Directional drilling demands practical fluids knowledge

Engineers, rig operators need answers about mud volumes, behavior, content and disposal before starting

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Drilling fluid cost is a big part of pipe line installation using horizontal directional drilling (HDD), especially when disposal costs are added. Fluids also account for most of a drilling project's environmental impact.

Design engineers and rig operators need practical answers about the mud before starting the job. These answers concern drilling fluid behavior and characteristics, including fluid and component quantity estimates, disposal methods, environmental impacts and solidly written construction specifications.

Depending on job location, a second big cost item can be fluid disposal. Operators need to consider disposal methods available and settle on a cost-effective answer. Best solutions probably will be land farming or dewatering and hauling.

Another planning must is environmental impacts. Fortunately, HDD fluids, as compared to oil and gas well drilling fluids, are chemically rather benign and this fact should be understood by regulatory agencies. But the physical disruptions of an inadvertent fluid return in an urban area or a high-visibility recreation area must be considered. Contingency plans for remediation must be prepared and communicated to regulatory agencies involved.

Underlying the entire project's success is a set of well-written specifications so everyone knows who's to do what and when. One step at a time is the correct design procedure.

QUANTITY ESTIMATING

Reasonable estimates of horizontal directional drilling (HDD) fluid and fluid component quantities which will be consumed or disposed of are important in assessing the impact of drilling activities. Calculated consumption can be accomplished by breaking the installation down into its separate phases and assuming drilling parameters for each phase.

Formulas for calculating quantities and a discussion of drilling parameters are below. These formulas are for use in estimating. They contain assumptions and simplifications.

Here is a formula for pilot hole drilling:

$$V_p = Q_p (L / P) f_p f_{lp} \qquad (1)$$

Where:

- V_p = Total volume, in bbl, of drilling fluid consumed (not available for recirculation) during pilot hole drilling.
- Q_p = Drilling fluid flow rate in bbl per minute (bpm). This will range from between 2 to 6 bpm for soil crossings and up to 12 bpm for rock crossings where a large-diameter motor is used.
- L = Total drilled length in feet.
- P = Estimated pilot hole production rate in feet per hour (fph). This is a production rate and not a penetration rate. It includes time spent redrilling, surveying and adding pipe.
- f_p = Pumping factor in minutes per hour. This indicates the actual time that the mud pump is pumping downhole. For example, a pumping factor of 30 indicates a pumping duration of 30 min. for every hour of drilling. The remaining time is spent surveying and adding pipe.
- f_{lp} = Pilot hole circulation loss factor.

Here is a formula for prereaming:

$$V_r = Q_r (L/T_r) f_{lr} \qquad (2)$$

Where:

- V_r = Total volume, in bbl, of drilling fluid consumed (not available for recirculation) during a single prereaming pass. Multiple prereaming passes may be executed. In this case, V_r should be either calculated for each pass or multiplied by the number of passes, depending on the accuracy required for the quantity estimate.
- Q_r = Drilling fluid flow rate in bbl per minute (bpm). This will range from 6 to 20 bpm depending primarily on the reamer's diameter.
- L = Total drilled length in feet.
- T_r = Estimated prereaming penetration rate, or travel speed, in feet per minute (fpm). This is the speed at which the reamer is being pulled along the pilot hole. It is dependent on soil conditions and reamer size and can range from a lower value of 0.5 fpm in rock to a higher value of 3 fpm in soft soils.
- f_{lr} = The prereaming circulation loss factor.

