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HDD – horizontal directional drilling, pressure related failures caused by pilot drilling operations

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HDD – Horizontal Directional Drilling, pressure related failures caused by pilot drilling operations

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ABSTRACT: In view of the growing use of HDD and the still relatively high frequency of damage, a detailed analysis of possible damage scenarios when using HDD, and the development of strategies to avoid or minimize damages, are becoming eminently important. This paper focuses on the damage incidents that cause "external" impacts, such as surface deformation, cave-ins, suspension leakages, etc., which adversely affect neighbors, adjacent buildings or infrastructure. The focus is on possible damage incidents that arise during the pilot drilling operation using Mud Motors and are caused by the high levels of drill mud pressure necessitated by the process. The interrelationships between the expert disciplines of geology, geotechnics, hydraulics and process engineering are revealed, as is the necessity of interdisciplinary coordination to ensure the risk-optimized structuring of the production process.

1 INTRODUCTION

1.1 *Initial situation*

The trench-less laying of conduits and of cables in the ground has been gaining increased significance in recent years. The reason for this is the ever increasing density of construction in areas of settlement, both above ground and underground. The trench-less laying of pipes has proved to be particularly advantageous when crossing streets, railway lines or watercourses. Moreover, ecologically sensitive zones can also be crossed with the aid of HDD in a manner which is not damaging to the environment. The continuous increase in the number of underground line structures which have been built using HDD during the last 20 years can also be traced back to the economic advantages this technique holds for clients. This advantage can be seen to be particularly strong in the case of projects which would lead to a serious disruption of traffic flow, which would hamper trade, as well as in the case of lines which, upon completion of the line structure, would require a great deal of effort to reestablish the already existing infrastructure. Furthermore, in the case of lines at depths of more than 3 meters, in the diameter range of DN 150 to DN 1500, and particularly in the case of longer line fixtures, a cost advantage is present in comparison to conventional open construction methods, as well as in comparison to other trench-less construction methods. This obvious cost advantage, in particular, has prompted many clients to rapidly advance this admittedly relatively new construction methods to the preferred construction method in the urban environment, as well as in the case of various crossings of streets and railway lines. This disproportionate growth in the HDD market – in comparison to other branches of civil engineering – has led to HDD suddenly being offered by a large range of companies. With this initial euphoria on the part of clients and companies, it was unfortunately often overlooked that use of HDD involves dangers in relation to surface deformations, caused, in part, by high pressure levels at the drilling head.

1.2 *Problem definition and background*

Due to the complex boundary conditions, procedure-related risks arise which require a more thoughtful approach. The interaction between sub surface and construction methods, as well as external boundary conditions require an increased level of coordination and cooperation among the individual specialist disciplines [3]. In the following, after a brief description of the HDD procedure, the primary procedure-related risks in the execution of HDD pilot drilling operations will be analyzed and ways to limit these risks will be presented.

The aim of the research was to investigate in detail the drilling process using Mud Motor drive and to analyze the ensuing pressure-related risks from the impact on the bedrock to be cut through. Possible critical constraints and phenomena that might

cause pressure-related damage can be displayed and interpreted on the basis of fundamental considerations relating to pressure-related damage mechanisms. In addition to an analysis of the pressure progression and dispersion in the various phases of the drilling process, a comprehensive laboratory analysis was also conducted to clarify the issue of time-dependent pressure progression in bentonite suspensions.

2 HDD PROCEDURE

2.1 *Construction process*

In the HDD procedure establishing the final drilling diameter is broken down into various steps [1] [2]. The first working step consists of the establishment of the pilot drilling hole. In the case of the roller-bit drilling head driven by the Mud Motor (Fig. 3), directional control is made possible by means of the the approx. 2 m long drilling head segment, which is bent at an angle of approx. $1° - 2°$ to the drilling axis, and by the asymmetrical slope in the case of the chisel-shaped drilling head with high-pressure flushing jets (Fig. 1). By stopping the rotational movement of the drilling rod assembly in a defined axis position and continuation of the feeding process (without rotation), it is possible to steer the drilling rod in the desired direction. By continuous rotation of the drilling rod assembly the asymmetry of the drilling head is eliminated and therefore direct drilling is made possible. The position of the drilling head can be ascertained by means of a magnetic compass, induction loops or a gyrocompass, which are contained in an antimagnetic housing located behind the drilling head [1].

