Direct Pipe® Installations underneath USACE Levees – Keeping Permitted Minimum Hydraulic Fracture Factor of Safety

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1. ABSTRACT

This paper discusses two Direct Pipe® (DP) crossings successfully installed underneath the United States Army Corps of Engineers (USACE) regulated levees. The first project discussed is the construction of Sabine-Neches Waterway Direct Pipe Project in the City of Port Arthur, Texas. Completed in May 2015, the project was the longest Direct Pipe installation in the North America at the time of completion. The project consisted of installing a 48-inch diameter steel casing pipe using the Direct Pipe method and then pulling a 30-inch diameter high density polyethylene (HDPE) pipe inside the casing pipe using an HDD rig. The total casing installation length was approximately 3,481 feet. This project was part of the City of Port Arthur's potable water conveyance system transporting water to Cheniere's new liquefaction plant in Louisiana. The designers of the pipeline had obtained permit to install the pipeline underneath the flood protection levee using DP method under the condition that the annular pressure be monitored during the installation and minimum factor of safety (FS) of 2 against hydraulic fracture be maintained within the levee monitoring zone. The second project discussed consisted of 1,850-feet long, 42-inch casing pipe installation underneath the Oyster Creek and flood protection levee in Clute, Texas, with the same permitting requirement of monitoring and FS of 2. Laney Directional Drilling successfully installed both pipeline crossings while maintaining the specified minimum FS within the levee monitoring zones. This paper discusses the challenges faced during construction of the projects and how they were overcome. The authors also present the installation data including productivity, thrust load and annular pressures.

2. INTRODUCTION

Direct Pipe® (DP) is a trenchless method of installing pipelines in areas where traditional open cut excavations are not feasible for environmental or logistical reasons. DP technology is a registered trademark for the trenchless pipeline installation method developed by Herrenknecht AG (Herrenknecht), Germany. It combines the advantages of the traditional Horizontal Directional Drilling (HDD) and microtunneling technologies to overcome challenging installation conditions.

Recently, the DP method has been used for a number of pipeline installations underneath USACE in lieu of HDD because of one particular advantage; that advantage being lower annular pressure compared to HDD during DP installation. Typically, USACE require a minimum factor of safety of 2 against hydraulic fracture within levee monitoring zone to permit any HDD or DP installation underneath their levee, with levee monitoring zone typically spanning 300-ft away from either toe of the levee. When the formation underlying the levee is predominantly saturated clay formation, it is challenging to design an HDD path that meets this requirement. This paper discusses two case studies where DP method met the design requirements for crossing the USACE levees and successful installations were achieved without any inadvertent returns. As shown by the second project discussed in this paper, even an HDD
design with factor of safety of 2 does not guarantee successful completion of installation because of limitations in prediction and monitoring of annular pressures during HDD installations.

In May, 2015, Laney Directional Drilling (Laney), a Texas based engineering and construction firm, completed the 3,481-feet long Sabine Neches Direct Pipe Project in the City of Port Arthur, Texas. The project consisted of installing a 48-inch diameter, 0.750 wall thickness steel casing pipe by DP method, and then installing a 30-inch SDR 11, HDPE pipe inside the casing. This was Laney’s second DP installation and was longest successful DP installation in the North America at the time of completion. Laney’s first DP installation of 1,350-feet in 2013, detailed in Sharma et al. (2014), was also the longest in the North America at the time of construction. Sabine Neches Direct Pipe Project consisted of the pipeline installation underneath a road, Sabine-Neches Waterway, Kansas City Railroad, and most importantly the hurricane protection levee regulated by United States Army Corps of Engineers (USACE). Sabine Neches Direct Pipe project was the first installation underneath a USACE regulated levee successfully completed by Laney. Laney partnered with Strike, LLC, a Texas based construction company, to procure the Sabine Neches Direct Pipe project through competitive bidding process.

In August, 2015, Laney completed another successful DP installation underneath a USACE levee. Oyster Creek Direct Pipe Project consisted of installing a 42-inch steel casing pipe underneath the Oyster Creek and the USACE levee and then installing a 16-inch steel product pipe inside the casing. The DP method was pursued to install the 1,850-feet section of the pipeline after an unsuccessful attempt of HDD installation by other HDD contractor had resulted in inadvertent returns in the levee. The inadvertent returns resulted in the USACE permitting further installation attempt only if DP method was used, and the annular pressure was monitored.

