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INNOVATION IN HDD CONSTRUCTION AND ENGINEERING: AN 8,850-FOOT 32-INCH SINGLE DRILL HDD

Christopher Price[1], and Matthew Pease[1]

[1] Staheli Trenchless Consultants, Bothell, Washington

ABSTRACT: This paper presents the construction of an 8,850-foot horizontal directional drill (HDD) crossing of the Rio Grande River in Santa Cruz, Bolivia. The crossing is a key component of a 32-inch diameter steel natural gas line traversing two countries to deliver gas from the fields in Bolivia to the coast of neighboring Brazil. The HDD river crossing will be performed as a single drill as opposed to utilizing the intersect method typical of longer crossings. This challenging project necessitated developing innovative solutions to the various issues inherent to an HDD crossing spanning over a mile and a half.

Factors that are not necessarily a concern for shorter crossings become engineering challenges that must be accounted for early in construction planning. In addition to hydrofracture and pullback loads evaluation, analysis of the drill pipe strength, critical buckling loads, fluid pressure losses, and maximum torque were vital in performing an adequate evaluation of this bore. A unique low friction pipe pulling plan along with a modified buoyancy control method was developed to reduce the pullback loads and ensure successful installation of the nearly 9,000 feet of steel pipeline. This paper discusses the specific challenges associated with this impressive bore along with the engineering solutions devised to ensure a successful and timely installation.

1. INTRODUCTION

Staheli Trenchless Consultants (STC) was contracted by TATCO Boring and Installations to perform engineering support during both the engineering phase and during the installation of a 32-inch diameter, 8,850 foot crossing of the Rio Grande River utilizing horizontal directional drilling (HDD) technology near Santa Cruz, Bolivia. The 32-inch steel pipeline will transport natural gas from fields in Bolivia to distribution points off the coast of Brazil.