Figure 1. Asymmetrical drill bit for the directional control of pilot drilling operations.

When the target point has been reached a reamer head is attached to the pilot rod assembly. From this moment the drilling operation is made towards the starting point and, simultaneously, the rod assembly is extended at the target point and cut off at the starting point. Depending on the diameter and the geology, in most cases several reaming operations will be necessary to attain the final cross-section. From the second reaming operation a guide body in front of the reamer head is used to ensure symmetrical expansion around the predetermined axis. The pilot rod assembly serves as a pulling rod. Afterwards, the pipes are pulled in, i.e. the pilot rod assembly func-

tions as a pulling rod to pull in the pipes and is recovered from the initial construction pit [1].

2.2 *Mud Motor*

If, in the course of the planned line structures, areas of geological formations which cannot be cut through using a conventional asymmetrical drill bits, have to be cut through then the roller-bit drilling heads driven by the Mud Motor –originally developed for petroleum exploration drilling – are used for these tasks (Fig. 2). This refers to a screw motor (Moineau motor) located on the drilling head, which is driven by the drill mud. The pressurized drill rinsing drives the rotor (screw-shaped rod), which is located in the stator (housing with counter-rotating screw contour). In this way, the power generated hydraulically above ground (defined pressure and amount of drill mud) is transformed into mechanical driving power in the Mud Motor directly at the drilling head. In this way, the large amount of power lost along the drilling rod assembly when employing the conventional rotational drilling procedure is avoided. Depending on the compressive strength and the cutting resistance of the rock, blade-type chisels or roller chisels with teeth or TCI drill bits are used.

Figure 2. Mud Motor with roller bit.

In drilling operations the Mud Motor is driven by a suspension pump usually using a constant number of revolutions per minute (=constant output). The pressure loss along the drilling rod until it reaches the Mud Motor can be calculated according to the Bernoulli method. The total pressure drop via the Mud Motor includes the current non-load pressure loss $\Delta p_{nonload}$ as well as the active operational pressure loss Δp_{drive} for each operational torque (T_{drive}), depending on the cutting resistance of the rock [4] (Fig. 3). The non-load pressure loss results from resistance to overcoming the inner friction of the Mud Motor. The operational pressure loss Δp_{drive} of the Mud Motor depends on the torque used in the roller bit. The active torque T_{drive} necessary for rotating the bit can be calculated from the feeding pressure and from the cutting resistance of the rock.
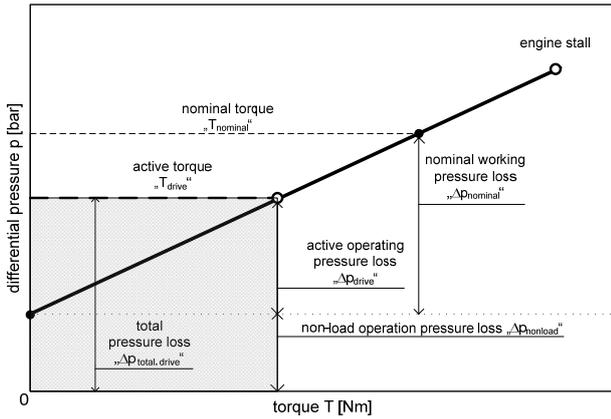
Figure 3.   Correlation between torque and differential pressure [4].

