axis, thus reducing the stiffness of the casing. Put simply, the shape devolves from the maximum stiffness achieved in a perfect cylinder to the least stiff case of a flat plate. This is intuitively obvious when comparing two casings with the same wall thickness and different diameters. The 12-inch diameter casing with 1-inch wall is much stiffer compared to the 12-foot diameter casing with 1-inch wall. As the diameter of the casing increases, while holding the wall thickness constant, the flexural stiffness decreases. To this end, the ATV-A161E standard utilizes the diameter to thickness (D/t) parameter to capture the stiffness parameter of a particular casing at a given diameter and thickness.

Interior Banding
For larger diameter pipe rams (48-inches and greater), it is common practice to fit the first section of pipe with an interior reinforcing band. This band serves to increase the stiffness of the leading pipe section, which allows penetration into dense to very dense soils without deformation. Full 360-degree interior banding is common practice in pipe ramming applications in dense soil formations and is critical to the success of a pipe ramming in these conditions.

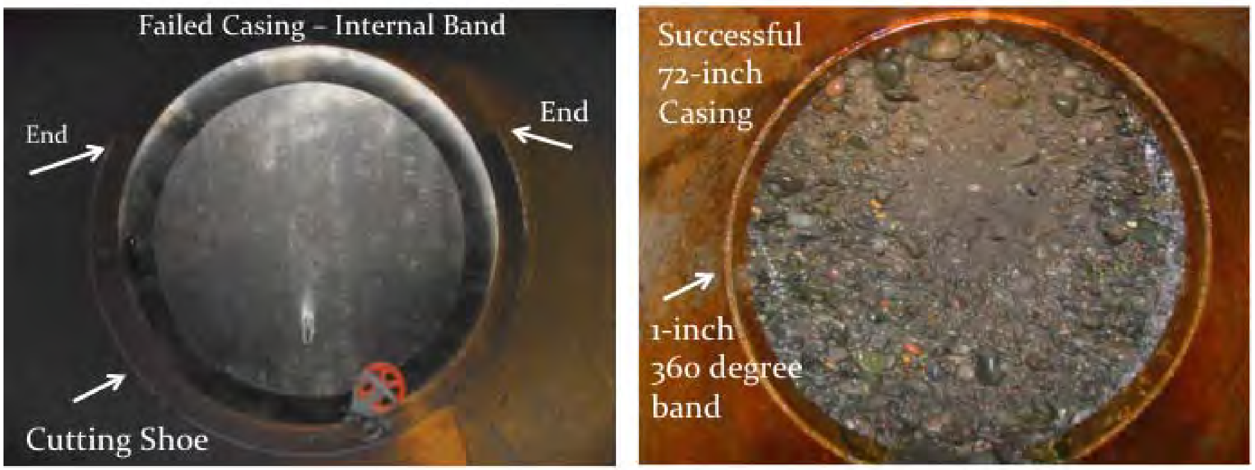

Figure 6. Partial Internal Banding (270 degrees) on the 120" casing (LEFT); Full Internal Banding used on successful 72" Pipe Ram in Dense Glacial Soils (RIGHT)

Figure 6 shows the 0.5-inch thick interior band on the 120 inch casing. The interior banding did not provide 360-degree coverage, but instead covered only 270 degrees of the casing, giving up hoop strength provided by using full 360 degree coverage. Full banding of the leading pipe segment provides significantly more stiffness than partial banding and contributed to the casing deformation. The interior banding scheme shown in the photo on the left of Figure 6, was used on both the 120-inch and 144-inch diameter crossings.

The photo on the right of Figure 6 shows the interior of a 72-inch pipe ram that was successfully completed in Oregon. On this project the soil was identified in the boring logs to be very dense glacial soil with cobbles and boulders. Due to the very dense soil formation, the contractor designed a one-inch thick full circumferential inner band to increase the flexural stiffness of the leading edge of the casing. This casing was driven successfully without deformation.