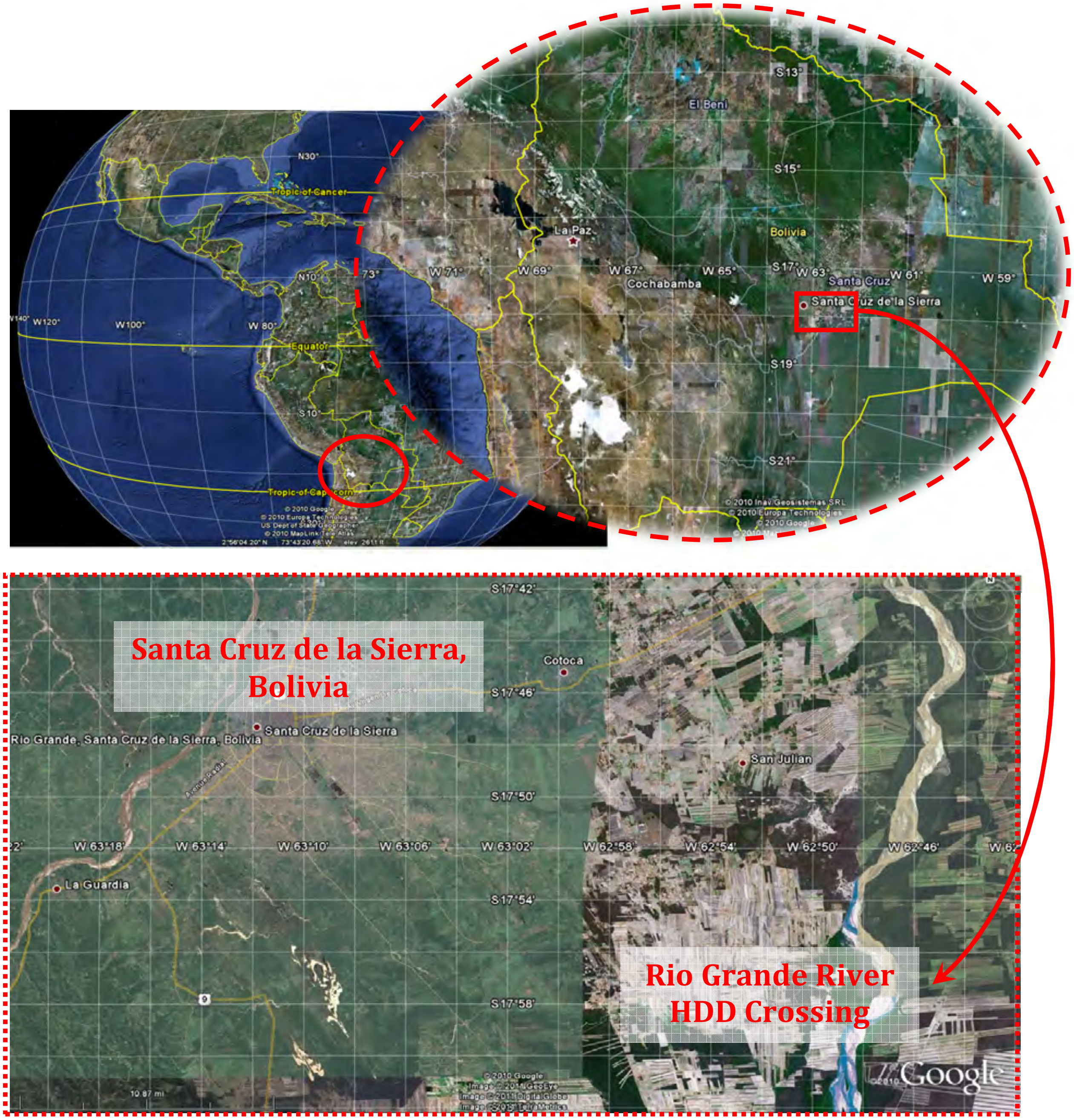


Figure 1. Rio Grande River Crossing Project Location.

Typical engineering support required during the construction of a horizontal directional drill (HDD) crossing consists of determining estimated pullback forces, developing a hydrofracture risk profile based on geotechnical conditions and crossing geometry, estimated drilling mud quantities and spoil volumes, and other routine calculations enumerated in *The HDD Good Practices Guidelines* (2008) and other resources.

In addition to these calculations, the significant length of this bore provided unique challenges involving equally unique engineering solutions which are discussed in this paper. They include the design of a second shorter HDD bore used to transport drilling fluids since an intercept scheme was not utilized, special attention to the engineering analysis of the proposed drill pipe which was determined to be the weakest link of the overall installation system, a modified buoyancy control method developed specifically to reduce the installation pull forces which would be adjusted on a real time in-the-field basis, and a complete thrust wall design developed to withstand the high predicted installation loads inherent in a single rig HDD of this scale. These challenges are discussed in detail in the following sections.

2. SECONDARY HDD FLUID RELIEF BORE

The Contractor elected to perform the HDD crossing with a single drill rig instead of utilizing the intersect method which is more common for bores longer than 5,000 feet. The Contractor also decided that a shorter and smaller diameter HDD bore would first be constructed by laying pipe along the ground surface from the large diameter HDD entry point, to an entry point much closer to the river edge. The smaller bore would then exit at the same location as the larger HDD bore exit point. This 6-inch pipeline constructed parallel to the 32-inch bore would be used to reduce the overall project costs during reaming operations by providing a closed loop for the drilling mud to be pumped from the exit point through the 6-inch return line back to the mud separation plant at the 32-inch entry site. This parallel crossing with surface-laid pipe allowed the contractor to eliminate the need for a separation plant at the exit site while maintaining drilling fluid circulation back to the primary HDD entry site. The drilling fluid return pipe also limited the amount of drilling fluid handling equipment required on the exit side of the river. Figure 2 presents a plan with both HDD bores shown for clarity.

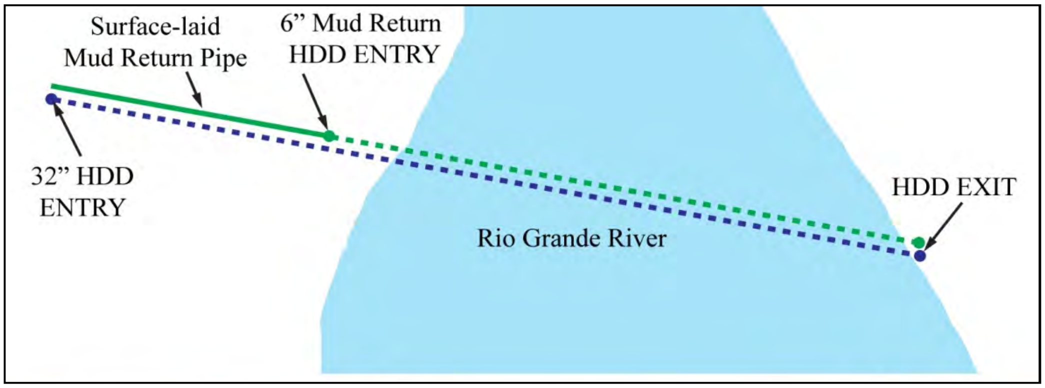


Figure 2. Plan Illustration of the 32-inch HDD and 6-inch Mud Return HDD.