3   DAMAGES ARISING FROM PILOT DRILLING OPERATIONS

3.1   *Principle pressure-related failures*

A precondition for the further phenomenological investigation of possible pressure-related damage includes theoretical considerations concerning damage models which can, in principle, be conceived. Both damage models presented here show the basic differences in the damage model, depending on the geometrical boundary conditions – here the relationship of the overlap "h" to the pressure working area "A". Failure (in this case elevation) can occur in principle as a result of:

a) Exceeding the shearing resistance (inner friction and cohesion) in the local silo pressure body directly above the drilling head with accompanying elevation.

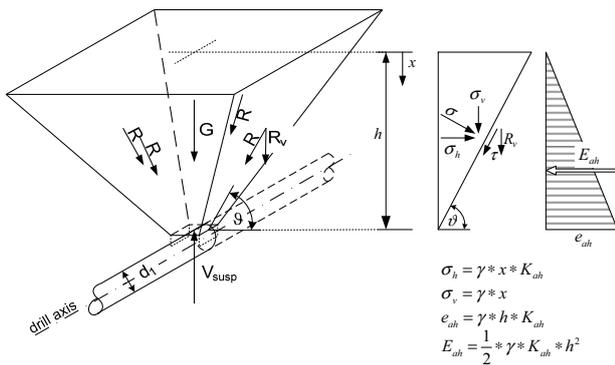This case arises when the relationship of pressure working area A to overlap h is very small (Fig. 4).

Figure 4.   Failure caused by excessive drill mud pressure – silo effect.

Silo break effect:

$$\vec{V}_{Susp} = \vec{G} + 4 \cdot \vec{R}_V \qquad (1)$$

Elevation force at the drilling head:

$$\vec{V}_{Susp} = A_{Susp} \cdot p_{Drill} \qquad (2)$$

Weight of the breakage body:

$$\vec{G} = \gamma \cdot \frac{4}{3} \cdot \frac{h^3}{(\tan \vartheta)^2} \qquad (3)$$

Horizontal mud pressure on a breakage body side:

$$e_{ah} = \gamma \cdot h \cdot K_{ah} \qquad (4)$$

$$E_{ah} = \frac{1}{2} \cdot \gamma \cdot K_{ah} * h^2 \qquad (5)$$

When considering the breakage phase, the following resistances act on the shearing area of the silo matter:

$$\tau = \tan \varphi \cdot \sigma(G, E_{ah}) + c \qquad (6)$$

Generated surface friction force on a breakage matter side:

$$\vec{R}_V = \tau \cdot \frac{M}{4} \cdot \sin \vartheta \qquad (7)$$

M … generated surface of the pyramids

With normal drill mud backflow – i.e. no leakage of drill mud into bank seams or crevices – the pressure working area A is as follows:

$$A_{Susp} \approx d_1^2 \qquad (8)$$

d_1 … borehole diameter
Acute elevation danger is present when:

$$\vec{V}_{Susp} = A_{Susp} \cdot p_{Drill} > \vec{G} + 4 \cdot \vec{R}_V \qquad (9)$$

b) Leakage of the drill mud into bank seams and the formation of a large-area caul with accompanying elevations.

This case will come into play if the relationship of the enlargement of the pressure working area (area over which the drill mud is leaked in the bank seam) to the overlap is very large (Fig. 5). In contrast to case a) no breakage phenomena or breakage body appear in this case, but rather a large-area elevation (plastic deformation) occurs – mostly outside the locality of the drilling head.

In order to produce elevations in this case, the product of suspension pressure [kN/m^2] and horizontal area (projected area), over which the suspension could spread [m^2], has to be greater than the weight of the overlying soil [kN]. In this case, effects arising from restraints and pressure vaults diminish.
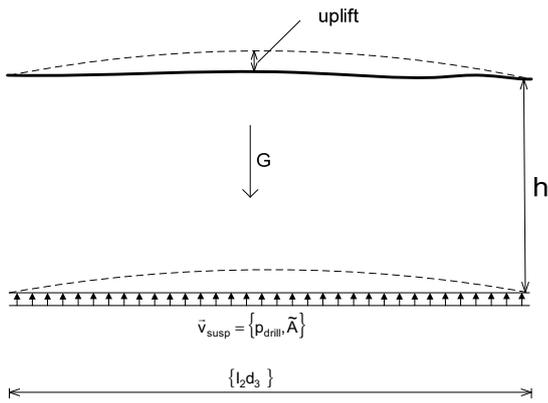
Figure 5. Surface deformation caused by large area drill mud flow in jointed rock.