Here is a formula for pulling back:

$$V_b = Q_b (L/T_b) f_{lb} \qquad (3)$$

Where:

- V_b = Total volume, in bbl, of drilling fluid consumed (not available for recirculation) during pullback (pipe installation).
- Q_b = Drilling fluid flow rate in bbl per minute (bpm). This will range from 6 to 20 bpm depending primarily on the diameter of the pipe being installed. *Continued*

Table 1. Typical drilling parameters for use in Eqs. 1 to 3

	Pipe diameter in soft soil			Pipe diameter in rock	
	6–20 in.	22–30 in.	36–42 in.	6–20 in.	22–30 in.
Q_p	5	5	5	10	10
P	50	40	30	20	10
f_p	30	35	40	45	50
f_{lp}	0.5	0.5	0.5	0.2	0.2
Q_r	8	14	20	8	14
T_r	3	2	1	0.5	0.5
f_{lr}	0.5	0.5	0.5	0.2	0.2
Q_b	8	14	20	8	14
T_b	10	8	5	10	8
f_{lb}	0.5	0.5	0.5	0.2	0.2

L = Total drilled length in feet.

T_b = Estimated pullback penetration rate, or travel speed, in feet per minute (fpm). This is the speed at which the pipe is being pulled into the reamed hole. It is dependent primarily on pipe diameter but can also be affected by the quality of the reamed hole. It can range from a lower value of 2 fpm to a higher value of 10 fpm.

f_{lb} = Pullback circulation loss factor.

Total estimated drilling fluid volume consumed, V_{cons}, for a given installation then is the sum of V_p, V_r, V_b and the fluid system line fill. The fluid system line fill is the volume of fluid remaining in surface piping, tanks and reamed hole annulus at pull-back completion. This will be well under 1,000 bbl for most installations.

This estimate does not take into account drilling fluid which has been discharged for disposal at the surface. The assumption is made for estimating that all fluids which return to the surface are recirculated. This is valid given the inaccuracy of the circulation loss factors. In actuality, drilling fluid will be discharged with wet spoil from the solids control system.

Once the total volume of drilling fluid consumed is calculated, it can be broken down into its individual components. Formulas for accomplishing this are presented below.

Here is a formula for viscosifier volume:

$$V_{vis} = V_{cons}/Y/W_{dry}\ (74.07) \qquad (4)$$

Where:

V_{vis} = Dry bulk volume, in cubic yards, of viscosifier consumed in the installation. The viscosifier typically will be bentonite.

Y = Drilling fluid yield of the viscosifier in bbl per ton. Bentonite yields in excess of 85 bbl of 15 cps fluid per ton. High yield bentonites, those enhanced by the addition of polymers, yield in excess of 200 bbl of 15 cps fluid per ton. The yield will vary based on the viscosity of the final fluid. The values stated above are suitable for quantity estimating purposes.

W_{dry} = Dry weight of the viscosifier in pounds per cubic foot. This is 55 pounds per cubic foot for packaged bentonite.

For estimating water, the water volume consumed is equal to the total volume of drilling fluid consumed.

Here is a formula for estimated drilled spoil:

$$\begin{aligned} V_{spoil} = {} & ((LD_o^2)/2200) \\ & 1 - (f_{lb} + f_{lr})/2 \end{aligned} \qquad (5)$$

Where:

V_{spoil} = The volume of the reamed hole in cubic yards reduced by the average of the circulation loss factors for reaming and pulling back. This takes into account the fact that spoil is transported to the surface suspended in drilling fluid. If the fluid does not return to the surface, neither does the spoil. For a conservative estimate, the circulation loss factors can be set at zero and V_{spoil} will equal the volume of the reamed hole. General observations of the quantity of spoil on drilled crossings indicates it typically is less than the volume of the reamed hole.

D_o = The outside diameter, in inches, of the pipe being installed. The formula presented uses a factor of 1.5 to determine the reamed hole diameter from the pipe outside diameter.

L = Total drilled length in feet.

Typical drilling parameters for use in Eqs. 1 to 3 are presented in Table 1.

Calculation example. Estimate the quantity of drilling fluid and fluid components involved with a 24-in. pipe line river crossing. The designed drilled length is 2,500 ft and the subsurface soils are soft alluvial deposits.