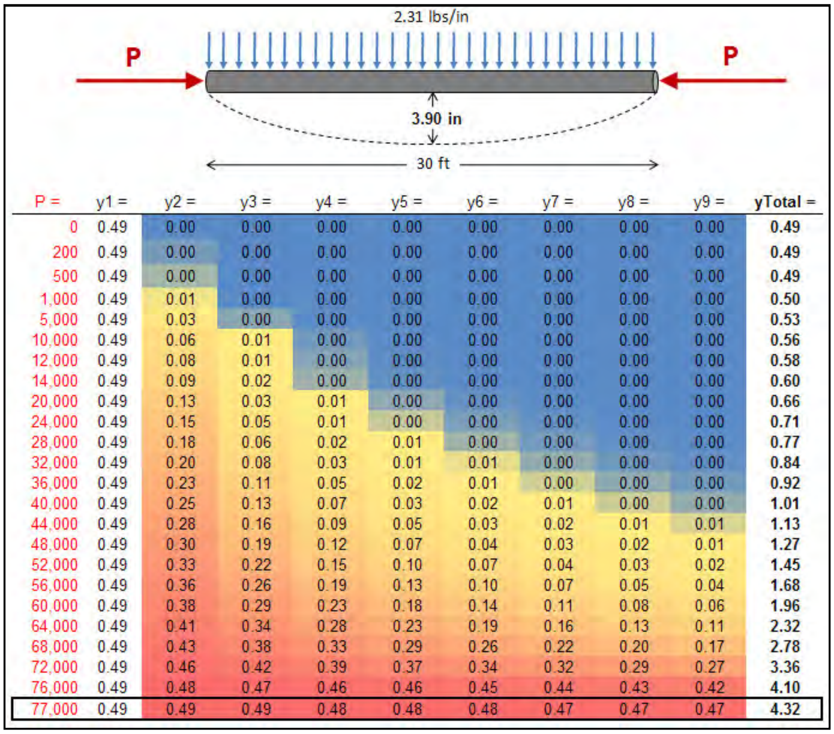
The 6-inch mud return HDD could be shortened since it was a temporary installation, while the 32’inch HDD could not encroach on the erosion prone zone of the river bank. The river is known to flood and scour the surrounding area and thus an adequate setback distance for the permanent pipeline was required.

3. DRILL PIPE: THE WEAK LINK

After performing preliminary engineering analysis of the crossing, it was determined that the drill pipe would be the “weak link” of the overall installation system. Typically the drill pipe size is based on the drill rig size, bend radius of the bore geometry, tooling requirements, and anticipated installation tensile forces. This project introduced additional engineering concerns including the drilling fluid pressure losses both in the drill string and in the annulus, drill pipe stiffness and steering response, maximum thrust forces with drill pipe buckling, and the maximum allowable torque due to combined drill pipe stresses.

New S135, 6-5/8”, 27.70lb/ft and S135, 5-1/2”, 21.90lb/ft drill pipe were purchased specifically to meet the high demands of the project. The new pipe decreased the overall risk of failure due to fatigue while increasing the confidence in the published drill pipe engineering properties relied upon in the HDD design.

