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Estimation of the maximum allowable drilling mud pressure for a horizontal directional drilling borehole in fractured rock mass

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ABSTRACT

The drilling mud loss risk is a major problem for horizontal directional drilling (HDD) projects when it was drilling in fractured rock stratum. The existing theoretical calculation methods for the maximum allowable drilling mud pressure in HDD borehole are particularly designed for soils, so they are not suitable when rocks are encountered. The maximum allowable drilling mud pressure was analyzed in this study for a fracture zone of a maxi-HDD project crossing Yangtze River. The geotechnical investigation disclosed multiple layers of soils and rocks: the upper part two sand layers and the lower part one sandstone layer. The fracture zone in the sandstone layer was investigated by digital panoramic borehole camera technique, so that the detailed fracture orientations and locations can be identified. The maximum drilling mud pressure for the upper part two sand layers was calculated using Delft equation. At the same time, the evolution of drilling mud pressure in the fracture zone was studied using numerical modeling method. Combing with the calculation results of both Delft equation and numerical modeling, the maximum allowable mud pressure at the fracture zone of the HDD borehole was obtained. The numerical modeling found that the persistent fracture system in the fracture rock mass has very low resistance to the drilling mud pressure propagation, so a low drilling mud pressure needs to be used when it was drilling/reaming in the fracture zone. The effects of fracture aperture, the drilling mud viscosity, and fracture roughness on the mud pressure evolution were also analyzed.

1. Introduction

The application of horizontal directional drilling (HDD) has greatly facilitated the construction of oil and natural gas pipelines under rivers and mountains. Hydraulic fracturing or the blowout of drilling fluids has always been one of the biggest problems in HDD projects, because it may cause problems to the safety of levees (Staheli et al., 1998), and contamination to the environment (Bennett and Ariaratnam, 2008).

The main functions of maintaining certain drilling mud pressure in HDD borehole are: (1) suspension and removal of cuttings from the borehole (Shu et al., 2015); and (2) maintaining borehole stability (Shu and Ma, 2015). In order to allow the drilling mud to flow back and at the same time transport cuttings back to the ground surface, the drilling mud pressure in the borehole must be large enough to overcome the static mud pressure and the pressure loss during the circulation (Shu and Ma, 2016). On the one hand, it usually needs relatively higher mud pressure for cuttings transport in rock stratum because no cuttings can be squeezed into the surrounding ground of the borehole as which can be done in soft soil layer. On the other hand, the drilling mud pressure should be kept below a certain value, in order to prevent drilling mud loss. If drilling mud loss happened, less or no drilling mud may return to the entry and/or exit points so cuttings can't be transported out of the borehole efficiently, which may lead to a stuck of the drill bit or pipe in the borehole. Even worse, drilling mud loss may cause environmental contamination issue. Therefore, it is important to find a reliable way to estimate the maximum allowable drilling mud pressure and predict drilling mud loss risk for rock HDD projects.

To evaluate the maximum allowable HDD drilling mud pressure, Luger and Hergarden (1988) introduced a method using cylindrical cavity expansion theory for soft soil, which is called Delft equation. After that, different researchers have continuously made contributions to improve or modify the original Delft equation.

Keulen et al. (2001) presented a revision to the original Delft equation based on the maximum allowable strain specifically for sand. Kennedy et al. (2004) compared the finite element analysis results with a simplified Delft equation, and it found that coefficient of the lateral earth pressure can significantly affect the mud pressure and the Delft equation result is unconservative. Xia (2009) proposed a new approach

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to estimate the maximum allowable mud pressure which considers the growth of maximum plastic radius with increasing mud pressure, and different lateral earth pressure coefficients. Yan et al. (2016) studied the formation fracturing of Qin River with both Delft equation and Xia's method, as well as finite element analysis. All of these studies are focused on soils.

As the application of HDD expands quickly from soil to rock, it is more and more common that drilling mud loss was encountered in rock stratum. It is noticed that drilling mud loss occurred in fractured rocks are substantially different from those occurred in soil. Buenker (2015) introduced the Hoek-Brown criterion to the cavity expansion theory and derived some analogous equations of the Delft equation to predict the maximum allowable mud pressure. However, these equations are much complicated than the original Delft equation and they can only be solved numerically (Buenker, 2015). They are still based on the cavity expansion theory so that it may not applicable to hard rocks. Besides, it did not consider the fractures in rock stratum as channels for drilling mud loss.

In conclusion, there is a lack of reliable methods to predict drilling mud loss risk or calculate maximum allowable drilling mud pressure for HDD boreholes in fractured rocks. It is therefore an emergent need to explore such a method either theoretically or numerically. This paper introduced a numerical modeling evaluation of the drilling mud loss risk using three dimensional discrete element method for a HDD project in fractured rock mass.

