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Design and Application of Trenchless Drill Rig Manipulator for Automatic Drill Pipe Loading and Unloading from the Soil

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ABSTRACT

The objective of this article is to analyze the design parameters related to a trenchless drill rig manipulator as material handling equipment for automatic drill pipe loading and unloading from the soil. Trenchless technology was explained using directional drilling (horizontal directional drilling) and certain criteria for this design to be achieved were stated. This article also covered the working principle of a trenchless rig. A great deal of literature was used to back up this design, describing the trenchless drilling rig and the various stresses experienced by pipelines during installation.

The interaction of pipe material with the soil was studied, and with the aid of structural mechanics' equations, mathematical relations were formulated and used to estimate vital properties required for subsurface construction, like the bending radius of the material (pipe) and pullback force under a certain soil component, which aided the system design and analysis.

The findings in this article show that the principal loading experienced by pipelines during installation and operation is bending, and the application of a trenchless drill rig manipulator under different soil types can help workers lift, maneuver, load, and unload heavy and large drill pipes as it has the ability to reach into tight spaces and carry out various functions.

Keywords

Trenchless technology, Drill pipe, Bending radius, Material handling, Soil.

Introduction

Subsurface construction with trenchless technology necessitates minimal or no digging at all, depending on the type of technology used. This group of procedures, materials, and equipment can be used to build new subterranean infrastructure or renovate existing underground infrastructure while causing the least amount of disruption to traffic, businesses, and other operations on the surface. (Wikipedia 2021) Horizontal directional drilling (HDD),micro-tunneling, tunneling and other methods for installing pipelines and cables below the ground with minimal excavation are included in this category of construction methods. (Wikipedia 2021)Trenchless construction differs from other subsurface construction methods in that it does not require digging a trench. It is possible to install subterranean services without damaging the surrounding pavement using trenchless technology if the right safeguards are taken. It simply means the laying of pipe without excavation, and this is widely applied in the pipe-laying construction of water supply, electricity, telecommunication, natural gas, coal gas, and oil. To improve efficiency, a rack and pinion transmission, a double-speed control system for power unit rating, thrusting, and pulling are equipped. A modern computer-aided tracking system allows monitoring the position and location of the boring head as well as controlling the drilling process at a depth of up to 21m with a diameter of up to 500mm and a pipeline length of up to 400m without art crop. The drill head is a whistling device that receives and monitors the drill head. (lavis 2018).

The use of manipulators in automated systems has a significant impact on their design. (Klaus Kurz. 2013)Manipulators are machines that are capable of performing a variety of activities. A manipulator's distinguishing feature is that it is not controlled by a computer program, but rather by a person. The goal of a gadget like this is to perform strenuous physical tasks, to broaden the user's working range, and to take over in dangerous situations. Manipulators, such as bomb disposal robots, can be operated via remote control or by lifting an arm. (Klaus Kurz. 2013) Since fully autonomous operation is not conceivable, the word "automated" is inappropriate. Material handling (MH) implies a short-distance movement taking place within the confines of an area, such as a plant or a warehouse, or between a building and a transportation agency. (Kay 2012)

Drill rig material Handling

The HDD rig machine consists of the carriage, the brake out unit, and the pipe handling system. When in operational position, both units are connected through a power chain to the hydraulic electric and drilling fluid supply. The rig is anchored to the sheet pile wall and drilling operations can start. The crane places and connects the first drill bit to the carriage. It is pushed forward into the entry pit while rotating constantly. (nair 2020)

As it relates to pipe handling, depending on the machine, it comes in different forms, namely:

- Pipe handling crane

It grabs the pipe out of the pipe storage (catwalk) and lifts them up to the rig to connect them to the already existing drill string, one after another the drill a pushed into the ground through the conical head for easy make up and break of connections.

- Horizontal to Vertical Arm (HTV)

During derrick make-up, tubulars are moved from their horizontal position on the catwalk or conveyor to their vertical position in the mouse hole. To make up doubles, triples, or quads, the HTV machine is combined with other equipment. The stands can either be placed in the setback area or delivered directly to the well center.

Reasons for pipe handling equipment

1. To make a connection**:** As the hole goes deeper, it is necessary to add a joint to the pipe.
2. To trip the pipe: Drill strip removal may be necessary in order to change bits, install a new bottom hole assembly in a drill string, or perform any other procedure requiring the pipe to be tripped from its original location.