3. HYDRAULIC FRACTURE ANALYSIS FOR DIRECT PIPE

The hydraulic fracture during an HDD or a DP installation is defined as the fracture of the formation initiating at the drilled or mined hole caused by the pressure developed in the annular fluid. The annular fluid pressure causes the hole to expand and eventually fracture if limit pressure is exceeded. This fracture may extend to the surface causing inadvertent returns of drilling fluid to the surface. The hydraulic fracture analysis is performed on the HDD or DP design to ascertain risks of such fracture to occur during construction. The hydraulic fracture analysis of a DP design is similar to that of a HDD design. First the formation limit pressure is calculated using the Delft equation. Then, the annular pressure during installation is estimated. The factor of safety against hydraulic fracture is calculated by dividing the formation limit pressure by the estimated annular fluid pressure. The detailed methodology for the hydraulic fracture analysis has been described in literature like Latorre et al. (2002) and Sparks et al. (2010).

3.1 Formation Limit Pressure for Direct Pipe Installation

The formation limit pressure for direct pipe installations, like for HDD installations, is estimated using Delft Equation (Delft Geotechnics, 1997) presented in equation 1.

\[ P_{\text{max}} = u + (\sigma_0' \ast (1+\sin\varphi) + c \ast \cos\varphi + c \ast \cot\varphi) \ast \left[ (R_o/R_{\text{pmax}})^2 + \left( (\sigma_0' \ast \sin\varphi + c \ast \cos\varphi)/G \right) \right]^{\sin\varphi/(1+\sin\varphi)} \]

Where:
- \( P_{\text{max}} \) Formation Limit Pressure
- \( u \) Pore water pressure at the drilled hole
- \( \sigma_0' \) Effective overburden pressure at the drilled hole
- \( \varphi \) Angle of internal friction of soil
- \( c \) Cohesion of soil
- \( R_o \) Radius of the drilled hole
- \( R_{\text{pmax}} \) Maximum radius of plastic deformation of drilled hole
- \( G \) Shear Modulus of soil

In case of saturated cohesive soils, the angle of internal friction is zero. In such case, Equation 1 reduces to Equation 2 shown below.

\[ P_{\text{max}} = u + \sigma_0' + c \]

3.2 Annular Fluid Pressure for Direct Pipe Installation
For an HDD installation, annular drilling fluid pressure consists of two components: (i) hydrostatic pressure of drilling fluid, and (ii) cutting transfer pressure or frictional head loss due to annular flow. As the length of the HDD increases, the cutting transfer pressure increases. Depending upon the drill bit size, drill rod size, pumping rate, and rheological properties of the drilling fluid, the cutting transfer pressure during pilot hole operation of an HDD installation may range from 0.03 to 0.045 psi per foot of pilot hole.

The DP method utilizes two separate fluid systems which transport lubrication fluid and slurry fluid. The primary purpose of the lubrication fluid is to reduce friction on the product pipe. The lubrication fluid also supports the tunnel wall. The purpose of the slurry fluid is to lower the temperature of the cutter-head and transport the cuttings. During a DP installation, the slurry fluid with cuttings are transferred inside the installation pipe through slurry lines. Therefore, the annular pressure comes only from the hydrostatic pressure of the lubrication fluid. Equation 3 can be used to estimate the annular pressure during DP installation.

\[
P_{\text{annular}} = \lambda_f \cdot H \tag{3}
\]

Where:
- \(P_{\text{annular}}\) Annular lubrication fluid pressure
- \(\lambda_f\) Density of lubrication fluid
- \(H\) Elevation difference between the point being calculated and the entry point

Saturated clays are common underneath the levees in Texas-Louisiana area. Since, the limit pressure in saturated clay is reduced to the sum of overburden pressure and the cohesion of the soil, the allowable pressure is often too low for HDD to be possible. In such cases DP may be used to make pipeline installation underneath the levee possible, without significant risk to the integrity of the formation.

4. SABINE NECHES DIRECT PIPE PROJECT

The Sabine Neches Direct Pipe Project consisted of installing a 48-inch diameter, 0.750 wall thickness steel casing pipe by DP method underneath a road, Sabine-Neches Waterway, Kansas City Railroad, and the flood protection levee regulated by United States Army Corps of Engineers (USACE). Figure 1 illustrates the DP alignment and the obstacle crossed by the DP method. The DP method was selected as the construction method for this project mainly because the DP method met USACE requirement of minimum factor of safety of two underneath the levee monitoring zone.