Cutting Shoe Bevel
Of critical importance for the cutting shoe is the direction in which the bevel of the leading edge is designed. The attack angle serves many purposes. First, it directs the soil into the casing. But, more importantly, the forces that act on the leading edge of the casing cause a localized moment force. If the bevel is cut in the proper direction, the moment force pushes the casing outward – toward the soil, which acts to hold the casing in a cylindrical shape.

Figure 7 shows the proper configuration of the cutting shoe and the forces and moments associated with a proper cutting shoe design.

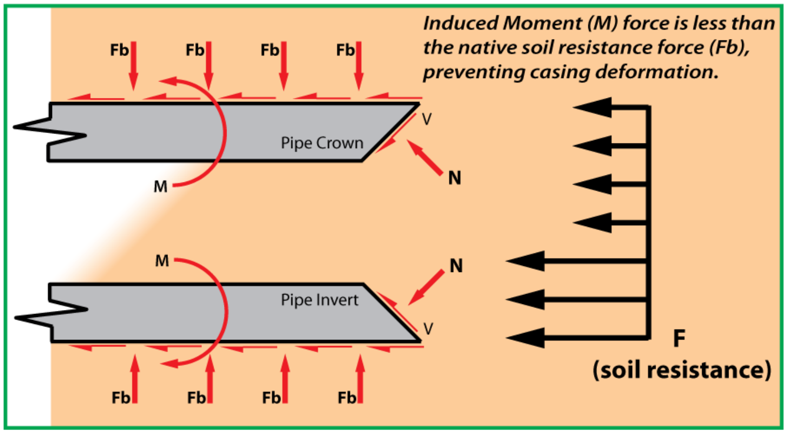

Figure 7. Force Diagram of Properly Designed Cutting Shoe

However, if the bevel is cut in the wrong direction – forcing the soil to the outside of the pipe, the moment force acts to deform the casing inward and can cause the casing to collapse. This force distribution is illustrated in Figure 8 and is especially significant in dense soil conditions where the concentrated forces on the leading edge of the cutting shoe can be very high.

Because of the high forces on the leading edge of the cutting shoe, for pipes with diameters greater than 48 inches, cutting shoes are often designed with an inward bevel or even a blunt front edge to avoid the creation of a moment force. (ATV-A161E, 2000) (Stein, 2005)

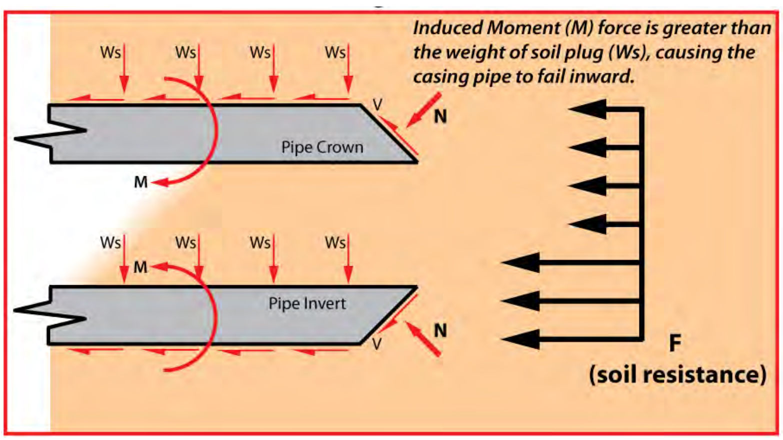

Figure 8. Force Diagram of Improperly Designed Cutting Shoe that Can Lead to Pipe Failure.

The cutting shoe bevel was cut in the incorrect direction, which lead to significantly high moment forces in the casing. The direction of the applied bevel is similar to that shown in Figure 8 and caused an internal moment in the casing as the pipe was rammed into the dense glacial soils called out in the contract documents. The resulting concentration of high stresses deformed the casing invert. As ramming progressed into the dense glacial soils, the deformed leading edge of the casing continued to fail until the invert of the pipe met the crown, resulting in total refusal of casing advance.