Either a Kelly or a top drive unit handling pipe can be used to make connections in a rotary table system. Equipment is needed to move it around the rig floor, connect joints, and get it into and out of holes. These pieces included in this equipment are: elevator, slips, tongs, power tongs, spinning wrenches, catheads, Kelly’s spinners, iron roughneck, rat hole, mouse hole and Air hoist. (HerrenknecghtAG 2016).

The driller is in charge of most of this equipment. There may be additional equipment needed for the transport of pipe from the deck to the rig floor. In order to drill any further, the rig will need a pipe joint. A Kelly and rotary table system can be connected in this way.

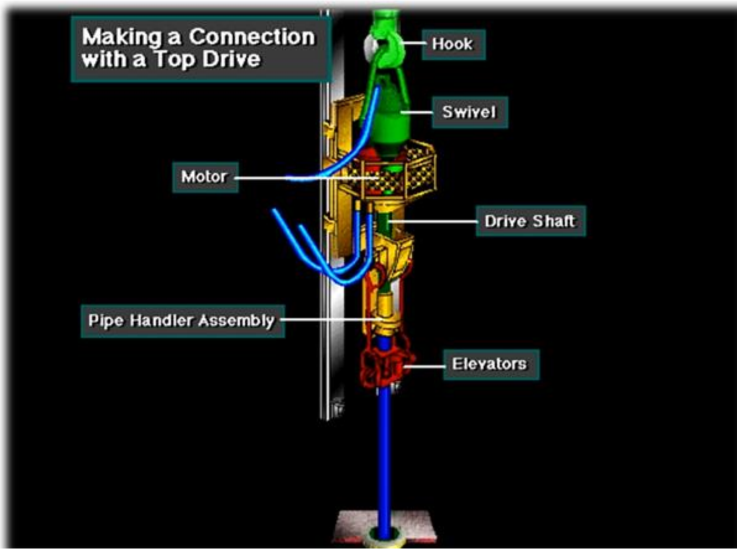


Figure 1: Connection of a rig driller

Soure: HerrenknechtAG

The hoisting mechanism is used to lift the Kelly, and the floor crew uses a huge wrench called Tongs to suspend the drill string in the hole. The drill string is loosened or broken free of the Kelly. In order to protect the drill pipe from spinning when they apply breakout torque with the Lead Tongs, they lock one set of tongs around the drill pipe, known as the Backup Tongs. As soon as a driller activates the breakout cathead, an automatic winch is lowered into place to assist in the extraction of material. A line tied to the lead tongs is pulled by the breakout cathead, which loosens the connection. The driller removes the drill pipe from the Kelly by carefully rotating the rotary table. They clung onto the Sabar sub and held it in place while the pipe spun out of control. The Kelly is then moved to the nozzle's joint of pipe by the crew. By inserting Kelly into new junction and latching breakup tongs around pipe joint in Mouse hole's tool joint, they were able to complete their task. When the drill spins the Kelly spinner into the joint, the backup tongs prevent the joint from rotating. (HerrenknecghtAG 2016)

The Kelly Spinner is a pneumatic or hydraulic device mounted near the top of the Kelly to make up the Kelly on the drill pipe to final tightness. The crew latches the lead tongs around the Kelly while holding the break-up tongs on the pipe tool joint box.

When tightening the Kelly on the drill pipe, a pneumatic or hydraulic equipment called the Kelly Spinner is used. The team uses the break-up tongs to hold the pipe tool joint box while latching the lead tongs around the Kelly. Using the draw works as a trigger, the drill activates the cosmetics cathead. Pulling on a chain attached to the head tweezers, a cosmetics cathead tightens a Kelly on to the drill pipe. Crew men assist the driller in hoisting the Kelly and new drill pipe junction from the mouse hole to the drill pipe joint on the rotating table, where it is reassembled. The crew member inserts the new joint into the suspended joint, and the driller activates the Kelly Spinner to spin up the new joint. Once the replacement joint has been spun up, the worker tightens it with the backup lead tongs. To begin drilling, the driller must first assemble his joint. Drilling proceeds as the team removes the slips and the driller lowers the Kelly and mates the Kelly with master pushing. (HerrenknecghtAG 2016)