From Table 1, the following drilling parameters are selected:

$Q_p = 5$, $P = 40$, $f_p = 35$, $f_{lp} = 0.5$, $Q_r = 14$, $T_r = 2$, $f_{lr} = 0.5$, $Q_b = 14$, $T_b = 8$ and $f_{lb} = 0.5$

Executing the formulas previously presented, using these parameters, produces the following results:

- 5,469 bbl of drilling fluid will be consumed during pilot hold drilling.
- 8,750 bbl of drilling fluid will be consumed during prereaming.
- 2,188 bbl of drilling fluid will be consumed during pullback.
- 17,406 bbl of drilling fluid will be consumed to installed the crossing.
- 117 cubic yards (87 tons) of high-yield bentonite will be consumed to install the crossing.
- 17,406 bbl (731,063 gallons) of fresh water will be consumed to install the crossing.
- 327 cubic yards of spoil will be removed and disposed of in installing the crossing.

The manual includes a Lotus spreadsheet routine on a floppy disk for performing these calculations. Fig. 1 is a copy of the printout from this routine.

RECOMMENDED DISPOSAL METHODS

Chief excess drilling fluid disposal method on an HDD pipe line installation project is dispersal at the site. As an alternative, excess fluid, or its components, can be hauled to a remote disposal location. Disposal of excess drilling fluid in a waterway is not recommended. The disposal method used at a specific crossing will depend on the crossing size and location as well as any applicable local regulations.

In addressing regulations, composition of HDD drilling fluid or its components is important. Typically, it's composed of water, high-yield bentonite and drilled spoil. Major component is water, normally taken from a

Routine for estimating the quantity of drilling fluid and fluid components involved with HDD pipe line installation

Project:	Example Calculation	
Diameter:	24	in.
Total Drilled Length:	2,500	ft

PILOT HOLE DRILLING

Drilling Mud Flowrate:	5	bbl per min.
Pilot Hole Production Rate:	40	ft per hr
Pumping Factor:	35	min. per hr
Circulation Loss Factor:	0.5	
Consumed Total =	5,469	bbl

PREREAMING

Drilling Mud Flowrate:	14	bbl per min.
Prereaming Penetration Rate:	2	ft per min.
Circulation Loss Factor:	0.5	
Number of Passes:	1	
Consumed Total =	8,750	bbl

PULLING BACK

Drilling Mud Flowrate:	14	bbl per min.
Pull Back Penetration Rate:	8	ft per min.
Circulation Loss Factor:	0.5	
Consumed Total =	2,188	bbl

COMPONENT QUANTITIES

Viscosifier Yield:	200	bbl per t
Viscosifier Dry Weight:	55	lb per cu ft
Drilling Fluid Consumed =	17,406	bbl
Viscosifier Consumed =	117	cu yd
	87	t
Water Consumed =	17,406	bbl
	731,063	gal
Drilled Spoil =	327	cu yd

Fig. 1. Example of printout from Lotus spreadsheet routine for estimating the quantity of drilling fluid and fluid components involved in a horizontal directional drilling pipe line installation.

waterway or municipal source. For almost all applications, the only foreign material introduced to the location is a naturally occurring bentonite. Applicable disposal regulations should be similar to those governing sedimentation and erosion control, hydrotest water disposal or general excess construction spoil disposal.

The amount of excess drilling fluid will govern the configuration of an installation's drilling fluid system and whether or not the excess fluid must be separated into its component parts for disposal. For smaller applications, the amount of excess fluid may be minimal and can be discharged directly at the drill site. The site can be restored in accordance with general construction specifications, leaving no appreciable impact from the drilling fluid discharge. For larger volumes, dewatering equipment may be employed to separate solids—bentonite and spoil—from the water. The water then can be discharged and the solids handled as general excess construction spoil.

Background. Until the early 1980s, excess drilling fluid on HDD waterway crossings was, in most cases, discharged directly into the waterway. Surface returns typically were not recirculated, but allowed to flow into the waterway from collection pits. Most crossings were in rural locations in the U.S. Gulf Coast region beneath rivers which carried a generally high sediment load. Return of river water containing additional suspended solids was not considered detrimental. This was particularly true when the increase in suspended s[illegible] involved with an open excavation method was compared to the HDD method.

