NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

August 15, 2011

MATERIALS LABORATORY STUDY REPORT Report No. 11-089

A. ACCIDENT INFORMATION

Place	:	San Bruno, California
Date	:	September 9, 2010
Vehicle	:	PG&E Natural Gas Transmission Pipeline
NTSB No.	:	DCA10MP008
Investigator	:	Ravindra Chhatre, RPH-20

B. TOPICS ADDRESSED

Calculation of static stresses and vibrations associated with pneumatic pipe bursting.

C. DETAILS OF THE STUDY

1. Ground vibrations transmitted from a bursting head

For details regarding the relative positions of the utilities, see the Operations Group Chairman's Factual Report and Operations Group Chairman's Factual Report Addendum. A drawing of the relative position of the gas pipe and sewer pipe, based on a survey of Glenview Drive and Earl Avenue, is shown in figure 1. The sewer was at a 61° angle to the pipeline and crossed under the pipeline 108 inch from the southern end of pup 1. When the bursting head breaks up the sewer pipe, vibrations are transmitted through the soil. The out-of-round deflection response of the pipe to these ground vibrations was estimated by two methods. The first method was based on the equation for maximum axial strain on a pipeline (ALA, 2005):

$$\Delta l = D\frac{V_{max}}{C}$$

The second method was based on the formula for complex soil displacement (Mavridis 1996):

$$\Delta l = max[w(l_2,t) - w(l_1,t)] = max\left[R_w\frac{V_{max}}{\omega}\left(e^{i\omega(t-l_2/V_s)} - e^{i\omega(t-l_1/V_s)}\right)\right]$$

Where Δl is the out-of-round deflection of the pipe, D is the pipe diameter, V_{max} is the peak particle velocity, C is the apparent wave velocity, l_1 and l_2 are the distance from the bursting head to the west side and east side of pup 1, respectively (see figure 1), V_s is the shear wave velocity (the velocity at which the vibration travels through the soil), R_w is a complex pipe/soil displacement ratio (taken as 1.0), ω is the angular frequency, and $w(l_i, t)$ is the pipe wall displacement at location l_i and time t. The apparent wave velocity was calculated according to:

$$C = \frac{D}{\frac{l_2}{V_s} - \frac{l_1}{V_s}}$$

l_1 and l_2 were calculated using the distance along the sewer line between the bursting head and the west side of the gas main, x (see figure 1), the distance from the intersection of the sewer line with the west side of the gas main to the south end of pup 1 (108 inch + 8.3 inch = 116.3 inch), the vertical separation between the center of the gas main and center of the sewer pipe (d = 30.4 inch), and the pipe diameter (D = 30 inch) according to:

$$l_1 = \sqrt{[116.3\ inch + x \cdot \cos 61°]^2 + (x \cdot \sin 61°)^2 + (d)^2}$$
$$l_2 = \sqrt{[116.3\ inch + x \cdot \cos 61°]^2 + (D + x \cdot \sin 61°)^2 + (d)^2}$$

The shear wave velocity of the soil is dependent upon soil type. For the purpose of the calculation, a value for clayey soils of 100 m/s (328 ft/s) was assumed (DeJong, 2007).

The 95 percent confidence interval for peak particle velocity can be described as a linear relationship between the log of the peak particle velocity and the log of the distance from the bursting head (Simicevic and Sterling, 2001). The equation describing the relationship was determined to be:

$$\log(V_{max}) = 1.1239 - 0.9261 \cdot \log(l_1/12)$$

Where V_{max} is given in inch/s and l_1 is given in inches.

The deflection, Δl, at the southern end of pup 1 was evaluated using both methods described above at multiple positions of the bursting head along the centerline of the sewer and for ground vibration frequencies from 5 Hz to 100 Hz. Typical ground vibration frequencies for pipe bursting are between 30 Hz and 100 Hz (Simicevic and Sterling, 2001). The peak deflection was determined to be a maximum with the bursting head at x = 102 inch (8.5 ft) from the west side of the gas main. The maximum deflection was the same for both methods:[1]

Δl = 0.0041 inch

[1] The maximum deflection calculated from complex soil displacements was at 5 Hz. Higher frequencies produced lower maximum deflection values.