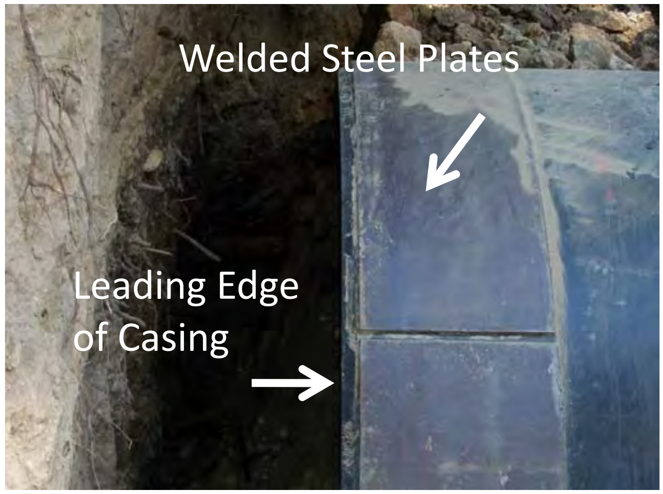

Figure 9. Failed Pipe Ram Cutting Shoe

Another problem of the cutting shoe design was that the reinforced band was applied behind the leading edge of the casing, forcing the casing steel to absorb the impact load of the soil instead of the cutting shoe. This is highly unusual as the concept of a cutting shoe is to apply a reinforced banding that will cut through the soil and relieve the stresses on the casing and avoid local failure of the casing material.

By not protecting the leading edge of the casing with a proper cutting shoe, it was prone to localized failure that manifested as “tearing” due to exceedingly high stresses. “Tearing” of the leading edge of the casing has been observed on other pipe ramming projects where insufficient cutting shoes have failed while ramming in dense soils where no obstructions were encountered.

Casing Design

The design of the casing boils down to two main factors, selection of steel properties and the wall thickness. The “Guidelines for Pipe Ramming” developed for the US Army Corps of Engineers prescribe that minimum 36 ksi steel be utilized for pipe ramming. (Sterling, 2001) The pipe ramming installation loads typically control casing wall thickness, however service load cases for shallow crossings or consideration of corrosion and service life should be investigated during design and may increase the wall thickness.

The rammed steel casing essentially acts as a stiff spring, with the impact of the hammer transferring energy down the length of the casing. The interaction between the casing and soil occurs in two primary ways, namely skin friction and face pressure. Skin friction is essentially constant for any given soil encountered, resulting in increasing force with drive length. As the drive progresses, the hammer energy dissipates through skin friction into the surrounding soil. Typically, this results in the highest internal casing stresses at the trailing end of the casing prior to entering the ground, where there is no soil to develop skin friction on the casing to absorb the applied energy. Thus, the connection point between hammer and casing is a critical area where geometry plays a role in increased localized stress. Collets and other reinforced transition pieces are required to efficiently transfer hammer impact energy into the casing without exceeding its strength. Differences between the hammer and casing diameter must be overcome with collets and/or bell transition pieces. Careful selection of the reinforced connection is critical to maximize the efficient transfer of hammer energy into the casing, while evenly distributing stresses into the casing wall. Recent research has shown that significant energy can be lost with inadequate hammer to pipe connections resulting in inefficiency and decreased drivability. (Stuedlein, 2012)

Face pressure is the cumulative effect of groundwater pressure, lateral earth pressure, and shear forces developed as the cutting shoe displaces the soil. The cutting shoe is designed to withstand the forces that develop at the leading edge of the casing. Pipe ramming face pressure is similar to tip resistance in driven vertical piles with notable differences. Vertical pile tips do not require durability through all soils encountered, rather only in so far as adequate skin friction or end-bearing capacity is achieved. Tip deformations occurring near or at the final pile depth are