In recent years, three trends have eliminated discharge into waterways as a suitable disposal method. First, HDD was used in locations with sensitive clearwater streams. Deliberately introducing suspended solids into these waterways has a negative environmental impact and cannot be allowed. Second, general sedimentation control on all construction projects became a requirement. It was not reasonable to protect a waterway with sedimentation control barriers and then bypass the barriers with a drilling fluid discharge line. Third, oil field drilling fluids were identified as substances requiring special disposal procedures. Although placing oil field drilling fluids and HDD drilling fluids in the same classification is not valid, there is concern and confusion regarding regulations governing oil field drilling fluids.

Recirculation. First step in effectively dealing with excess drilling fluid disposal is to eliminate, or minimize, the excess. This is accomplished by recirculating drilling fluid returns to the extent practical. Collected surface returns should be processed through a solids control system, which removes spoil from the drilling fluid, allowing the fluid to be reused.

Returns transportation. Recirculation on an HDD waterway crossing is complicated because a significant portion of the returned drilling fluid surfaces at the exit point on the bank opposite the drilling rig. This requires using either two drilling fluid systems, or transporting the returns from the exit point to the rig site. Transportation can be accomplished by truck, barge or a temporary recirculation line drilled beneath the waterway bottom. Site conditions will determine the most advantageous system. In some projects, temporary recirculation lines have been laid directly on the waterway bottom. This procedure involves the risk of a rupture and the resulting discharge of drilling fluids into the waterway.

Solids control/removal. The solids control system is designed to remove drilled spoil from drilling fluid. Oil field experience has demonstrated that spoil removal enhances drilling performance by providing cleaner fluid with a minimum low-gravity solids content.[1] A detailed discussion of solids control systems can be found in Chapter Y of the *IADC Drilling Manual*.[2] The basic method used for unweighted water-base HDD fluids is mechanical separation. A typical mechanical separation system, with general particle-removal ranges, is composed of the following:[2]

- Standard shale shaker—440 microns and larger
- Fine screen shaker—74 microns and larger (weighted muds)
  44 microns and larger (unweighted muds)
- Mud cleaner—74 microns and larger (weighted muds)
  44 microns and larger (unweighted muds)
- De-sanders—100 microns and larger
- De-silters—15 microns and larger
- Centrifuge—4 to 8 microns and smaller (weighted muds)
  4 to 8 microns and larger (unweighted muds)

(1 micron = .00003937 in.)

Solids control systems are not 100% efficient. That is, spoil discharged is not dry and totally free of drilling fluid, and fluid discharged is not totally free of drilled spoil. Experience on oil field drilling rigs indicates that the efficiency of solids control systems ranges from 60% to 80%.[3] The consistency of the spoil discharged from a solids control system may be similar to ready mix cement or a very viscous drilling fluid, depending on factors such as the subsurface material being penetrated, drilling fluid properties, or the operator's skill.

Land farming. Land farming provides an efficient and effective way to dispose of excess drilling fluids or drilled spoil. It involves distributing excess material evenly over an open area and mechanically incorporating it into the soil. The degree of tilling will be dictated by the waste's character and amount. Small quantities of whole fluid will dissipate with little or no tilling. If large quantities of fluid or wet spoil are involved, a significant tilling effort will be required to ensure the waste does not form a dry crust and remain in a semi-solid state over an extended period. Condition of the land farming site should be governed by standard construction clean-up and site restoration specifications.

Dewatering. Dewatering system's objective is to remove all solids from the drilling fluid. Solids removed include not only drilled spoil, but also commercial solids, typically high-yield bentonite, that have been added to enhance fluid properties. Dewatering can take place during drilling or after completion. If dewatering is concurrent with drilling, processed water should be returned to the active fluid system for mixing and re-use. If dewatering follows construction, processed water should be discharged in accordance with local regulations.

