ANALYSIS OF SUBSURFACE PRESSURES INVOLVED WITH DIRECTIONALLY CONTROLLED HORIZONTAL DRILLING

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Abstract

Utilization of directionally controlled horizontal drilling for the trenchless installation of pipelines continues to grow. This process presents designers and contractors with significant advantages in installing pipelines beneath a wide range of surface obstacles and is being considered with greater frequency for use on projects in urban environments. Because it involves the uncontrolled subsurface discharge of drilling mud, careful analysis of subsurface pressures is critical to insure that no damage is done to adjacent structures. In this paper, the author describes a technique used to calculate downhole mud pressures on a 20-inch (508mm) gas pipeline installation in New Orleans, Louisiana. The results of the calculations were used to specify maximum allowable drilling parameters and thus obtain permission from government agencies to install the line. Geotechnical considerations affecting design of the drilled path are also reviewed. The presentation concludes with recommendations for future field instrumentation programs which will improve knowledge of drilling mud behavior in directionally controlled horizontally drilled pipeline installations.

Introduction

In 1988, Riverway Gas Pipeline Company (a subsidiary of Texaco) extended its natural gas pipeline system to provide service to future industrial development in suburban New Orleans. This extension involved approximately eight miles of 20-inch (508mm) welded steel pipeline and cost $9.5 million. A 3,800 (1158m) foot segment of the extension fell beneath St. Claude Avenue in the suburb of Arabi. From a construction standpoint,

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this segment posed a significant problem. Installation of the line by conventional cut and cover techniques would have severely disrupted traffic on St. Claude Avenue. Construction would have also been costly because of the special steps required to open a new ditch safely in this crowded urban environment and avoid damage to existing surface and subsurface structures. For this reason, Riverway chose to employ directionally controlled horizontal drilling, a method it had used in the past to install pipeline river crossings.

**General Description of Method**

Installation of a pipeline by directionally controlled horizontal drilling is a two stage process. The first stage consists of drilling a small diameter pilot hole along a designed directional path. The second stage involves enlarging this pilot hole to a diameter which will accommodate the product pipe and pulling the pipe back into the enlarged hole.

Pilot hole directional capability is accomplished by using a small diameter nonrotating drill string with an asymmetric leading edge. This asymmetry creates a steering bias in its direction and plane. When a change in direction is required, the drill string is rotated so that the direction of bias is the same as the desired change in direction. Bit rotation, when required, is provided by a downhole mud motor. Drilling progress can also be achieved by hydraulic cutting action. The actual path of the pilot hole is monitored during drilling by taking periodic readings of the inclination and azimuth of the leading edge. These readings, in conjunction with measurements of the distance drilled since the last survey, are used to calculate the horizontal and vertical coordinates of the leading edge relative to the initial entry point on the surface. Periodically during pilot hole drilling, a wash pipe may be rotated concentrically over the nonrotating drill string. This wash pipe prevents sticking of the smaller nonrotating string and allows its drilling bias to be freely oriented.

Enlarging the pilot hole is accomplished using either prereaming passes prior to pipe pull back or simultaneously during pull back. For prereaming, reaming tools are attached to the drill pipe at the exit point. The reamers are then rotated and drawn to the drilling rig. Pipe is added behind the reamers as they progress toward the drill rig. This insures that a string of pipe is always maintained in the drilled hole. For smaller diameter lines, pre-reaming passes may be omitted and the final installation pass undertaken upon completion of the pilot hole. In this case, the prefabricated pipeline
pull section is attached behind the reaming assembly and follows the reamers to the drill rig.

**Inadvertent Drilling Mud Returns**

A problem presented by the use of this construction method in an urban environment is the possibility of high downhole mud pressures resulting in formation fracturing. Problems have been experienced on past river crossing installations with mud flowing up piles to the foundations of adjacent structures and surface returns at locations other than the entry and exit points. On river crossings, typically at undeveloped locations, these occurrences do not present a serious problem. However, damage to adjacent structures along St. Claude Avenue and mud flow in the public street could not be tolerated. Permits required that downhole mud pressures be analyzed by a registered professional engineer prior to construction and the results of the analysis presented to permitting agencies for review. Downhole pressures and inadvertent returns had to be minimized and contingency plans had to be in place to deal with any surface returns.

**Geotechnical Considerations in Drilled Path Design**

Five borings were taken along the alignment to determine the subsurface soil properties. The borings indicated soil generally consisting of very soft to medium clay materials with some organics, sands and silts to a depth of approximately 70 feet (21.3m) below the surface. At this approximate depth surficial Pleistocene deposits were encountered. These consisted of medium stiff to very stiff clays with some silt and sand pockets.