4.1 Project Challenges

4.1.1 Entry Workspace

One of the advantages of the DP method is that the entire operation can be carried out from the entry side, except to retrieve the machine from the exit side. In more challenging situations, the machine can also be retrieved from the exit side, but this project did not require such measures. The exit point was inside the Lakefront Park, as shown in Figure 1. Behind the park was wetlands area, therefore the exit side could not be used as entry, although Laney considered that idea. Figure 2 illustrates the entry area of the project.

4.1.1.1 Neighborhood Complaints

The entry point was near a residential neighborhood. Sound walls were used to block the construction noise going into the neighborhood. The DP operations continued twenty four hours during the tunneling phase of the project. Laney and Strike attended biweekly town hall meetings during the construction to address any complaints or concerns that the residents had about the project. The noise was monitored and kept to the acceptable limits during the construction.

4.1.1.2 Pipe Stringing

From the productivity standpoint as well as from the risk standpoint, it is preferable to minimize, if not eliminate, mid-weld during the tunneling operation. However, due to amount and topography of available space behind the entry point, the longest pipe string possible was 400-feet. The storm water drainage shown in Figure 2 would prevent one continuous string from the entry point. Therefore, nine pipe strings and eight mid welds were required during the construction. With the help of the City of Port Arthur, and their engineers Arsenio, Wilson and Cole, Inc. (AWC), Strike and Laney obtained permit to close on lane of the Highway 82. Space between the Highway 82 and the storm water drainage was used to stage 400-feet strings of casing pipe which would be used for each mid-weld. Due to the
angle of the alignment, the space between the Highway 82 and storm water drainage could not be used for one continuous string. This would require tight horizontal radius at the over-bend.

Figure 1. Obstacles Crossed during Sabine Neches Direct Pipe Project

4.1.2 Maximum Allowable Pressure

The original DP plan and profile design met USACE requirement of hydraulic fracture factor of safety of 2 underneath the levee monitoring zone. However, at few locations within the levee monitoring zone, the factor of safety was at 2.0 with no margin for error. The estimated lubrication fluid pressure and the maximum allowable pressures were very
close. In order to add margin of error, Laney proposed a 10-feet deep entry pit to launch the Direct Pipe operation. This would lower the lubrication fluid hydrostatic pressure and also reduce the over-bend height required for the pipe support. Figure 3 illustrates the DP profile proposed by Laney, estimated annular pressures for both HDD and DP based on the proposed profile, and the maximum allowable pressure calculated by GeoEngineers and traced from the bid document. Figure 3 not only illustrates the difference in annular pressure that would be required for HDD and DP, but also shows that for the Sabine Neches Direct Pipe Project, the maximum allowable annular pressures within the levee monitoring zone were very close to that estimated. Additionally, the hydraulic fracture factor of safety underneath the Sabine Neches Waterway was above 1, but below 2 because of low overburden available at the channel.

Figure 3. Estimated Annular Pressures for Sabine Neches Direct Pipe Project

4.2 Construction Methodology

4.2.1 Entry Pit and Foundation
The original designed called for the DP to be launched from the surface with an option of a pit that the contractor needed to design if the contractor chose. Laney chose to launch from a 10-feet deep pit because it had advantages of lower over-bend height and lower lubrication fluid pressure. Laney performed additional geotechnical boring at the entry point location for the purpose of the entry pit and the thruster foundation design. The entry pit and the thruster are illustrated in Figure 4. The pit consisted of 30-feet driven sheet pile. The thruster foundation consisted of six driven piles to withstand compression, uplift as well as lateral thrust reaction forces. Sharma et al. (2014) present the typical magnitude and direction of the reaction forces.

4.2.2 Lubrication Fluid Pressure Monitor
The 48-inch microtunnel boring machine (MTBM) used for the project is described in Sharma et al. (2014). Laney requested Herrenknecht, A.G., the manufacturer of the MTBM to add a special sensor to monitor the lubrication fluid pressure on the MTBM. Standard MTBMs do not come with such sensors. The sensor provided the continuous reading of the lubrication fluid pressure. Figure 5 compares the actual recorded lubrication fluid pressure with the estimated lubrication fluid pressure. It can be seen that the actual recorded lubrication fluid pressure lines up with the estimated
pressure very well. It can also be noted that at station 11+00 approximately, the recorded pressure exceeded the estimated as well as the allowable pressures. As per pre-agreed plan, Laney stopped the operation, reconfigured the lubrication fluid properties and the discharge rates, and restarted the operation and maintained within the allowable pressures. No lubrication fluid loss or inadvertent returns were observed during construction including under the Sabine Neches Waterway where hydraulic fracture factor of safety was below 2.