Solids produced by an appropriate dewatering system should be "dry." That is, they can be handled with standard earth moving and hauling equipment. Disposal should comply with local regulations. Typically, this will be similar to general excavation spoil. Regardless of the disposal requirements for dry spoil, costs will be reduced significantly by eliminating liquid waste and minimizing total mass.

Briefly, dewatering involves injecting coagulants or flocculating chemicals into the drilling fluid as it enters a large clarifying centrifuge. This coagulates the fine drilled particles allowing them to be separated from the water. Basic steps in dewatering a typical HDD drilling fluid are:[4]

- Drilling fluid from the active system is diverted into an injection unit and treated with flocculants.
- Treated fluid is passed into a clarifying centrifuge where flocculated solids are separated from the water. The solids are disposed of in an appropriate manner.
- Water passes into a quality control tank where it can be monitored and reprocessed, if necessary.
- Suitably processed water can then be passed back into the active system or disposed of in an appropriate manner.

If a weighted fluid is being used, provisions must be made to recover the weighting material before the fluid is diverted to the injection unit.

Centrifuges with a bowl length exceeding 48 in. or longer, in combination with chemical injection, can remove all solids from a drilling fluid to produce clear water. The combination of chemical injection and larger centrifuges differentiates a dewatering system from a conventional solids control system. A dewatering system removes solids that a conventional solids control system cannot.[4]

However, dewatering systems are expensive. They are not appropriate for every HDD application. Economics will dictate that dewatering systems be used in projects involving large quantities of drilling fluids.

Solidification. Solidification, or stabilization, is a method used for years to treat excess oil field drilling fluids. It involves mixing the fluids with a reagent, which initiates fixation and produces a stable, solid waste. Reagent examples are fly ash, blast furnace slag, cement-kiln dust and clays. The reaction can produce a concrete-like solid and the waste fluid does not need to be dewatered before treatment.[5]

Solidification should not normally be required for an HDD application. Land farming and dewatering typically will provide more cost-effective disposal solutions. However, if a job is in a zero-discharge area or involves drilling through contaminated material, solidification and transportation to a select disposal site may be warranted.

ENVIRONMENTAL IMPACT

Research on the environmental impact of drilling fluids has focused predominantly on oil field fluids. Drilling fluids used on HDD installations are similar to oil field drilling fluids. Their similarity allows oil field fluid research to be used to assess environmental impact of HDD fluids. However, the two fluids are not the same. HDD fluids typically are much simpler than oil field drilling fluids and the distinction is important when considering environmental impact data.

Toxicity. The toxic characteristics of a drilling fluid are determined by its composition. The simplest type of water-based fluid suitable for drilling under many oil field conditions is lignosulfonate mud. Basic components of a lignosulfonate mud are barite, bentonite, caustic soda, lignite and chrome lignosulfonate. Since 1980, the trend in the oil field has been to use polymer muds. The basic components of a polymer mud are barite, partially hydrolyzed polyacrylamide polymer, xanthan gum, carboxymethyl celluloses or starches and caustic soda.[6]

Bioassay. Disposal of drilling fluids in U.S. offshore waters is regulated by the mysid shrimp test. Briefly, this test involves placing mysid shrimp in specifically prepared mixtures of drilling fluid and seawater at various concentrations. The concentration that produces a 50% mortality rate in the mysids over a period of 96 hours is referred to as the LC_{50} value. The lower the LC_{50} value, the higher the toxicity. Ranges are:[7]

LC50 < 100 ppm	Highly toxic
100 ppm < LC50 < 1,000 ppm	Moderately toxic
1,000 ppm < LC50 < 10,000 ppm	Slightly toxic
10,000 ppm < LC50	Practically nontoxic

The U.S. Environmental Protection Agency prohibits discharging water-based mud and cuttings into the Gulf of Mexico if the mud's LC_{50} is less than 30,000 ppm.[8] Drilling fluids that contain only the components listed for the basic lignosulfonate and polymer muds tend to test favorably in bioassays with LC_{50} values in the 700,000 to 1,000,000 ppm range.[6] If these muds are not contaminated by petroleum or salts in the formations drilled, they can be discharged at sea.