The chief concern in designing the elevation of the crossing was the possibility of inadvertent surface mud returns. Because of this, a depth of 140 feet (42.7m) below the surface was selected. At this depth, the line would be placed well within the Pleistocene deposits. This stiff clay formation had the best properties for containing mud flow. Additionally, an inadvertent flow path established toward the surface had the possibility of intersecting a sand deposit which would tend to absorb all or some of its volume. A factor of safety against any surface settlement due to subsoil erosion was also provided. Since depth does not significantly effect the cost of a drilled installation (within the same horizontal drilled length), a philosophy of "the deeper the better" was established. The configuration of the drilled path (surface penetration angles, radii of curvature) was based on standard practice.
The transition zones from the entry and exit points at the surface to the design elevation still presented problems with respect to mud flow and settlement. These could only be dealt with by careful advance planning for remedial action if a flow pattern was established or settlement observed.

Analysis of Downhole Pressures and Mud Flow

The requirement of permitting agencies that downhole pressures be analyzed resulted in the establishment of new procedures. This type of analysis is not typically done for directionally controlled, horizontally drilled installations.

In order to calculate downhole pressures, it is necessary to assume that a complete flow circuit exists. That is, drilling fluid is pumped down the interior of the drill pipe, exhausted at the leading edge and flows back to the surface in the annulus between the pipe and hole wall. The total pressure imposed on the formation downhole will then be the sum of the pressure required to maintain flow along the circuit and the static pressure imposed by the weight of the flowing mud column.

Except for directional drilling, two drilled paths are available for flow from the leading edge to the surface. Annular flow can proceed along the annulus to the entry point or along the annulus to the exit point. Calculations were made based on the assumption that total flow will proceed along whichever path requires the least pressure and will totally shift when the relative pressures change. In this way a conservative maximum pressure was calculated at the point where flow shifts.

In the real world of horizontally drilled pipeline installation, it is not easy to maintain constant fluid circulation at all times. Subsurface formations are not continuous. Porous strata, lenses or structural anomalies can be encountered which provide a path of resistance to flow less than the pipe/hole annulus. Cuttings can accumulate in the low side of the hole forming an obstruction. Pressure will build up until the obstruction is overcome or another flow circuit is established. The drilling process is dynamic and momentary downhole pressure increases occur when tools are being positioned or hard drilling is encountered. In these instances, however, the excess pressure is relieved quickly with minimal flow into the surrounding soils.

The method used to calculate pressure loss due to annular flow was borrowed from the oil well drilling industry as presented in Volume I., Section V. of NL Baroid’s Manual
of Drilling Fluids Technology. Formulae are summarized below:

\[
V_c = \left[1.08(PV) + 1.08(PV)^2 + 9.26(dh-dp)^2 \cdot YP(W) \right]^{1/2}/W(dh-dp)
\]

\[
V_a = Q/[2.45(dh^2-dp^2)]
\]

\[
P_{dl} = [PV(L)V_a]/1000(dh-dp)^2 + [YP(L)]/200(dh-dp)
\]

\[
P_{dt} = [f(L)W(Va^2)]/25.8(dh-dp)
\]

Where:

- \(V_c\) = critical velocity, ft/sec
- \(V_a\) = average fluid velocity, ft/sec
- \(Q\) = mud flow rate, gal/min
- \(P_{dl}\) = pressure loss in laminar flow through a uniform annular space \((V_c>V_a)\)
- \(P_{dt}\) = pressure loss in turbulent flow through a uniform annular space \((V_c<V_a)\)
- \(PV\) = mud plastic viscosity, cp
- \(YP\) = mud yield point, lb/100 ft
- \(dh\) = hole diameter, in
- \(dp\) = outside diameter of pipe, in
- \(W\) = mud density, ppg
- \(L\) = length of hole, ft
- \(f\) = Fanning friction factor entered from graph.

Note: In most cases annular flow is laminar and the Fanning friction factor does not apply.

The calculations performed were based on a set of steady state assumptions for the various phases of a drilled pipeline installation. The formation was considered to be overpressured when the calculated mud pressure exceeded the soil overburden pressure. Overburden pressure for the soils in question increased with depth at the approximate rate of 0.75 psi/foot. Assumptions made and the results of calculations are reviewed below. Additionally, calculation results are depicted graphically in figures 1 through 5.

**Directional Drilling**

**Worse Case Condition** - The small diameter nonrotating string has advanced 200 feet(61m) ahead of the wash pipe with the total horizontal distance drilled at approximately 2700 feet(823m). All flow is directed back to the entry point along the wash pipe hole annulus.