The impact of this deflection on a transmission pipe with a partial seam weld, similar to the ruptured pipe, was modeled using the same finite element model used in an earlier study (NTSB, 2011a). The weld defect was shaped similar to a notch. It concentrated the stresses and strains so that the material at the tip of the notch exceeded the elastic limit and began to deform in a plastic manner below the maximum operating pressure. The following method was applied to the model:

1) Raise the internal pressure from 0 psi to 350 psi in 10 steps;
2) Raise the internal pressure to 365 psi (the operating pressure on the day of the sewer pipe replacement) in a single step;
3) Impose an inward radial deflection of 0.004 inch on the outer surface of the weld defect.

In order to prevent rigid-body motions, the pipe was held fixed (no displacement or rotation) at a single node at the bottom of the pipe, opposite the weld. The vertical displacement was assigned to a single node at the top of the pipe, in-line with the weld defect. In order to prevent unwanted torsion in the pipe section, the node was constrained in such a way that only a radial displacement was allowed.

The pipe model was also pressurized from 365 psi to 375 psi in 1 psi increments without additional externally imposed deflections. The maximum plastic strain magnitude at the tip of the notch was noted for each case (table 1).

Table 1: Maximum plastic strain magnitude at the tip of the notch for various prescribed loading methods on the model similar to pup 1.

Prescribed Loads and Displacments	**Maximum Plastic Strain Magnitude at Tip of Notch**
Pressurized to 365 psi	0.386
Pressurized to 365 psi Deformed by 0.004 inch	0.391
Pressurized to 368 psi	0.392
Pressurized to 375 psi	0.406

2. Static loads on the side wall of a receiving pit

The static soil pressures on the side of the gas main were calculated based on a video of the sewer pipe bursting process, a survey of the utilities at Glenview Drive and Earl Avenue (figures 1 and 2), information provided by the foreman in charge of the sewer replacement project, and the Boussinesq solution for a point load on a surface (Johnson 1994). The video showed that a load was exerted on the sidewall of the pit by a winch that was pulling the bursting head toward the receiving pit. The pulley was braced against a short piece of sheet piling at the bottom of the west wall where the cable entered the pit. The central piece of sheet piling in turn was supported by two pieces of sheet piling, both driven into the soil at the bottom of the pit, one on either side. For more details about the configuration of the receiving pit, see the Operations Group Chairman's Factual Report Addendum.

The soil pressure on the side of the gas main was calculated at the closest point to the winch brace, located along the length of double submerged arc welded (DSAW) pipe (see figure 1), and at the pup 1 rupture initiation site (21.5 inch north of the girth weld) (see figure 2). The soil pressures were calculated based on a maximum winch load of 14,000 lbs. The Boussinesq solution for a point load on a surface was used rather than the solution for a distributed load. The point load pressures are higher than for distributed loads, but the two solutions converge at longer distances and are within 8 percent of one another at distances greater that two times the diameter of the distributed load. The stresses were calculated according to:

$$\sigma_z = \frac{3Pz^3}{2\pi R^5};\ \sigma_r = -\frac{P}{2\pi R^2}\left[-\frac{3r^2 z}{R^3} + \frac{(1-2\nu)R}{R+z}\right]$$

$$\sigma_\theta = -\frac{(1-2\nu)P}{2\pi R^2}\left[\frac{z}{R} - \frac{R}{R+z}\right];\ \tau_{rz} = \frac{3Prz^2}{2\pi R^5}$$

Where P = 14,000 lbs, $\nu \sim 0.3$, R is the distance from the point load, z is the vertical component of the distance from the point load, and r is the radial component of the distance from the point load (see figures 1 and 2). Note that the gas main and sewer pipe centerlines were vertically offset by 30.4 inch. Therefore R_i and r_i values shown in figures 1 and 2 are projections onto the road surface. Based on the dimension in figures 1 and 2, the following values were used (table 2):

Table 2: Values used for the Boussinesq solution for two positions along the gas main.