HDD drilling fluids. As mentioned above, drilling fluids typically used in HDD installations are simpler than oil field fluids. They generally consist only of a high-yield bentonite and fresh water. Possible sources of heavy metals such as barite and chrome lignosulfonate are rarely, if ever, used. HDD fluids do not usually drill through hydrocarbon or brine-bearing formations. Therefore, their environmental impact is on the level with general construction sedimentation or erosion, pipe line hydrotest water disposal or general excess construction spoil disposal.

Inadvertent returns. HDD involves the uncontrolled subsurface discharge of drilling fluids. Downhole fluid flow will take the path of least resistance. This can be dispersal into the surrounding soils or discharge to the surface at some random location. This is not a critical problem in an undeveloped location. However, in an urban environment or high profile recreation area, inadvertent returns can be a major problem. In addition to the obvious public nuisance, drilling fluid flow can buckle streets or wash out embankments. Drilling parameters may be adjusted to maximize circulation and minimize the risk of inadvertent returns. Nonetheless, the possibility of lost circulation and inadvertent returns cannot be eliminated. Contingency plans addressing possible remedial action should be made in advance of construction and regulatory bodies should be informed.

Inadvertent returns are more likely to occur in less permeable soils with existing flow paths. Examples are slickensides clay or fractured rock structures. Coarse grained, permeable soils exhibit a tendency to absorb circulation losses. Manmade features, such as exploratory boreholes or piles, may also serve as conduits to the surface for drilling fluids.

CONSTRUCTION SPECIFICATIONS

Here is general wording for construction specifications relative to drilling fluids. These specifications are not meant to be applicable in all cases. Permit requirement and right-of-way agreements may dictate site-specific wording and conditions.

Composition. The composition of all drilling fluids proposed for use shall be submitted to company for approval. No fluid will be approved or utilized that does not comply with permit requirements and environmental regulations. Water required for drilling fluid may be taken from the waterway.

Permission to draw water from the waterway may need to be confirmed.

Recirculation. Contractor shall maximize recirculation of drilling fluid surface returns. Contractor shall provide solids control and fluid cleaning equipment of a configuration and capacity that can process surface returns and produce drilling fluid suitable for reuse. Company may specify standards for solids control and cleaning equipment performance or for treatment of excess drilling fluid and drilled spoil.

If substantial excess drilling fluid is anticipated, specific treatment methods should be stated in the specifications. See recommended disposal discussion above.

Disposal. Disposal of excess drilling fluids shall be the responsibility of contractor and shall be conducted in compliance with all environmental regulations, right of way and workspace agreements and permit requirements. Excess drilling fluids may be disposed of at the rig site. Drilling fluid disposal procedures proposed for use shall be submitted to company for approval. No procedure may be used which has not been approved by company.

If substantial excess drilling fluid is anticipated, disposal methods and disposal site requirements should be stated.

Inadvertent returns. Drilling fluid returns at locations other than the entry and exit points shall be minimized. Contractor shall employ the best effort to maintain full annular circulation of drilling fluids. Annular circulation shall be aided by careful control of fluid properties (density and viscosity) to reduce annular pressure. In the event circulation is lost, contractor shall take steps to restore circulation. If inadvertent returns of drilling fluids occur, contractor shall contain them with hand placed barriers such as hay bales, sand bags and silt fences, and collect them using pumps as practical. If the amount of returns is not great enough to allow practical collection, the affected area will be diluted with fresh water and the fluid will be allowed to dry and dissipate naturally. If the amount of returns exceeds that which can be contained with hand-placed barriers, small collections sumps, less than 5 cu yd, may be used. If the amount of returns exceeds that which can be contained and collected using small sumps, drilling operations shall be suspended until surface return volumes can be brought under control.

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