The driller uses the hoisting system to remove the pipe from the hole after the team members latch the elevator around the rotary table joint. Once the third joint is clear of the rotary table, the floor hands, and then the tongs and a spinning wrench are used to hoist the fourth joint, a driller typically lifts the pipe until the slips around the top of the fourth joint clear the rotary table opening. After removing the drill string's three-jointed stand, the crew places it back in the mast. While this is going on, the Derrick is in charge of manipulating the three joint stands at the top of the mast. He uses a fingerboard, a series of projections near the Derrick man's work platform known as the monkey board, to place the stand's top into a fingerboard. As long as there is drill string in the hole, the driller and rotary deck assist in removing it. (HerrenknecghtAG 2016)

In the past few years, there have been repeated improvements in technology. These many advancements in technology have given rise to trenchless technology—a process whereby a continuous trench (gutter) doesn't have to be dug for the installation of underground pipes. This implies that drill pipe loading and unloading can go on underground without obstructing the activities on the surface. Directional drilling methods have made trenchless drilling practicable. A drill string is a long, hollow tube that is used to drill holes in the ground. Rotational force is applied to it as it is hanging from the rig. The bottom hole assembly is the lower portion of the drill string, which is typically a few hundred meters long. Drill collars and stabilizers center the BHA in the hole using hefty pipes and longer, larger-diameter stabilizers. (Detournay 2013) This gave rise to the design and application of trenchless rig drilling manipulators as material handling equipment for automatic loading and unloading of drill pipe.

Materials and methods

System Design

Pipelines are put under the most stress when they are installed and operated because of bending. (Silva, et al. 2009) In the directed drilling operation, the borehole and BHA interact. The bit kinematics influence how the borehole geometry changes. It's important to note that the bit penetration is dependent on BHA forces, which in turn are related to the BHA's deformation behavior within the borehole itself. There are three main components to this model. (Detournay 2013).

a. kinematic relationships link the kinematics of the bit and the evolution of the borehole, that is, the propagation of the lower boundary of the borehole is defined as the surface of interaction between the bit and the rock.

b. The bit/rock interface laws relate the kinematics of the bit as it penetrates the rock formation to the interaction forces at the bit/rock interface.

c. The BHA is an elastic object constrained by the stabilizers to conform to the geometry of the borehole. By interacting with the rock, it determines its lower boundary condition. The model of the BHA can thus be solved to provide relations between the bit forces and orientation, the geometry of the borehole, and external loads on the BHA. (Detournay 2013)

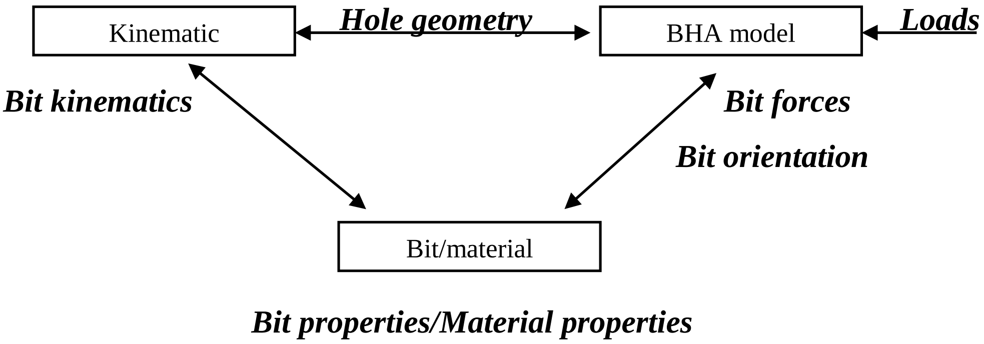


Fig. 1: Three elements of the model. Source: Detournay, 2013

In this system's design, the following criteria are taken into consideration: the drill path, the bending radius, the pullback force, and the combined stress. Drill length should be kept to a minimum while yet meeting all location and depth control points on the proposed drill route. Depending on the plane in which they are drilled, drill paths are made up of a succession of straight lines and curves that are either sagging, over-bends, or side bends. If feasible, it is best to avoid complex bends. The drill path should have as few bends as possible while designing it. Drill-rod life is extended as a result. In order to get the depth needed for steering control and cover, the ideal bore path begins with a straight tangent section at a predetermined entrance angle. At the desired depth, the drill head's trajectory is directed upward with a curve before switching to a horizontal segment and then a vertical segment, and finally straightening out at the exit angle. As a result, while designing HDD paths, the bending radius is an important consideration. Only two curves and two straight sections are required to define HDD profiles in some circumstances. ***(Silva, et al. 2009)***