2. Project description

This maxi-HDD project is to install a 610 mm (24 in.) in diameter oil pipeline crossing Yangtze River. The designed layout of the HDD borehole route and the corresponding geotechnical investigation line were shown in Fig. 1. The geotechnical investigation line was located about 15 m upstream of the designed HDD route. It is not right on the HDD borehole route in order to avoid influence of geotechnical investigation drill holes to the HDD construction. There are totally 37 geotechnical investigation drill holes distributed more or less evenly along the line with an average spacing of approximately 60 m. The geotechnical investigation disclosed that there are roughly more than 40 m of sand on the top of a thick sandstone layer. Because there is some bad experience of pipeline damaging when they were installed in the soil layer of a river bed (Lan et al., 2014), this time, the pipeline was designed to be mainly installed in the sandstone layer to avoid such pipeline damaging.

The cross section of the HDD route is shown in Fig. 2. The HDD route is mainly located in the medium weathered sandstone layer, and its depth is 60.3 m to the ground surface. The total crossing length of the HDD route is about 2200 m.

From the geotechnical investigation, it found that the core samples from drill hole #14 were highly fractured, while other boreholes came out with very good quality intact core samples. It means that there are a local fractured zone at the location of drill hole #14 and the nearby area. Digital panoramic borehole camera technique (DPBCT) was used to find out the detailed geological conditions in drill hole #14, especially the fracture orientations, apertures and locations. The location of drill hole # 14 was shown in Fig. 1, as well as Fig. 2.

The picture of DPBCT shown many open fractures in drill hole #14, see Fig. 3. Through the analysis of the DPBCT images, twelve fractures were identified and their orientations and elevations were listed in Table 1.

The geological conditions at borehole #14 are shown in Fig. 4. From the top to the bottom, there are 4.9 m of river water, 8.9 m of silty sand, 18.9 m of fine sand, and then a thick sandstone layer that was not drilled through. The designed HDD borehole is just located in the sandstone layer, 14.0 m below the soil/rock interface. The depth of the HDD borehole at borehole #14 is 41.8 m from the bottom of the river.

Even though from the DPBCT pictures, it seems that the fracture apertures are very large, some of them can reach up to 10 mm. However, considering that the borehole wall was cleaned up with steel wire brush and hydraulic jetting before DPBCT was used, it is very possible that some rocks at the fracture were broken from the borehole wall and therefore the original fracture aperture can be much smaller than what we can see. Based on the measurement of fracture apertures from the field core samples as well as the DPBCT imaging, an average fracture hydraulic aperture of 1.0 mm is used with the consideration of the joint roughness in this study.

The physical and mechanical properties of silty sand, fine sand, and sandstone are shown in Table 2, and the mechanical properties of rock fractures are shown in Table 3.

The detailed geotechnical investigation shows that there are many open fractures found in borehole #14 which might cause drilling mud loss in the designed HDD borehole. Therefore, in the following study, in addition to the calculation of the maximum allowable drilling pressure for the sand layers, the drilling mud pressure loss in the fractures from the HDD borehole to the soil/rock interface was estimated using discrete element numerical modeling.

3. Theoretical calculation

3.1. Minimum required mud pressure for drilling mud to return

In order to make sure that the drilling mud can return to the ground surface from the borehole, the drilling mud pressure in the HDD borehole should be larger than a minimum required mud pressure. The minimum required drilling mud pressure includes two parts: the static drilling mud pressure, and the drilling mud pressure loss.

The static drilling mud pressure can be calculated with Eq. (1), and the result is 0.62 MPa.

$$P_S = \rho \cdot g \cdot h \tag{1}$$

where P_s is the static drilling mud pressure, Pa; ρ is the density of the drilling mud, 1050 kg/m^3; g is the gravity acceleration, 9.8 N/kg; h is the depth from the ground surface to the location of study, 60.3 m.

There are three commonly used flow models for drilling mud: Newtonian flow model, Bingham Plastic flow model and Power Law flow model. The equation of mud pressure loss for Power Law fluid in annulus space for laminar flow is shown in Eq. (2) (Bourgoyne et al., 1991):

$$P_l = \left(\frac{4v}{(D-d)} \cdot \frac{(2n+1)}{n}\right)^n \cdot \frac{4 \cdot K \cdot L}{(D-d)} \tag{2}$$

where P is the mud pressure loss, Pa; L is the flow length of drilling mud, m; v is the average flow velocity of drilling mud, m/s; D is the diameter of borehole, 0.241 m; and d is the diameter of drill rod, 0.168 m; n is the flow index, dimensionless; and K is the consistency index, Pa·s^n. The n, K, and v were set to be 0.46, 2.34, and 0.7 m/s, respectively, according to HDD engineering experience. With a return length L of 748 m, the calculated drilling mud pressure loss P_l is 0.99 MPa. Plus the static mud pressure to the mud pressure loss of 0.62 MPa, the minimum required drilling mud pressure for drilling mud to return from the fractured zone to the ground surface is 1.61 MPa.

3.2. Maximum allowable mud pressure for sand layers

In this section, the maximum allowable drilling mud pressure for the silty sand and fine sand layers was calculated using the Delft equation. Drilling mud loss usually occurred during pilot hole drilling stage because the borehole is small and it always need high mud pressure to assist with hydraulic jetting and cuttings transport, so in the following study, we consider only the pilot hole drilling part.

The Delft equation, as shown in Eq. (3), assumes that soil surrounding the borehole experience perfectly elastic deformation until

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