Downhole critical buckling of the drill pipe was calculated as part of the engineering design, however due to the confining nature of the pilot bore, additional loading is allowable, i.e. the pipe is not “unrestrained”, and therefore critical buckling of the drill string inside the bore hole was not necessarily the limiting design parameter. In practice, although harmful over the life of the drill pipe, forcing sinusoidal buckling of the drill string inside the pilot bore can be used as a technique to clear a blockage and regain drilling fluid circulation under certain conditions, e.g., a loss of circulation due to accumulated cuttings that cause a blockage around the drill pipe that cannot be cleared by sliding the drill pipe as when advancing and retracting the drill string. By forcing the drill string to buckle it is possible to move the blockage laterally, thus clearing a path for the drilling fluid to flow more freely and regain fluid circulation. The limiting factor controlling the maximum drill rig thrust is the stiffness of the drill pipe outside of the bore hole. Critical buckling of the unconfined drill pipe attached to the drill rig prior to entering the bore hole would require much less thrust than the same drill pipe once confined inside the bore hole. Figure 3 shows the calculation of moment magnification and amplification factor used in the cumulative deflection equation for determining the theoretical maximum thrust that could be applied to the 30-foot drill pipe without exceeding the drill pipe strength. The 'y' variables are the calculation of deflection in an iterative fashion according to the moment deflection and amplification factor method used to determine the total moment in the drill pipe at the midspan. This accounts for the primary deflection due to the drill pipe weight (y1) and the secondary moments caused by the application of axial load P.



P =	y1 =	y2 =	y3 =	y4 =	y5 =	y6 =	y7 =	y8 =	y9 =	yTotal =
0	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.49**
200	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.49**
500	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.49**
1,000	0.49	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.50**
5,000	0.49	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.53**
10,000	0.49	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	**0.56**
12,000	0.49	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.00	**0.58**
14,000	0.49	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.00	**0.60**
20,000	0.49	0.13	0.03	0.01	0.00	0.00	0.00	0.00	0.00	**0.66**
24,000	0.49	0.15	0.05	0.01	0.00	0.00	0.00	0.00	0.00	**0.71**
28,000	0.49	0.18	0.06	0.02	0.01	0.00	0.00	0.00	0.00	**0.77**
32,000	0.49	0.20	0.08	0.03	0.01	0.01	0.00	0.00	0.00	**0.84**
36,000	0.49	0.23	0.11	0.05	0.02	0.01	0.00	0.00	0.00	**0.92**
40,000	0.49	0.25	0.13	0.07	0.03	0.02	0.01	0.00	0.00	**1.01**
44,000	0.49	0.28	0.16	0.09	0.05	0.03	0.02	0.01	0.01	**1.13**
48,000	0.49	0.30	0.19	0.12	0.07	0.04	0.03	0.02	0.01	**1.27**
52,000	0.49	0.33	0.22	0.15	0.10	0.07	0.04	0.03	0.02	**1.45**
56,000	0.49	0.36	0.26	0.19	0.13	0.10	0.07	0.05	0.04	**1.68**
60,000	0.49	0.38	0.29	0.23	0.18	0.14	0.11	0.08	0.06	**1.96**
64,000	0.49	0.41	0.34	0.28	0.23	0.19	0.16	0.13	0.11	**2.32**
68,000	0.49	0.43	0.38	0.33	0.29	0.26	0.22	0.20	0.17	**2.78**
72,000	0.49	0.46	0.42	0.39	0.37	0.34	0.32	0.29	0.27	**3.36**
76,000	0.49	0.48	0.47	0.46	0.46	0.45	0.44	0.43	0.42	**4.10**
77,000	0.49	0.49	0.49	0.48	0.48	0.48	0.47	0.47	0.47	**4.32**

Figure 3. Illustration along with Table of Values Used to Determine the Maximum Allowable Rig Thrust.

A practical method used to increase the allowable applied rig thrust is to position the drill rig clamping vice near the midpoint of the drill pipe that is attached to the drill rig. This essentially halves the un-braced length of the drill pipe by providing support at its middle allowing for application of higher drill rig thrust. This method was recommended to the Contractor as a means of increasing the allowable thrust applied to the drill pipe during construction.

It was also determined that using two sizes of drill pipe in concert would prove advantageous when used in the lengthy pilot bore drill plan. Using a specific length of smaller diameter drill pipe followed by larger diameter drill pipe allowed the required flexibility for steering through the vertical curves while maintaining the degree of stiffness needed to advance over the lengthy straight bore section. The stepped sizes in drill pipe also allowed for a larger annulus over a portion of the bore, facilitating drilling fluid returns.