Position	R, inch	r, inch	z, inch
Closest Point (DSAW Pipe)	97.6	54.2	81.1
Initiation Site on Pup 1	121	111	46.8

The calculated soil pressures were normal to the sidewall of the pit, but not normal to the sidewall of the gas main. Therefore the stresses were transformed by a rotation about the z-axis followed by a rotation about the θ-axis (orthogonal to the page). The resulting pressures and rotations were (table 3):

Table 3: Sidewall soil pressure on the gas main.

Position	Sidewall Soil Pressure, psi	z-rotation, degrees	θ-rotation, degrees
Closest Point (DSAW Pipe)	0.58	34.1	29
Initiation Site on Pup 1	0.10	15.9	29

The effect of the external soil pressure on the deformation of the pipe was examined by replacing the soil pressure with an equivalent line load on the side of the gas main and applying the line load to a two-dimensional finite element model of a piece of typical DSAW pipe and a model of a pipe with a seam weld defect similar to pup 1 (see figures 3a and b). The models have been previously described (NTSB, 2011a). The line load was calculated according to:

$$F_l = Sidewall\ Pressure \cdot Diameter\ of\ Pipe$$

The line load was first applied to the model of a typical DSAW pipe. In order to prevent rigid-body motions, the pipe was held fixed (no displacement or rotation) at a single node 90° away from the weld. The line load was assigned to a single node 180° away from the fixed node. In order to prevent unwanted torsion in the pipe section, the node was constrained in such a way that only a radial displacement was allowed (figure 3a). It is known that the soil surrounding the pipe provides added support to the pipe, but to simplify the model, that effect was omitted.

The line load was applied to the pipe under two scenarios: no internal pressure and with an internal pressure of 365 psi. The deflection in the unpressurized case was also calculated using the modified Iowa deflection formula assuming no soil support (ALA, 2005):

$$\frac{\Delta y}{D} = \frac{D_1 K_z P}{\left(\frac{Et^3}{12R^3}\right)}$$

The deflection in the pressurized case was also calculated using the modified Spangler Stress Formula, also assuming no soil support (Warman 2009):

$$\frac{\Delta y}{D} = \frac{D_1 K_z P}{\left(\frac{Et^3}{12R^3} + 2K_z p_i\right)}$$

Where Δy is the out-of-round deflection of the pipe, D is the pipe diameter, D_1 is a deflection lag factor (taken as 1.0), K_z is a deflection parameter (taken as 0.108), P is the externally applied soil pressure, E is the modulus of elasticity for steel (30,000 ksi), t is the wall thickness of the pipe (0.375 inch), p_i is the internal pipe pressure (taken as 365 psi), and R is the pipe radius (15 inch).

The maximum bending stress, σ_{bw}, for each case was calculated according to (Warman 2009):

$$\sigma_{bw} = \frac{2K_b E}{K_z}\left(\frac{\Delta y}{D}\right)\left(\frac{t}{D}\right)$$

Where K_b is a moment parameter (taken as 0.235).

The stresses were also estimated using the formula for highway cyclic stresses given in API RP 1102 (section 4.7.2.2.4) assuming a highway stiffness factor, K_{Hh}, of 20, a highway geometry factor, G_{Hh}, of 0.7, a pavement type factor, R, of 1.0, a highway axle configuration factor, L, of 0.65, and an impact factor, F_i, of 1.0 (API 2007). The 14,000 lbs load was distributed over a 144 in^2 area.

The results are summarized below (table 4):

Table 4: Calculated pipe deflection and bending stress of DSAW pipe with an applied external soil pressure, or equivalent line load, of 0.58 psi.