![Image of lubrication fluid pressure](image)

**Figure 4. Entry Pit for Sabine Neches Direct Pipe Project**

![Graph of lubrication fluid pressure](graph)

**Figure 5. Recorded Lubrication Fluid Pressure for Sabine Neches Direct Pipe Project**

### 4.2.3 Thrust Loads

The standard procedure for DP operation consists of monitoring and recording thrust load applied by the thruster unit (thrust force) at the clamp and the load experienced by the cutter head at the tunnel face (face force). The difference between the thrust force and the face force is attributed to the friction between the pipe and the tunnel wall, and the weight of the pipe. Figure 5 illustrates the thrust and face forces recorded during the Sabine Neches Direct Pipe Project.
The face force was maintained in the range of 120,000 pounds to 160,000 pounds for the majority of the tunneling operation. The maximum face force was 199,538 pounds. For approximately first 700-feet of the installation, the thrust force was lower than the face force. This was potentially due to the weight of the pipe and the MTBM applying additional force at the tunnel face. The frictional force showed linearly increasing trend after the approximately 1,700-feet of installation was completed. The frictional force before that point was negligible. Figure 6 also shows spikes in thrust forces at few locations. Such spikes were experienced because of static friction while resuming the tunneling operation after mid-weld.

![Figure 6. Recorded Thrust Loads for Sabine Neches Direct Pipe Project](image)

### 4.2.3 Schedule and tunneling rates

The 3,581-feet installation was complete ahead of schedule. The tunneling operation was completed in 24 days of 24 hour operation, which included 5 total days of stoppage for mid-welds. The average tunneling rate was approximately 8.5-feet per hour not accounting for stoppages and setup times, and including only tunneling hours.

### 5. OYSTER CREEK DIRECT PIPE PROJECT

Laney completed another successful DP installation underneath a USACE levee. The Oyster Creek Direct Pipe crossing was a part of Philips 66 Sweeny Midstream Pipeline Project. Oyster Creek and levee crossing was originally designed an HDD crossing. This design met the USACE criteria of factor of safety of 2 underneath the levee. The HDD installation of the 16-inch ethane pipeline crossing was attempted by another HDD contractor. However, the attempt was unsuccessful after inadvertent drilling fluid returns were observed at the levee and USACE did not allow further attempt using the HDD method. The USACE, however, allowed the pursuance of installation if the Direct Pipe method was used. Therefore, further construction attempt consisted of a 42-inch steel casing pipe underneath the Oyster Creek and the flood protection levee using the Direct Pipe method and then installing the 16-inch steel product pipe inside the casing.

### 5.1 Construction Methodology
5.1.1 Entry Pit and Foundation
Laney designed the Direct Pipe plan and profile with an entry pit similar to that for the Sabine Neches Direct Pipe Project. Again, the purpose was to reduce the hydrostatic pressure on the lubrication fluid, and reduce the over-bend height required for the pipe support.

5.1.2 Lubrication Fluid Pressure Monitor
A brand new 42-inch microtunnel boring machine (MTBM) manufactured by Herrenknecht, A.G., was used for this project. The MTBM came with a special sensor to monitor the lubrication fluid pressure. Standard MTBMs do not come with such sensors. The sensor provided the continuous reading of the lubrication fluid pressure. Figure 7 compares the actual recorded lubrication fluid pressure with the estimated lubrication fluid pressure. It can be seen that the actual recorded lubrication fluid pressure lines up with the estimated pressure very well. No lubrication fluid loss or inadvertent returns were observed during the construction.

![Figure 7. Recorded Lubrication Fluid Pressure for Oyster Creek Direct Pipe Project](image)

5.1.3 Thrust Loads
Figure 5 illustrates the thrust and face forces recorded during the Sabine Neches Direct Pipe Project. The face force was maintained below 100,000 pounds for the majority of the tunneling operation. The frictional load was also kept maximum of 130,000 pounds while the maximum thrust force was 185,000 pounds.
6. CONCLUSIONS

Although Direct Pipe is relatively new technology to the North America, this method has been used numerous times to solve difficult situations when methods like HDD and Microtunneling could not be used. One of the main applications of Direct Pipe has been to cross USACE regulated levees where the potential of hydraulic fracture and inadvertent returns is very high. The success of the Sabine Neches Project and Oyster Creek Direct Pipe Projects show that Direct Pipe method can be used without any impact to the levees which are key infrastructures in the areas with potential impacts of hurricanes and flood. The 3,581-feet Sabine Neches Direct Pipe also shows how the limits of Direct Pipe is being continually pushed in North America with great success.

7. REFERENCES