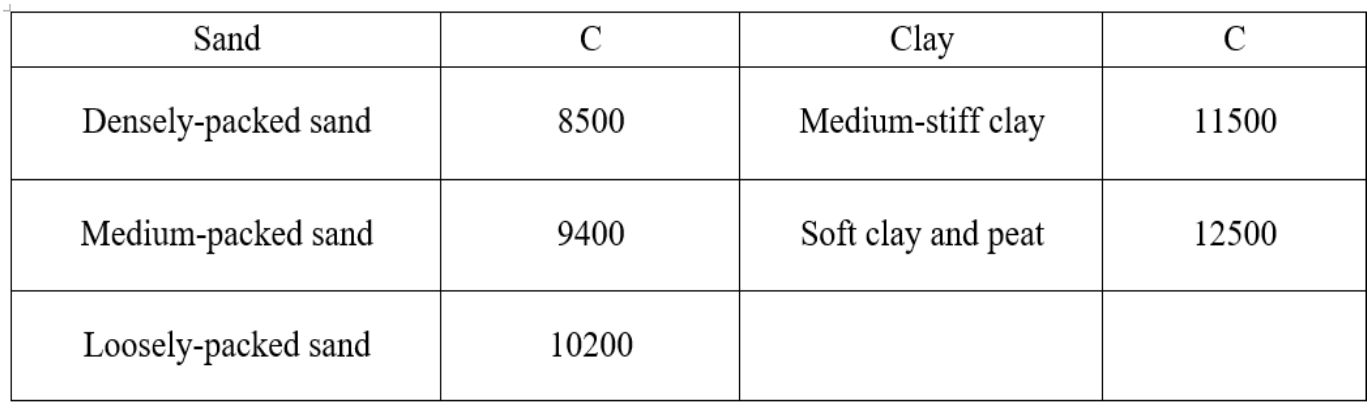
The bending radius, or radius of curvature, is an important design parameter for a bridge that makes use of horizontal directional drilling. The product pipe's bending characteristic determines the bending radius, which rises in proportion to the pipe's diameter. HDD pathways commonly take a bending radius equal to 1000 times the nominal pipe diameter into account while creating the path. Steel line pipe bend radius is 100 ft/1in diameter, which is equal to 1200 times the pipe's nominal diameter, as another general rule. Rather of relying on theoretical analysis, these are based on recognized practice for steel pipe. The stress-limiting criterion typically dictates a minimum radius of fewer than 1,000 times the nominal diameter. It's more difficult to bend a pipe with a thicker wall since it's more resistant to soil reaction.

It is critical to calculate the pullback force of a horizontal directional drilled pipe prior to installation in order to avoid overstressing the pipe, choose a drill rig with adequate pullback capacity, and apply an inexpensive design. HDD pullback force is determined by the interaction between a drill pipe, soil, and drilling fluid. Contact forces between the pipe and the soil are responsible for generating frictional forces. Due to the pipe's flexural stiffness, which changes as it adapts to boreholes' curves, contact forces have two key components: the pipe's effective weight and directional variations (Silva, et al. 2009). An effective weight, borehole shape, soil clearance, and pipe flexural stiffness all have a role in how much these contact forces may be felt. A good example of this is steel pipe, which has a high pulling load capacity and is capable of handling large pullback loads.

Pipeline stresses are influenced by factors such as the angle of approach, bending radii, length of borehole, pipe diameter, and soil conditions at the site. By selecting the pipe material and correct radius of curvature, the installation stresses will not be greater than what the pipeline can handle. When designing an HDD crossing, the steel pipe's bending stresses must also be taken into consideration. Steel pipe's allowed bending stress relies on a variety of factors, including the steel grade, wall thickness and pipe diameter. ***(Silva, et al. 2009)***

The soil type is also taken into consideration, in the journal, *Design Guidelines for bending radius for large-diameter HDD* (BRINK 2007) and some typical soil constant values were presented. A higher constant value is associated with softer soils than a lower constant value is associated with soils with greater stiffness (and strength). This is shown in table 1.