4. MODIFIED BUOYANCY CONTROL METHOD

The engineering analysis of the estimated installation pullback forces revealed that an empty product pipe would have exceedingly large installation loads. Traditional buoyancy control relies on filling the product pipe during installation via a tremie pipe. Analysis showed that a water-filled product pipe would also have exceedingly large installation loads, due both to the frictional drag in the bore hole and due to the additional weight on the pipe rollers. In order to reduce installation forces during pullback to a minimum, a modified buoyancy control method (MBCM) was developed that results in a neutrally buoyant product pipe for approximately 75 percent of the total bore length. The MBCM is dependent upon several key parameters including the product pipe pullback speed and the field-measured drilling fluid density determined at the time of pullback.

The MBCM assumes that a tremie pipe will be used to fill the product pipe as it enters the bore during pullback. The tremie pipe should be installed in a manner allowing the fill water to discharge at the flow rate required by the MBCM as the product pipe is pulled into the bore. The illustration below shows the method of filling the product pipe with the proper amount of water to create a neutrally buoyant condition for approximately seventy-five percent of the bore. When pulling the product pipe through the initial vertical curve, the pipeline is filled adequately so that the additional weight aids in decreasing the pull force. When entering the horizontal section of the bore, the fill rate is adjusted until the product pipe becomes neutrally buoyant. In the last vertical curve, the pipe buoyancy aids in reducing the installation forces.

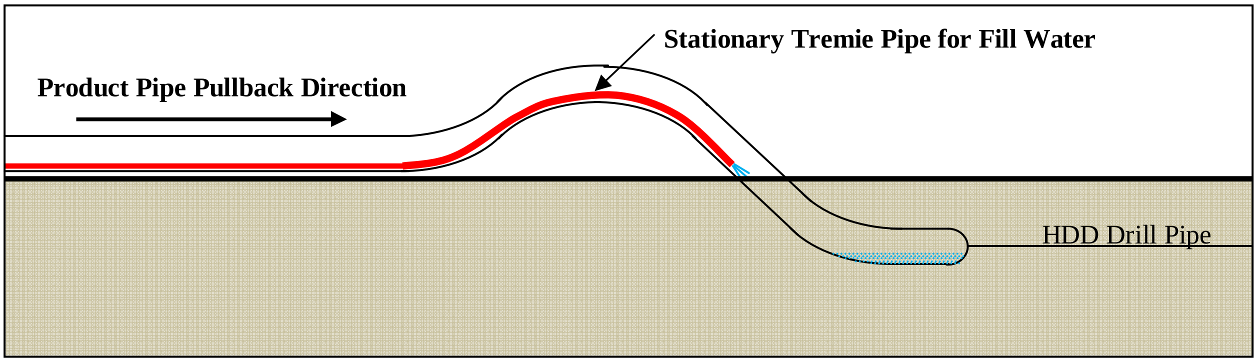


Figure 4. Modified Buoyancy Control Method – Fill Schematic

Figures 5 and 6 are charts developed for in-the-field determination of the required water fill rate. The MBCM allows the contractor to use the added water ballast to aid in reducing the installation forces as the product pipe is installed. The MBCM requires a premeasured tremie pipe to deliver the ballast water to the proper location inside the product pipe, a stopwatch to determine average pullback rate, a sufficient water source capable of providing the required flow rates, an inline tremie pipe flow meter including a total water volume meter, average drilling fluid densities measured at the time of pullback, and the field MBCM chart to determine the water ballast flow rate. As can be seen from Figure 5, the fill rate that must be used increases as mud weight increases and as pullback rate increases.