3.2 *Critical basic conditions and phenomena*

Those hydraulic, hydrological, rheological and geological preconditions which promote underground pressure expansion / pressure propagation and, thereby, the occurrence of ground elevations, are discussed in the following points:

• Pressure expansion/pressure propagation within the suspension (drill mud) has to be possible, i.e. the viscosity of the suspension has to permit a propagation of pressure over a defined distance. In this context, the time-dependant change in viscosity is to be taken into account.

• A flow of the suspension under the given suspension pressure (operating pressure) has to be in principle possible. This depends on the following influencing factors:
– viscosity of the suspension
– consistency of the suspension
– width of crevice
– harshness of crevice
– spatial extent of the crevice
– relationship of the crevice width to the "grain size" of the suspension
– pressure

• An increase in pressure within a crevice system which is filled with suspension can occur if:
– the small crevice width or a narrowing of the crevice hinders any further dispersion of the suspension or
– the crevice system is completely full and therefore, an immediate rise in pressure takes place as a result of the incompressibility of the suspension.

4 PRESSURE FLOW AND DISPERSION WITH PILOT DRILLING OPERATIONS

4.1 *Pressure flow – pilot drilling operation in homogenous, non-creviced underground*

If the drilling runs in a homogenous, non-creviced underground, then the total amount of suspension (drill mud), after passing through the drilling crown or the Mud Motor escapes once again as a backflow at the mouth of the drill hole. The pressure flow over the whole drilling rod is shown in Figure 6. The pressure "p_{Drill}" is to be applied in the deepest of the drill hole, which is that suspension pressure which prevails after the drilling rod and the drilling crown or the mud motor have passed through. The drop in pressure now takes place in the annulus, along the drilling rod, according to Bernoulli.
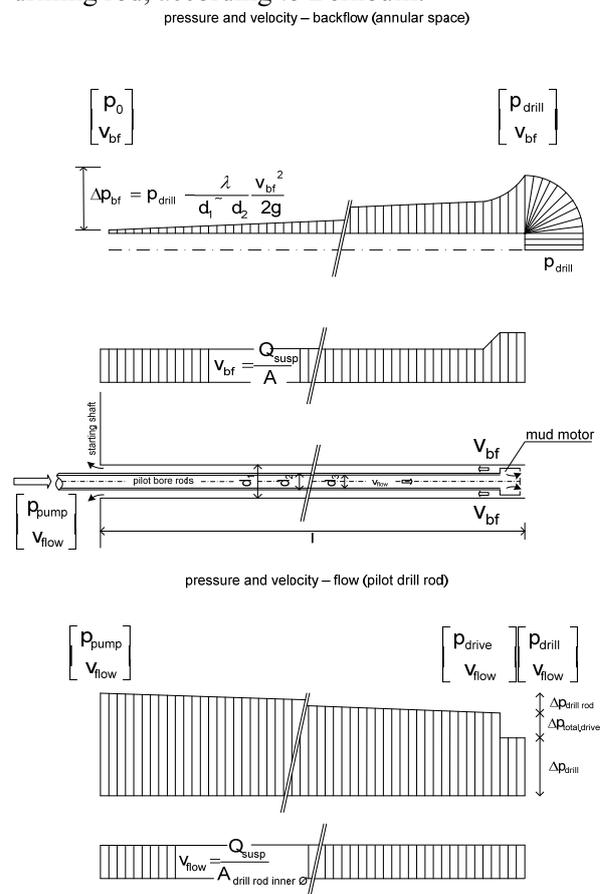

Figure 6. Hydraulic drill mud pressure along the bore hole in homogenous unjointed rock.