Approach	Pipe Deflection, inch	Bending Stress, ksi
Finite Element – no internal pressure, external soil pressure replaced with equivalent line load	0.060	3.087
Modified Iowa Deflection Formula (no internal pressure)	0.048	2.62
Finite Element – 365 psi internal pressure, external soil pressure replaced with equivalent line load	0.017	1.337
API RP 1102 Highway Cyclic Stress Method	—	0.885
Spangler Stress Formula (365 psi internal pressure)	0.016	0.867

For the external soil pressure against pup 1, the equivalent external line load was applied to the pipe model under an internal pressure of 0 psi and 365 psi. The location of the pup 1 longitudinal seam was previously determined to be 71° from the top of the pipe toward the east side (NTSB, 2011b). Therefore, the line load was applied 19° clockwise from the seam weld defect (i.e., on the east side of the pipe) (see figure 3b). The maximum Mises stress or plastic strain magnitude at the tip of the pup 1 notch was noted after applying the external line load or additional internal pressure in each case. The results are summarized below (table 5):

Table 5: Computed maximum plastic strain magnitude and Mises stress for the pipe model similar to the pup 1 longitudinal seam.

Approach	Maximum Plastic Strain Magnitude at Tip of Notch	Maximum Mises Stress, ksi
365 psi internal pressure	0.386	84.0
365 psi internal pressure, line load equivalent to external soil pressure of 0.10 psi	0.388	84.0
375 psi internal pressure	0.406	84.0
0 psi internal pressure, line load equivalent to external soil pressure of 0.10 psi	—	6.6
2.5 psi internal pressure, no external load	—	7.0

3. Winch vibration loads on the side wall of a receiving pit

A calculation was performed to consider the possibility that the bursting head could move forward with each stroke and the cable could relax by an amount that depended on the distance moved by the bursting head and the stiffness of the cable, before the winch had a chance to restore full tension on the cable.

The maximum force amplitude, ΔF, on the west wall of the pit was calculated by considering how far the bursting head moved with each stroke, the minimum length of cable running from the bursting head to the winch, and the stiffness of the cable.

$$\Delta F = \pi \left(\frac{d}{2}\right)^2 S \left(\frac{\Delta l}{l}\right)$$

Where *d* is the diameter of the cable (d = 0.562 inch), *S* is the stiffness of the cable (approximately 0.76 the modulus of elasticity for steel or 22,900 ksi), l is the minimum length of cable between the bursting head and the winch, and Δl is the average distance moved by the bursting head between successive bursts.

The minimum value of l was determined to be approximately 25.2 feet as follows:

1) Vertical distance from winch to bottom of pulley ~ 6.5 feet
2) Distance from west edge of receiving pit to tip of bursting head at start of static pull ~ 18.7 feet

The distance moved by the bursting head with each stroke was measured from video of the bursting process. The distance moved with each burst was approximately:

$$\Delta l = \frac{Bursting\ Head\ Velocity}{Bursting\ Frequency}$$

The bursting head frequency was measured from the audio track on the video and was 3.57 Hz (214 strokes/min). The bursting head velocity was estimated from:

1) Movement of the cable as it was reeled in by the winch (figure 4);
2) Movement of the replacement sewer pipe as it entered the insertion pit (figure 5).

The bursting head velocity was calculated by measuring the movement of identifiable features over a known time interval on the video. For the case of the winch, the diameter of the cable, 0.562 inch, was used to scale the distance moved. For the case of the sewer pipe, the outside pipe diameter, 10 inch, was used to scale the distance moved. The velocity calculated from footage of the winch was 0.22 inch/s. The velocity calculated from footage of the replacement sewer pipe was 0.12 inch/s. Approximately 260 feet of pipe were burst using the pneumatic tool. The winch video footage gave an estimated time to completion of 3.9 hours. The sewer pipe video footage gave an estimated time to completion of 7.2 hours. The foreman estimated that the bursting process took approximately 6 hours. Taking the higher velocity value, the results were:

Δl = 0.0051 ft/stroke (0.062 inch/stroke)
ΔF = 1158 lbs

Following the Boussinesq approach outlined in Section 2 for static loads, the associated soil pressure amplitude on the side of the pipe was calculated for the point of closest approach and for the side of pup 1 near the initiation site. The results are summarized below (table 6):

Table 6: Calculated soil pressure amplitude on the east side wall of the transmission pipe due to possible periodic relaxation of the winch loads against the side wall of the receiving pit.