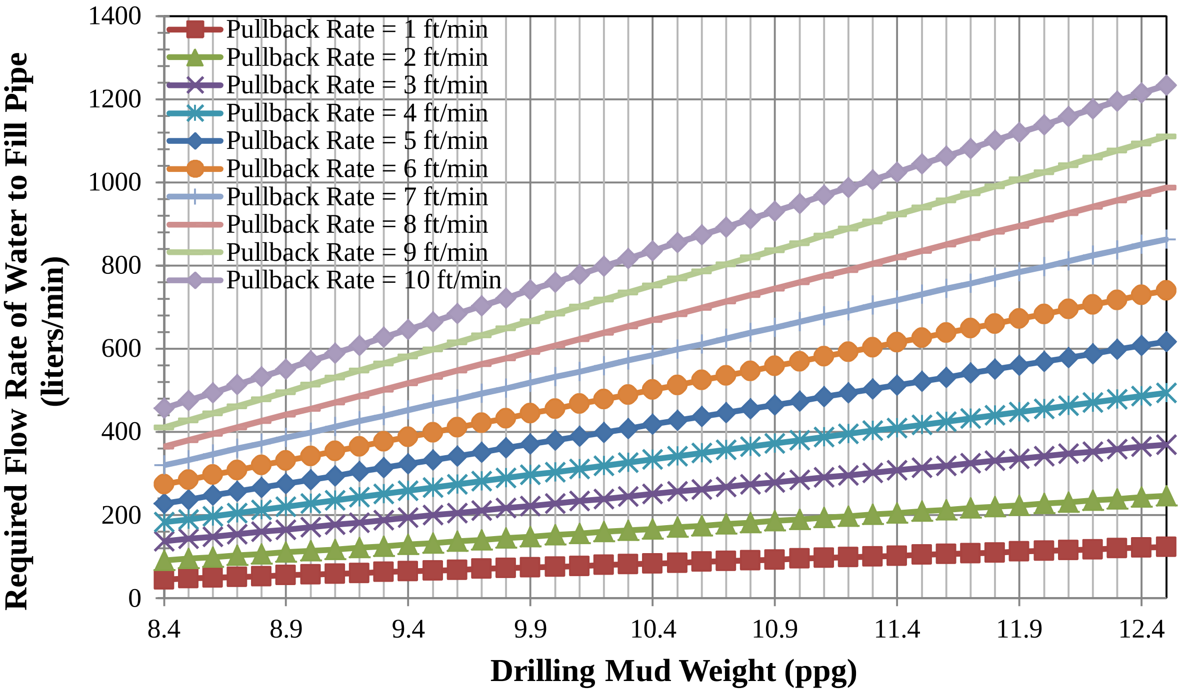
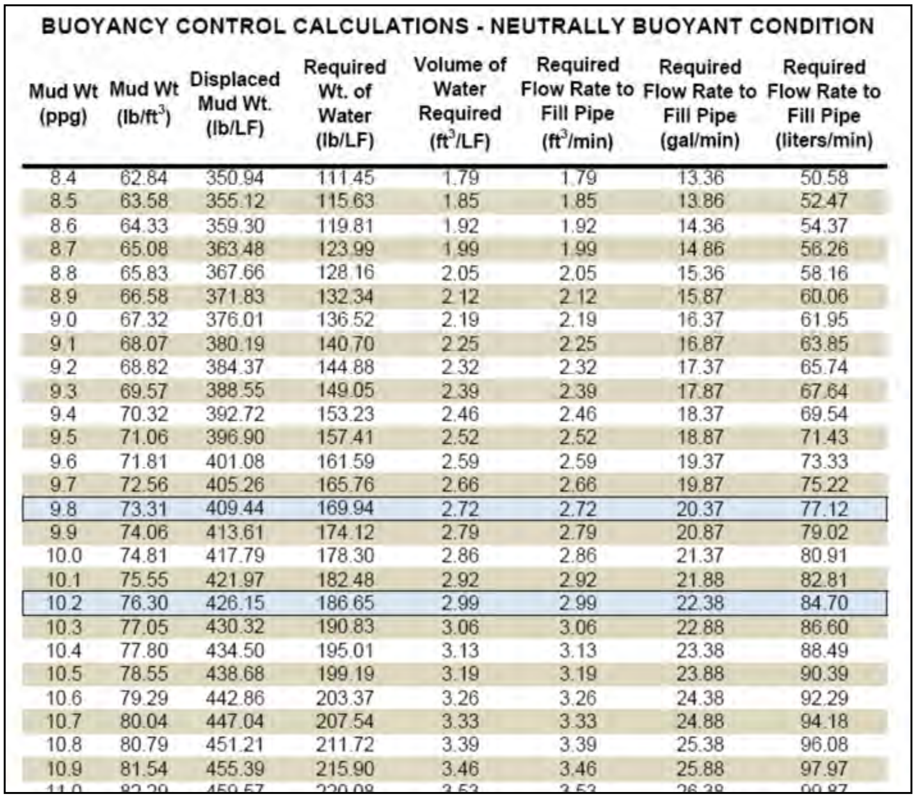


Figure 5. Modified Buoyancy Control Method – Fill Rate Graph.