Because of the relatively small pressure working area – it corresponds to the projected drilling area – and the small enlargement in transverse direction to the drilling axis, problems with regard to the applicable suspension pressures arise here only in the case of very small cover or very unfavorable geotechnical parameters. In the normal case, no problems arise with the functioning backflow, if, in addition, the conditions contained in chapter 3.1 are complied with.

4.2 *Pressure flow – pilot drilling operation in creviced underground*

If, in the course of drilling, individual joint planes or joint networks are cut, then leakage of the suspension occurs in these void spaces. A part of the suspension will now flow uncontrolled in the joint network and will fill these until it is either completely full, or increasing flow resistance prevents any further leakage. The pressure flow along the drilling rod is in principle the same as shown in Figure 6. As soon as the joint network is filled with suspension (final state) no further pressure drop can take place because of very small flow velocity or complete cessation of the suspension in the region of the joint system (Bernoulli), and thereby the hydrostatic pressure "p_{Drill}" (current pressure at the drilling head) becomes effective over the complete pressure working area.

Depending on the enlargement of the joint network or bank seams in relation to the overlap, this situation can very often give rise to critical conditions with respect to the danger of ground elevations. The force component, directed in an upwardly vertical direction, and which results from the suspension pressure and the large pressure working area, is here solely counteracted by the load from the weight of the soil which covers the influenced area. If these two force components are placed opposite each other it will very soon become clear how great the danger of a ground elevation is using the operating pressures which are common in drilling operations.

Elevation criteria in the case of large-area suspension dispersion:

$$\widetilde{V}_{Susp} \geq \gamma \cdot h \cdot \widetilde{A} \tag{10}$$

Weight of the lapping:

$$\vec{G} = \gamma \cdot h \cdot \widetilde{A} \tag{11}$$

This leads to elevation pressure in the case of large-area suspension leakage in a bank seam:

$$p_{Drill} \geq \gamma \cdot h \tag{12}$$

5 TIME-DEPENDANT PRESSURE PROPAGATION IN BENTONITE SUSPENSION

5.1 *Problem definition*

In the interpretation of potential or already existing damage the following questions are frequently the focus of interest:

− How far is pressure propagation in bentonite suspension within a crevice system possible?
− What changes have taken place in this phenomenon over a period of time?

Since hardly any usable papers concerning pressure propagation in viscous liquids are to be found in the literature, a laboratory experiment was carried out at the Institute for Construction Engineering and Management, ETH Zurich to answer these elementary questions.

5.2 *Carrying out the experiment*

Before undertaking any concrete planning of the conditions for the experiment, it was necessary to elucidate whether a steel pipe could be used to simulate underground crevices and bank seams for the complete range of possible geological circumstances. Discussing this question with geotechnical experts and geologists led to the conclusion that the results of this experiment are valid only for all those geological conditions in which no ion exchange between bentonite suspension and groundwater takes place [5].

The experimental set-up (Fig. 7) consisted of a 15.00 m long horizontal steel pipe, in which a pressure gauge had been built in every 5.00 m using a T piece. A filling tube and a connection for the pressure increase pump, each of which could be separately locked using a conical valve, were attached to the experimental pipe.
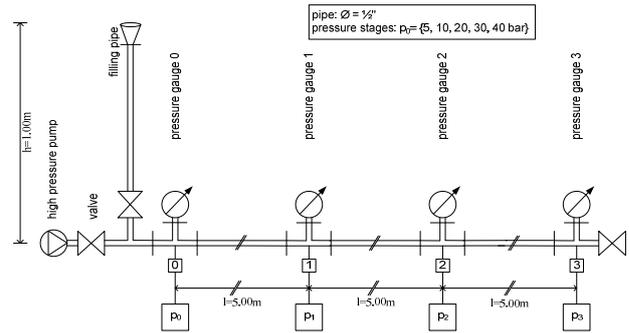

Figure 7.   Experimental setup.