Table 1: Soil dependent constant



Sand	C	Clay	C
Densely-packed sand	8500	Medium-stiff clay	11500
Medium-packed sand	9400	Soft clay and peat	12500
Loosely-packed sand	10200		

Source: Brink et al. 2007

Mathematical model

Given the following parameters (Keyence corporation 2021);

- π (3.14): Circular constant
- DC (mm): Drill diameter
- n (min^{-1}): Spindle speed
- fr (mm/rev): Feed per revolution (feed rate)
- ld (mm): Drilling depth
- i: Number of holes
- I: Lead
- n: Number of threads
- P (mm): Pitch
- d (mm): Effective diameter of thread

Cutting Speed (vc) $$VC = \frac{\pi * DC * n}{1000} \left(\frac{m}{\mathrm{min}}\right) \quad (1)$$

This is for calculating the cutting speed from the drill diameter and the spindle speed.

Spindle Feed (vf) $$vf = fr * n \left(\frac{mm}{\mathrm{min}}\right) \quad (2)$$

This is for calculating the spindle (z-axis) feed from the feed per revolution (feed rate) and the spindle speed.

Machining Time (Tc) $$Tc = \frac{ld * i}{n * fr} \quad (3)$$

This is for calculating the machining time from the drilling depth, the number of holes, the spindle feed, and the feed per revolution.

Thread Lead Angle (tan α) $$tan\alpha = \frac{1}{\pi d} = \frac{nP}{\pi d} \quad (4)$$

This is for calculating the lead angle of a screw thread. The lead angle can be calculated from the lead, the number of threads, the pitch, and the effective diameter of the thread.

An understanding of how bending radius, pullback force and combined stress are calculated can be derived from the following equations in the strength of materials. (Silva, et al. 2009)

$$\sigma_{bend} = \frac{M}{I} r_{pipe} \qquad M = \frac{\sigma_{bend} * I}{r_{pipe}}; \quad \frac{1}{r_{bend}} = \frac{M}{E*I} \quad \& \quad r_{bend} = \frac{E*I}{M}; \qquad \sigma_{bend} = \frac{E*D}{2* r_{bend}} \tag{5}$$

Bending Radius (BRINK 2007)***;*** $r_{bend} = C * \sqrt{D * t}$ (6)

Allowable bending radius (WILLOUGHBY 2005); $r_{min} = \frac{3* E* r_{pipe}}{2* S_a}$ (7)

Where σ is the bending stress and E is elasticity's modulus, the moment of inertia is I, bending moment is M, pipe outside diameter is D, the bending radius is r_{bend}, a soil-dependent constant (C) and a pipe wall thickness (t).

Pullback force; $F = \left[\frac{SMYS*fi}{fi} - \frac{E*D}{2* r_{bend}}\right] * A$ (8)

When the maximum pullback force (F), the cross-sectional area of the pipe (A), the steel's minimum yield strength (SMYS), and the maximum load factor f_l and safety factor (f_s) are known, it may be determined that the pipe is safe to use. (WILLOUGHBY 2005)

$$\begin{aligned} \sigma_{allow} &= 0.75 * SMYS\ for \frac{D}{t} \leq 10340/SMYS \\ \sigma_{allow} &= \left[0.84 - \frac{(1.74*SMYS*D)}{(E*t)}\right] * SMYS\ for\ \frac{10340}{SMYS} < \frac{D}{t} \leq 20680/SMYS \\ \sigma_{allow} &= \left[0.72 - \frac{(0.58 * SMYS * D)}{(E * t)}\right] * SMYS\ for\ \frac{20680}{SMYS} < \frac{D}{t} \leq 300/SMYS \end{aligned} \tag{9}$$

Where σ_{allow} is the allowable bending stress. (API RP 2A-WSD 2000)

Combined Stress; the relation below is used for the combined stress analysis.

$$\frac{\sigma_{tension}}{0.9*SMYS} + \frac{\sigma_{bend}}{\sigma_{allow}} \leq 1 \tag{10}$$

Results and Discussion

The above-stated equations were used to estimate the bending radius of the pipe. Using Equation 6, medium sand was considered. It's worth noting that for large diameter pipes, different bending radius values can be discovered. This is shown in Table 2, and is depicted by a graph in Figure 1.