BUOYANCY CONTROL CALCULATIONS - NEUTRALLY BUOYANT CONDITION

Mud Wt (ppg)	Mud Wt (lb/ft^3)	Displaced Mud Wt. (lb/LF)	Required Wt. of Water (lb/LF)	Volume of Water Required (ft^3/LF)	Required Flow Rate to Fill Pipe (ft^3/min)	Required Flow Rate to Fill Pipe (gal/min)	Required Flow Rate to Fill Pipe (liters/min)
8.4	62.84	350.94	111.45	1.79	1.79	13.36	50.58
8.5	63.58	355.12	115.63	1.85	1.85	13.86	52.47
8.6	64.33	359.30	119.81	1.92	1.92	14.36	54.37
8.7	65.08	363.48	123.99	1.99	1.99	14.86	56.26
8.8	65.83	367.66	128.16	2.05	2.05	15.36	58.16
8.9	66.58	371.83	132.34	2.12	2.12	15.87	60.06
9.0	67.32	376.01	136.52	2.19	2.19	16.37	61.95
9.1	68.07	380.19	140.70	2.25	2.25	16.87	63.85
9.2	68.82	384.37	144.88	2.32	2.32	17.37	65.74
9.3	69.57	388.55	149.05	2.39	2.39	17.87	67.64
9.4	70.32	392.72	153.23	2.46	2.46	18.37	69.54
9.5	71.06	396.90	157.41	2.52	2.52	18.87	71.43
9.6	71.81	401.08	161.59	2.59	2.59	19.37	73.33
9.7	72.56	405.26	165.76	2.66	2.66	19.87	75.22
9.8	73.31	409.44	169.94	2.72	2.72	20.37	77.12
9.9	74.06	413.61	174.12	2.79	2.79	20.87	79.02
10.0	74.81	417.79	178.30	2.86	2.86	21.37	80.91
10.1	75.55	421.97	182.48	2.92	2.92	21.88	82.81
10.2	76.30	426.15	186.65	2.99	2.99	22.38	84.70
10.3	77.05	430.32	190.83	3.06	3.06	22.88	86.60
10.4	77.80	434.50	195.01	3.13	3.13	23.38	88.49
10.5	78.55	438.68	199.19	3.19	3.19	23.88	90.39
10.6	79.29	442.86	203.37	3.26	3.26	24.38	92.29
10.7	80.04	447.04	207.54	3.33	3.33	24.88	94.18
10.8	80.79	451.21	211.72	3.39	3.39	25.38	96.08
10.9	81.54	455.39	215.90	3.46	3.46	25.88	97.97

Figure 6. Modified Buoyancy Control Method – Sample Fill Rate Matrix (anticipated mud weights highlighted).

The MBCM cannot be considered exact, however it does provide the contractor with a tool that can be utilized and most importantly, field adjusted to the actual conditions in order to decrease pipe installation loads. An additional periodic check of the total volume of ballast water added to the product pipe also proves advantageous in accomplishing a neutrally buoyant product pipe throughout the majority of the pullback. A total water volume check table calculated at discrete locations or installation lengths aid the contractor in this goal. This approach also allows corrections to any previous ballast errors as the product pipe is installed.

The Contractor developed an innovative solution that also helped to reduce the installation forces by utilizing a low friction pipe pulling plan (LFPP) which consisted of placing the pipe rollers at surveyed elevations that slope toward the pipe entry point. This scheme reduced the amount of force required to pull the pipe string on the surface into the bore hole. Although the LFPP proved helpful, it only became truly effective when combined with the MBCM which prohibited filling the pipe string prior to entering the bore hole, thus reducing the overall friction forces.

5. THRUST WALL RESTRAINT DESIGN

In order to ensure that the drill rig was sufficiently anchored during construction, the Owner required the Contractor to submit a detailed engineered thrust restraint design. Having had previous experience with sheet pile systems, the Contractor requested a sheet pile wall thrust design sufficient to withstand the estimated loadings. Previous engineering design calculations estimated the maximum allowable thrust applied to the drill pipe while advancing the pilot bore and also the maximum estimated tensile forces during product pipe pullback. The sheet pile wall was designed to support a lateral loading of a million pounds. Several options were developed for the Contractor in order to provide economy and flexibility in construction. Figures 7 and 8 illustrate the general design configuration and layout of the system.