Position	**Normal Soil Pressure Amplitude, psi**
Closest Point (DSAW Pipe)	0.048
Initiation Site on Pup 1	0.008

D. REFERENCES

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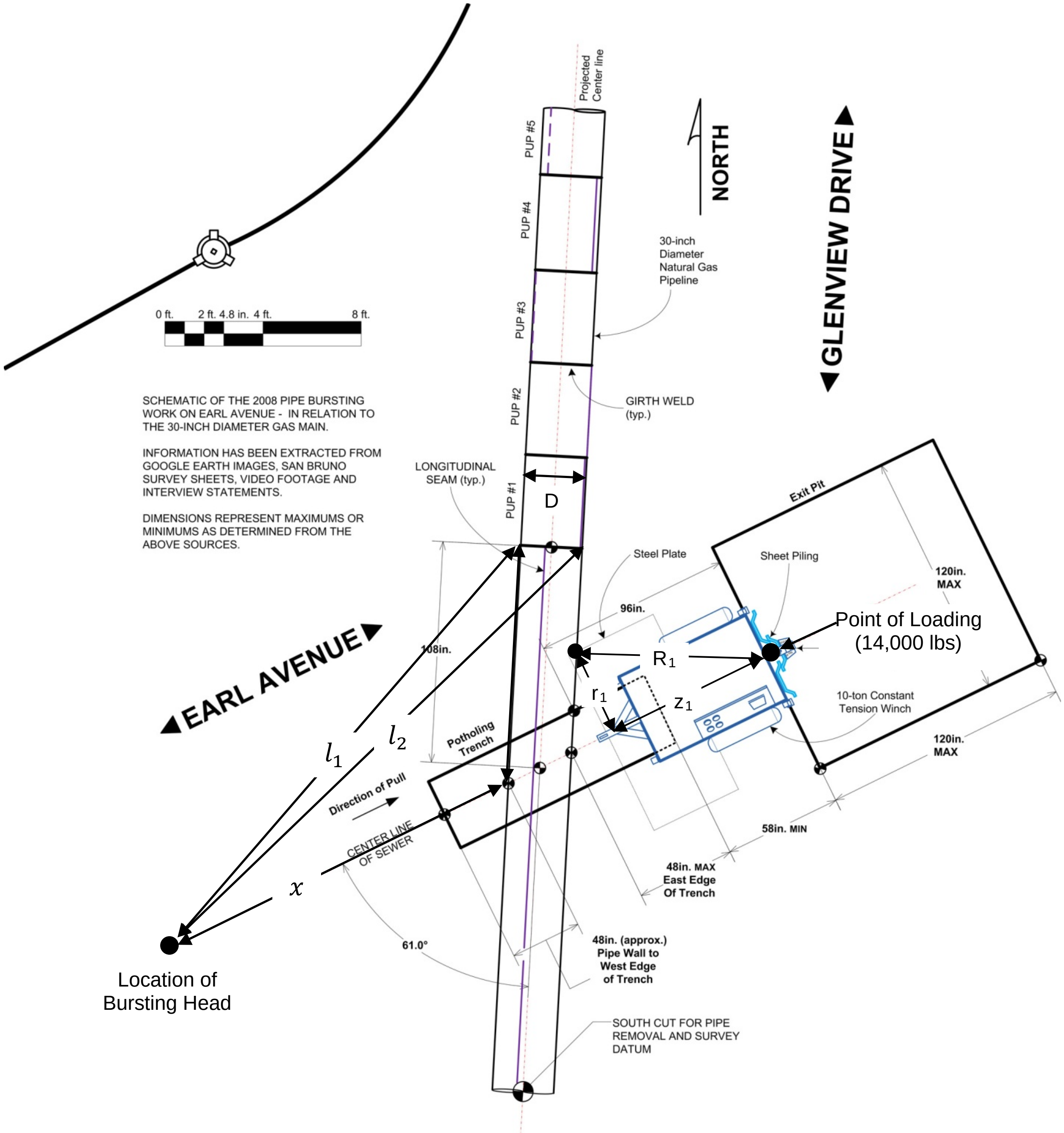


Figure 1: 30-inch natural gas main layout with nearby services. The layout shows the excavation over the 30-inch natural gas line and sewer line as well as the exit pit used to retrieve the bursting head. The distance between the bursting head and the sidewalls of the pipe, l_1 and l_2, are projected onto the surface. The figure also shows the distance between the winch brace and the closest point on the gas main, R_1. The force from the brace is applied along the centerline of the sewer pipe 30.4 inch below the centerline of the gas main.