WALL THICKNESS RECOMMENDATIONS		
Pipe	Minimum Wall Thickness	
Diameter	Bores up to 65 ft (20 m)	Bores over 65 ft. (20m)
Inches (mm)	Inches (mm)	Inches (mm)
6" (150)	.25" (6.3)	.27" (7.1)
8" (200)	.25" (6.3)	.27" (7.1)
10" (250)	.25" (6.3)	.27" (7.1)
12" (300)	.25" (6.3)	.27" (7.1)
14" (350)	.27" (7.1)	.31" (8.0)
16" (400)	.27" (7.1)	.31" (8.0)
18" (450)	.31" (8.0)	.39" (10.0)
20" (500)	.31" (8.0)	.39" (10.0)
24" (600)	.39" (10.0)	.47" (12.0)
28" (700)	.39" (10.0)	.47" (12.0)
30" (750)	.47" (12.0)	.55" (14.0)
32" (800)	.47" (12.0)	.55" (14.0)
36" (900)	.47" (12.0)	.62" (16.0)
40" (1000)	.47" (12.0)	.62" (16.0)
42" (1050)	.59" (15.0)	.62" (16.0)
48" (1200)	.59" (15.0)	.70" (18.0)
51" (1300)	.62" (16.0)	.70" (18.0)
54" (1400)	.70" (18.0)	.78" (20.0)
60" (1500)	.75" (19.0)	.87" (22.0)
66" (__00)	.75" (19.0)	.87" (22.0)
72" (1800)	.87" (22.0)	1.0" (25.0)
80" (2000)	.875" (22.2)	1.0" (25.0)
84" (2135)	1.0" (25.0)	1.25" (32.0)
96" (2440)	1.0" (25.0)	1.25" (32.0)
108" (2745)	1.125" (29.0)	1.50" (38.0)
120" (3048)	1.125" (29.0)	1.50" (380)

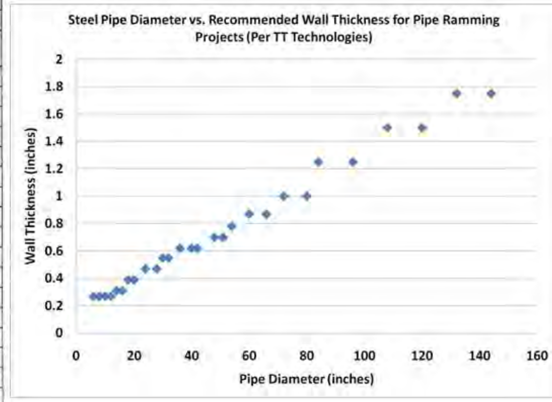

Figure 10. Minimum Wall Thickness Recommendations for Pipe Ramming (Courtesy of TT Technologies)

acceptable and rarely discovered. In contrast, deformations at the cutting shoe are not acceptable for pipe rammed installations. Even small, localized deformations can cause total casing collapse or excessive driving forces that may exceed hammer capacity.

Casing Wall Thickness

TT Technologies, one of the leading manufacturers of pipe ramming tools, publishes a list of recommended pipe wall thickness for pipe ramming projects based on pipe diameter and the length of the pipe ram. (Figure 10)

As seen in the Table in Figure 10, the minimum recommended pipe wall thickness for a 300 ft, 120-inch pipe ram is 1.5 inches. A pipe wall of only 1.125 inches was used for both of the creek crossings. The recommended pipe wall thickness would have provided a 32.9% increase in cross sectional area for the 120-inch casing. It is important to note that a wall thickness of 1.125" is sufficient (Figure 10) for crossing lengths of up to 65ft and that the casing began to deform at a length of 70 feet.

Although the table does not have values for pipe diameters as large as 144 inches, it is clear that the minimum wall thickness increases with diameter. Figure 10 includes a graph of pipe diameter versus wall thickness based on the TT Technologies table recommendations. From extrapolation of the data, the "recommended" wall thickness for a 144-inch pipe would be 1.75 inches, where only a 1.125 inch thick casing was used. The recommended wall thickness would have resulted in a 54.9% increase in cross sectional area of the pipe.