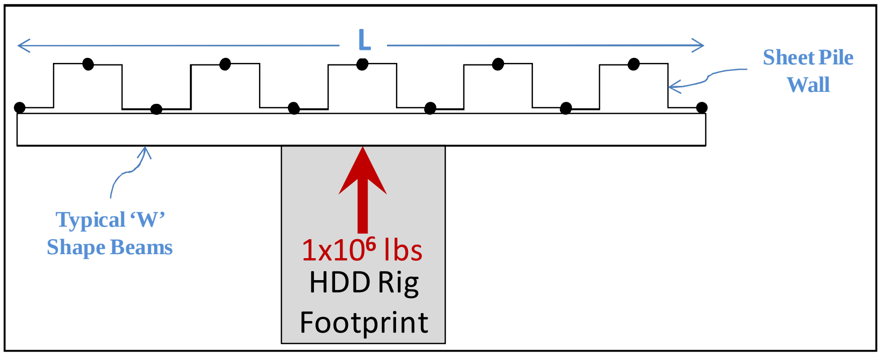


Figure 7. Plan illustration of the sheet pile anchoring system.

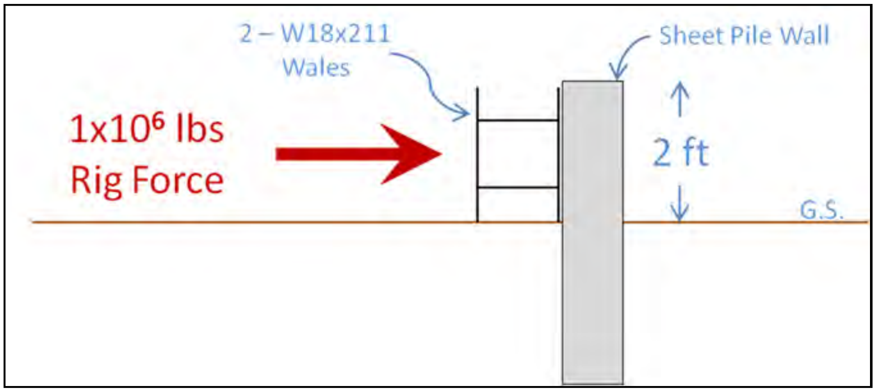


Figure 8. Profile illustration of the sheet pile anchoring system.

Specific information from the geotechnical report was used in the design for the sheet pile wall thrust restraint system. The design required an iterative solution that progressed according to the limiting factors of the maximum pile drive depth, available sheet pile section modulus, and constructability concerns. The Contractor was provided with two solutions for constructing the sheet pile restraint wall. The first consisted of very large box-shaped interlocking sheets that would form a single wall in front of the rig. A second alternative utilized a more common sheet pile shape that would form a wall in front of the rig with returns at the ends of the wall extending to the rear of the rig to provide the required strength. This second alternative also required increased bracing between the front wall and the extended returns to transfer the loads sufficiently throughout the wall system.

6. CONCLUSION

This project design proved challenging in many different aspects as it progressed. Working with the Contractor to develop feasible and economic solutions proved advantageous and helped save engineering costs by allowing on-the-fly design changes that were compatible with the Contractor's skills and experience level. Innovative solutions developed both by the Contractor and Engineer to overcome the high installation forces were instrumental to the success of the project. Every aspect of HDD design becomes a challenge when dealing with single drill bores of extended length. Details that are commonly excluded to simplify an analysis must not only be considered, but accounted for in the design phase of lengthy HDD bores. Mud frictional losses, large mud volumes, alternate mud circulation methods, hydrofracture analysis, drill pipe strength in combination loading, tooling wear and fatigue, product pipe buoyancy control, pipe roller friction, potential product pipe coating damage from roller support spacing, rig anchoring design, and product pipe pull head design are only a sample of the engineering aspects considered for the project. Each of these issues exhibited independent challenges but also as a group of interconnected parts that required balance. One aspect that cannot be overrated is the ability of the Contractor to develop unique solutions as problems arise. A partnership in which the Contractor and Engineer can both share their tricks of the trade and their experience proves the most advantageous for any HDD project.

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