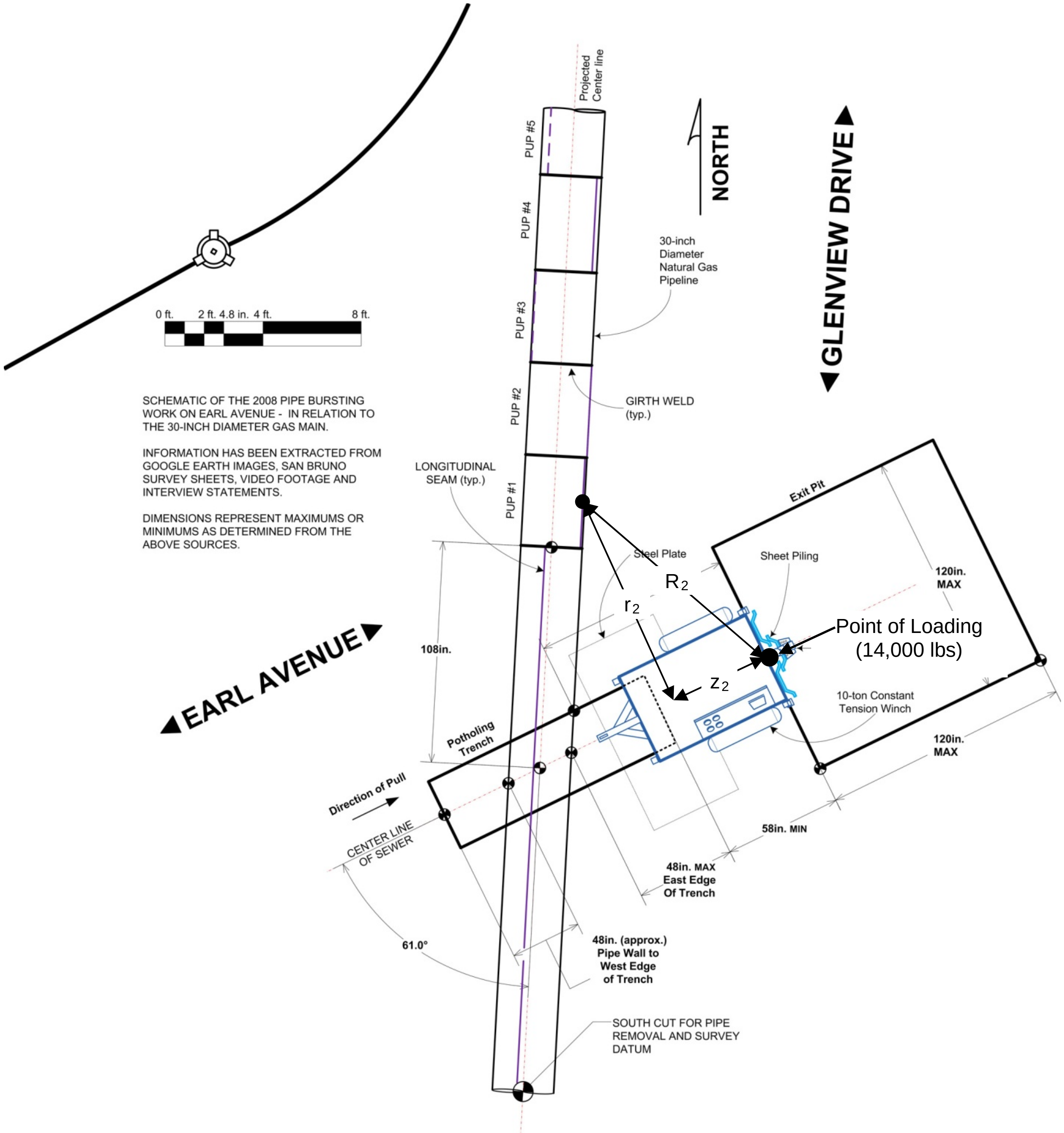
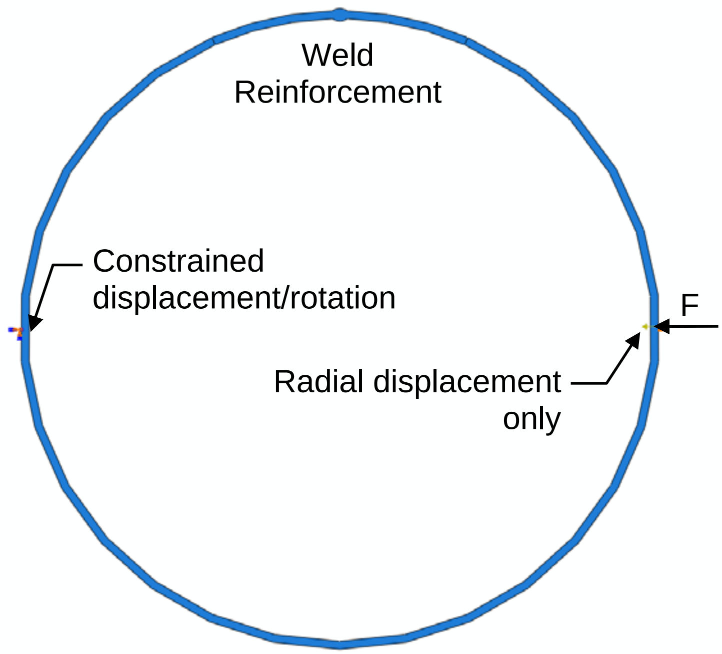
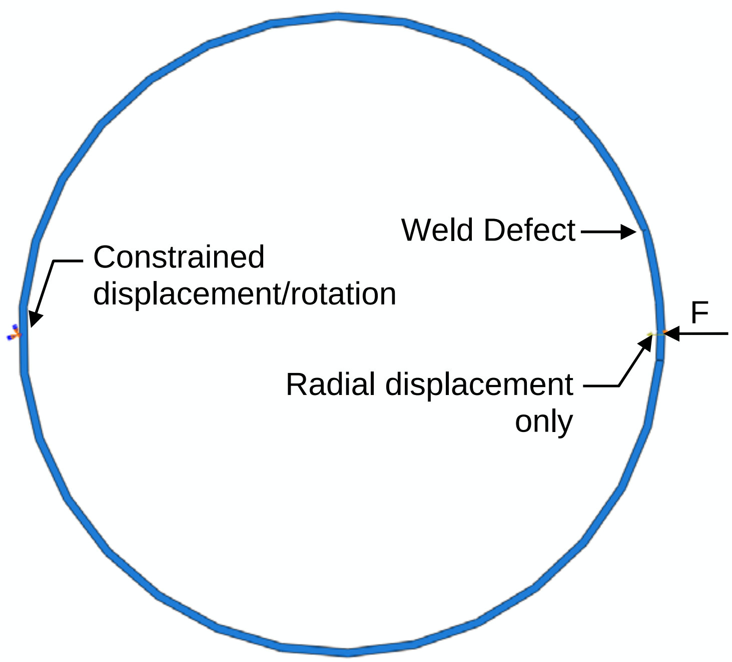


Figure 2: Same as figure 1 showing the distance between the winch brace and the initiation point on pup 1. The lengths r_2 and R_2 are projected onto the road surface.



a)



b)

Figure 3: Finite element models and boundary conditions used in determining the effects on the pipe from loading by the winch on the sidewall of the receiving pit; a) a model similar to DSAW pipe with the weld reinforcement at the top; b) a model similar to the geometry of pup 1 with the weld defect 71° from the top of the pipe.

a)

b)

Figure 4: Video frames showing motion of the cable as it pulled the bursting head toward the receiving pit. The frames were separated by 1.12 s. The images were calibrated using the diameter of the cable (0.562 inch).

a)
b)

Figure 5: Video frames of the sewer pipe as it entered the ground at the insertion pit. The frames were separated by 4.80 s. The images were calibrated using the diameter of the sewer pipe (10 inch).