**Calculation Results** - Overburden pressure is exceeded over the approximate entire drilled profile.
MUD PLASTIC VISCOSITY, cp = 30.0
MUD YIELD POINT, lbs/100sqr ft = 15.0
MUD DENSITY, lbs/gal = 8.7

FLOW TO ENTRY POINT  NO FLOW TO EXIT POINT

DOWNHOLE PRESSURE

OVERBURDEN PRESSURE

FIGURE 1. DIRECTIONAL DRILLING
MUD PLASTIC VISCOSITY, cp = 30.0
MUD YIELD POINT, lbs/100sq−ft = 15.0
MUD DENSITY, lbs/gal = 8.7

FLOW TO ENTRY POINT  FLOW TO EXIT POINT

FIGURE 2. RUNNING WASHPIPE
MUD PLASTIC VISCOSITY, $c_p = 30.0$
MUD YIELD POINT, lbs/100sqr-ft = 15.0
MUD DENSITY, lbs/gal = 8.7

FLOW TO ENTRY POINT    FLOW TO EXIT POINT

DISTANCE FROM ENTRY POINT, feet

FIGURE 3. PRECRAINING
MUD PLASTIC VISCOSITY, cp = 30.0
MUD YIELD POINT, lbs/100sfq-ft = 15.0
MUD DENSITY, lbs/gal = 8.7

FLOW TO ENTRY POINT  FLOW TO EXIT POINT

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DOWNHOLE PRESSURE, psi

OVERBURDEN PRESSURE

DOWNHOLE PRESSURE FLOW TO EXIT

DOWNHOLE PRESSURE FLOW TO ENTRY

DISTANCE FROM ENTRY POINT, feet

0 1000 2000 3000

FIGURE 4. REAM & PULL BACK W/O PREREAM
MUD PLASTIC VISCOSITY, $c_p = 30.0$
MUD YIELD POINT, lbs/100sq.-ft = 15.0
MUD DENSITY, lbs/gal = 8.7

FLOW TO ENTRY POINT  FLOW TO EXIT POINT

FIGURE 5. REAM & PULL BACK WITH PREREM
Running Wash Pipe

**Worse Case Condition** - The small diameter nonrotating string has advanced to within 200 feet (61m) of the exit point and wash pipe is being run up to it. No flow has been established to the exit point. All flow is directed back to the entry point along the wash pipe hole annulus.

**Calculation Results** - Overburden pressure is exceeded from a point approximately 2,500 feet (762m) from the entry point to a point approximately 3,400 feet (1,036m) from the entry point. At this location the nonrotating string is advanced to the exit point and flow is established to the exit point relieving pressure.

**Prereaming**

**Worse Case Condition** - Prereaming has progressed to a point at which the pressure required to move fluid back to the exit point from the reaming assembly is equal to the pressure required to move fluid to the entry point from the reaming assembly. Flow to the exit point is through an annulus between a 20-inch (508mm) reamed hole and a 5-inch (127mm) drill pipe. Flow to the entry point is through an annulus between a 10-inch (254mm) drilled hole and a 5-inch (127mm) drill pipe.

**Calculation Results** - The maximum calculated downhole pressure is 78 psi occurring approximately 2800 feet (854m) from the exit point. Calculated overburden pressure at this point is 105 psi.

**Ream & Pull Back without a Preream**

**Worse Case Condition** - Pull Back has progressed to a point at which the pressure required to move fluid back to the exit point from the reaming assembly is equal to the pressure required to move fluid to the entry point from the reaming assembly. Flow to the exit point is through an annulus between a 30-inch (762mm) reamed hole and the 20-inch (508mm) natural gas pipeline. Flow to the entry point is through an annulus between a 10-inch (254mm) drilled hole and a 5-inch (127mm) drill pipe.

**Calculation Results** - The maximum calculated downhole pressure is 82 psi occurring approximately 2500 feet (762m) from the exit point. Calculated overburden pressure at this point is 105 psi.
Ream & Pull Back with a Preream

Worse Case Condition - Pull Back has progressed to a point at which the pressure required to move fluid back to the exit point from the reaming assembly is equal to the pressure required to move fluid to the entry point from the reaming assembly. Flow to the exit point is through an annulus between a 30-inch (762mm) reamed hole and the 20-inch (508mm) natural gas pipeline. Flow to the entry point is through an annulus between a 20-inch (508mm) reamed hole and a 9-inch (127mm) drill pipe.

Calculation Results - The maximum calculated downhole pressure is 74 psi occurring approximately 1500 feet (457m) from the exit point. Calculated overburden pressure at this point is 105 psi.

Conclusion and Recommendations for Future Study

The St. Claude Avenue drilled segment installation was successfully carried out in the Spring of 1988. Some surface inadvertent returns were experienced in the inclined portions of the drilled path (prior to achieving total depth), however, preparations had been made for the possibility of surface returns and clean-up was accomplished with negligible public inconvenience.

For the benefit of future urban applications, it is recommended that more attention be focused on downhole mud pressures associated with directionally controlled horizontal drilling. The calculations described in this paper are well established for use in vertical oil wells drilled in deep consolidated soils. Nevertheless, their application to horizontally drilled pipeline installations has been relatively rare. The parameters used in the subject analysis were in large part assumed. Further definition of parameters by actual field measurement would be very beneficial. Definition (both into and out of the hole) of mud flow rate, yield point, plastic viscosity and density is required. This data, correlated to drilling parameters such as penetration rate, pump discharge pressure, hole diameters, bit configuration and soil conditions, will allow confirmation of the proposed analysis procedure. The data can only be gathered through a careful field measurement program implemented on multiple projects.