The bentonite suspension used had a solids content of 32.5 kg bentonite HDG per m³. This mixture ratio corresponds to the recommendations of the manufacturer ($30 - 35$ kg/ m³).

The measuring cycle provided for the following pressure levels at the measuring point 0 (pressure gauge on the pumping side of the 15 m long experimental pipe): $p_0 = 5, 10, 20, 30$ and 40 bar. The respective test pressure was maintained for the duration of 10 minutes or it was ensured that no changes in pressure whatsoever occurred at the individual measuring points. When each pressure level was reached at the manometer 0 the pressures were recorded at the pressure gauges $1 - 3$. When the highest pressure level was reached (40 bar) the pressure was released on the pumping side.

The measuring cycle was first carried out on an hourly basis over 48 hours, and then every 12 hours over 7 days.

5.3 *Experiment results and interpretation*

A decrease in pressure of the pressure gauges 1 - 3 in relation to pressure gauge 0 was not observed at any time during the measuring period (9 days). It could therefore be established that:

- even after days without any flow movement and despite its thixotropic properties, the bentonite suspension behaves like an incompressible liquid and thereby conveys the pressure in the case of pressurizing in an immediately isotropic manner.
- the changes in the consistency of the bentonite suspension over time during the period of observed measurement do not have any discernible influence on the pressure propagation.
- pressure propagation in the bentonite suspension can also take place unhindered over greater distances in the case of longer service times (length of the experimental equipment 15 m).

6 CONCLUSION

If drilling runs in homogenous, non-creviced underground and no loss of suspension can therefore be determined (by continuous, even backflow), the relatively high suspension pressures ($p_{Drill} < 35$ bar) will mostly not cause any damage, due to the favorable geometrical boundary conditions (relationship of cover to pressure working area – here approximately: $A = d_1^2$) i.e. no measurable elevation phenomena on the surface.

While drilling through joint planes or bedded rock formations, the suspension leaks uncontrolled in the ground, it follows the basic principles described in point 5.2. During the suspension leakage, the risk of a ground elevation is basically dependent on the possibility of the pressure decrease in the area of the suspension-filled joint system – i.e. the greater the flow velocity and the smaller the flow resistance in the crevice system is the greater the pressure drop will be.

If larger suspension leakages occur during drilling operations, which in practical drilling operations could without doubt be registered, then the phenomena described in point 4.2 occur in the final state.

The surface elevation is a dynamic process, during which, in the case of decreasing or absent backflow, the suspension in phase 1 runs firstly in the bank seams system, without the occurrence of any appreciable elevation phenomena. The decrease in pressure within the crevice system takes place on the basis of the existing flow velocity. The risk of a ground elevation increases with decreasing flow velocity in the crevice system. If the running of the suspension abates then the critical phase 2 commences.

In the underground the situation at this moment appears as follows. Further dispersion of the suspension is prevented, either because of complete filling of the crevice system, or as a result of an increase in the flow resistance (small crevice widths, crevice harshness, viscosity of the suspension etc.). If the drilling operations are now continued, pressurizing of this crevice system, which is filled with an incompressible liquid, occurs. The unrestricted pressure propagation in this system, over longer distances and also after longer time periods (see point 5.3), means – for practical drilling operations – that any further attempts at drilling, even after longer interruptions, are associated with an increased risk.

The analysis of the conditions in the case of suspension leakage into crevice and bank seams systems clearly shows the possible system-related dangers as well as the limits of our comprehension, interpretation and control of such incidents in drilling operations. Owing to the procedure itself, HDD drilling operations in the area of crevice or bank seams systems, as well as of layers with strongly varying resistances, result in a wide range of damage, whose cross-case analysis, including the technical application which can be derived from it, requires further research efforts.

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