Table 2: Bending radius (m); 28" – 30" (API-X65); 42" – 48" (API-X70)

D (in)	Eq. 5	Eq. 7	Eq. 6	1000 D	1200 D	t (in)
28	185.2	277.8	1047.9	711.2	853.4	0.625
32	211.7	317.5	1217.1	812.8	975.4	0.750
42	257.7	386.5	1594.6	1066.8	1280.2	1.000
48	294.5	441.7	1803.0	1219.2	1463.0	1.125

Source: Nkwazema

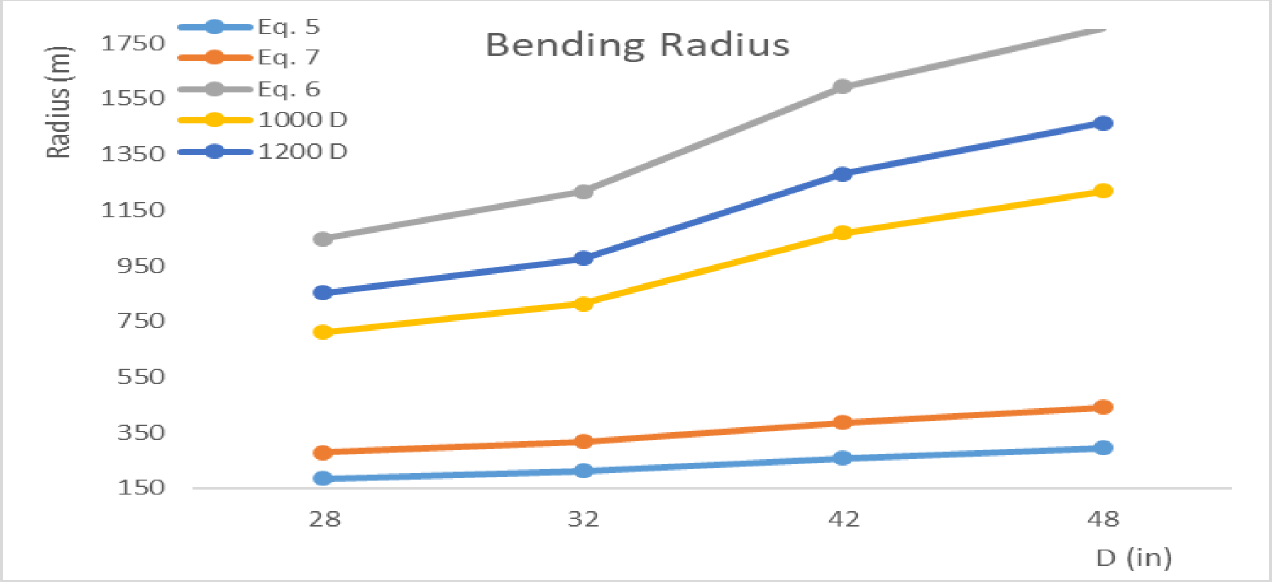


Figure 2: Bending Radius

Source:Nkwazema

Conclusion

The interaction of pipe material with the soil was studied, and with the aid of structural mechanics' equations, mathematical relations were formulated and used to estimate vital properties required for subsurface construction, like the bending radius of the material (pipe) and pullback force under a certain soil component, which aided the system design and analysis.

The design parameters of trenchless drill rig manipulators as material handling equipment for automatic loading and unloading of a drill pipe from the soil and the various stresses experienced by pipelines during installation have been studied. Horizontal directional drilling was the basis on which this design laid emphasis. Material handling as it relates to pipes was taken into consideration. According to this study, trenchless drill rig manipulators can assist in the lifting, loading, and unloading of massive and heavy drill pipes since they can reach into tiny locations and perform a wide range of operations.

The interaction of materials with sand was studied, leading to the bending radius, pullback force, and combined stress analysis. Mathematical relations for these constraints were formulated with the help of structural mechanics' equations and were used to estimate the behavior of the pipe at certain sand types.

There are still some unanswered concerns, such as the minimum bending radius required to ensure successful horizontal directional drilling pullback. Trenchless drilling operations must be made more reliable through more study into rational analysis processes and enhancing quality assurance measures in HDD operations, which is necessary to improve the reliability of HDD installations. For instance, the minimum and maximum bending radius and the angles at which the loading and unloading of the pipe will take place must be taken into account to avoid lapses during installation.

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