Increasing the stiffness of the pipe with a thicker casing and proper cutting shoe would have provided a greater ability to penetrate the dense glacial material without deformation. Clearly, the inadequate stiffness was the cause of failure of the steel casings. This was evident by the means and methods that were used to finish the pipe rams after the initial pipe deformation was discovered. Once the deformed sections of casing were removed, the Contractor proceeded to install a 4-foot long, 360-degree reinforcing band to stiffen the "new" leading edge. The pipe was further stiffened with cross bracing and longitudinal bracing to prevent moment forces from bending the pipe inward. This stiffening of the leading section of pipe allowed the contractor to continue to ram forward and complete the pipe ram installations.

Casing Failure Summary

The ultimate cause of the casing failure was an improper design of the lead casing pipe that was not stiff enough to prevent deformation. The primary inadequacy was the design of the cutting shoe which was beveled incorrectly, applied at the wrong location, and was not of sufficient thickness, which caused an abundance of stress at the bottom of the pipe that led to the deformation of the invert and ultimate failure. Other contributing factors to the failure were insufficient internal banding of the lead pipe and a casing wall thickness that was less than recommended for the casing diameters.

3. CONCLUSIONS AND RECOMMENDATIONS

Both of the pipe ram installations examined in this paper failed in the same manner, with the invert of the casing beginning to deform at the initial point of failure and then progressively failing until the casing invert met the crown of the pipe. The solution that allowed completion of both rams gives credence to the lack of stiffness being the root cause, as the “fix” involved building reinforcement of the lead casing pipe to prevent the casing from deforming. Both rams were then completed without further incident. These failures could have been prevented with adequate design of the casings and cutting shoes.

Pipe ramming is a viable and attractive method of installation in many cases, however, careful planning and design based upon experience is essential until clear guidelines and standards are developed. As further research is performed and the failure modes of pipe ramming are investigated, one point remains clear; more guidance is needed for designing pipe ram installations. Sound guidance is even more critical for larger diameters and longer pipe ramming installations and in challenging geotechnical conditions like those found in the case histories presented herein.

Use of the diameter to thickness (D/t) ratio in order to account for pipe stiffness is desirable and should be adopted by designers. It is a simple means of expressing stiffness of the casing and cutting shoe. For larger diameter pipe ramming applications through difficult soils, experience shows that a D/t ratio of no more than 60 is advisable. For smaller diameter casings, or relatively short crossings, this maximum value may be reduced. The author plans to further investigate the relationship between structural mechanics buckling equations and the D/t ratio. This relationship may prove advantageous in developing suggested D/t values for various pipe diameters, lengths, and ground conditions.

The author is aware of ongoing research into hammer efficiency, energy transfer, and drivability. Fully understanding these parameters is paramount in order to advance the technology. Accurate calculation of maximum estimated installation forces are key in shaft spacing, which contributes to overall project risk and cost. Further investigation into the casing pipe and soil interaction in terms of both skin friction and cutting shoe face pressure will lead to more reliable calculations for contractors and engineers to rely upon for design.

4. REFERENCES

Stein, D., “Unmanned, Non-Steerable Techniques,” in *Trenchless Technology for Installation of Cables and Pipelines,* 1st ed., D. Stein, Ed. Germany: Stein & Partner, 2005, pp.198-206.

Sterling, R.L., and J. Simicevic, “Guidelines for Pipe Ramming – TTC Technical Report No. 2001.04,” for US Army Corps of Engineers, Engineering Research and Development Center. Vicksburg, MS, December 2001.

Stuedlein, A.W., and T. Meskele, “Preliminary Design and Engineering of Pipe Ramming Installations,” *Journal of Pipeline Systems Engineering and Practice*, ASCE, Vol. 3 (4), pp. 125-134, November 2012.

German Association for Water Wastewater and Waste, “ATV Working Sheet A 125E: Pipe Driving,” General Technical Specifications for Building Works, Germany, Tech. Std., September 1990.

German Association for Water Wastewater and Waste, “ATV Standard A 161E: Structural Calculation of Driven Pipes,” General Technical Specifications for Building Works, Germany, Tech. Std., January 1990.