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Analysis of steering in horizontal directional drilling installations using down-hole motors

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ABSTRACT

Horizontal directional drilling is becoming an increasingly popular technique for the installation of pipes in urbanised environments or in locations where trenching is difficult, such as under rivers or railways. This technique utilises down-hole bits to create the bore before it is expanded with back-reamers to allow installation of the product pipe. Controlling the path of the bore is critical to the success of many horizontal directional drilling installations and the potential inability to maintain such positional control is a factor that prevents the widespread adoption of this technique in place of traditional open cut methods.

Two types of drill bit are commonly used in horizontal directional drilling; shaped jet-cutting bits and bits mounted on bent-subs and driven by mud-motors, the former being utilised in weak ground conditions and the latter in stronger formations. This paper analyses a dataset of survey data from pilot bores for fifty-four HDD installations that used mud-motors to investigate the parameters that impact upon the control of the position of the drilling bit. The drives are broken down into sections of rotary and slide drilled borepath and these are investigated separately. Drilling practice, drilling equipment, length of drive and the geology in which the bore is being established will have an effect upon the ability to control the position of the drilling bit.

1. Introduction

Horizontal directional drilling (HDD) is a versatile technique, adapted from oilfield technology, that is increasingly being used to install cables and pipes under rivers and infrastructure. HDD traditionally uses two cutting tools; shaped blades (that jet-cut with drilling mud) for soft soils and down-hole drill bits, powered by mud-motors, for stronger formations.

This paper focuses upon the control of steering HDD pilot bores created using down-hole mud-motors. Fifty-four HDD installations, comprising 86 drives over 42 km, were investigated; using site investigation survey data, HDD operators' steering records (developed prior to installation to ensure that the desired borepath is achieved) and recorded drilling data, to analyse the performance of HDD in various ground conditions. The installations investigated used tri-cone roller (TCR) bits without stabilising elements within the down-hole assembly. Those installations using polycrystalline diamond compact (PDC) bits, stabilisers or were identified as being undertaken in 'problematic' ground conditions were not investigated.

The data for each drive was organised into sections describing each length of rotary drilling and slide drilling used to establish the borepath. The ratio of actual steering performance against predicted performance was identified for each of the sections to determine the factors that impact upon steering control in HDD installations (following the approach by Lesso et al., 1999; Studer et al., 2007). The study identified a number of factors that impact upon the ability to control steering in HDD, including; the length of slide drilled sections; the distance from the drilling rig to the down-hole assembly; the drill bit type and bend angle of the bent-sub; the geology in which the installation takes place. Prior to the presentation of the results from the investigation of these factors, a brief summary on the use of down-hole assemblies in HDD installations and the need to control steering in HDD is given.

2. Control of steering in HDD installations using down-hole motors

Positive displacement down-hole motors are incorporated into drill strings, with bent-subs, to power rotary drill bits that are

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Abbreviations: BUR, build up rate (°/m); DBR, drilling build rate (°/m); DTR, drilling turn rate (°/m); HDD, horizontal directional drilling (dimensionless); MT, mill-tooth (TCR bit) (dimensionless); PDC, polycrystalline diamond compact (dimensionless); ROP, rate of penetration (m/min); SBE, sliding build effectiveness (dimensionless); STE, sliding turn effectiveness (dimensionless); SBR, sliding build rate (°/m); STR, sliding turn rate (°/m); TCR, tri-cone roller (dimensionless); TCI, tungsten carbide insert (TCR bit) (dimensionless); WOB, weight on bit (kN).

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efficient at cutting through rock formations. Incorporating a drill bit that can be rotated irrespective of the rotation of the drill string has resulted in the development of two drilling practices; drilling (or rotary drilling) and sliding (or slide drilling) (Fig. 1). Drilling refers to the rotation of the drill string whilst providing thrust from the drilling rig and sliding refers to the provision of thrust only. In both cases the mud-motor drives the drill bit. Drilling creates straight sections of bore whereas sliding creates the curved sections (which are orientated by managing the angle of the tool face and controlled by the angle of the bent-sub). The presence of the bent-sub within the drill string results in rotary drilled sections having greater bore diameters than those created by slide drilling (Fig. 1), this can have an impact on the ability to control the position of the drill bit. Equipment is available that attaches to the down-hole assembly and allows for the creation of curved sections whilst rotary drilling, although this is rarely incorporated into HDD installations and is not considered herein.

3. Bit types commonly used in HDD

The oilfield industry utilises either PDC bits (these shear the formation), or TCR bits (which gouge and crush the formation); milltooth bits (MT) or tungsten carbide insert bits (TCI). However, HDD installations tend to be dominated by TCR bits as PDC generate significant torque and have side cutting capabilities, and in the comparatively weak geological conditions associated with HDD installations PDC bits suffer from excessive bit-walk. Bit-walk describes the lateral drift of the drill bit due to rotational forces acting on the bit (Liu and Shi, 2002). TCR bits will experience bit-walk but at a lower level to the PDC bit, due to the reduced level of torque generated by the bit (Norris et al., 1998) and the reduced side-cutting potential (Ernst et al., 2007). However, TCR bits experience reduced rate of penetration (ROP) and require a greater minimum force applied to the bit; known as the weight on bit (WOB) (kilonewtons), in order to cut effectively, when compared to PDC bits.

4. Monitoring the position of the down-hole assembly

The use of down-hole motors within a drilling assembly is not without its problems as the sensors used to monitor the position of the drill suffer from interference generated by the motor (using conventional HDD equipment) and must be placed several metres behind the bit (Fig. 2). Thus the operator does not accurately know the position of the bit in real time and must wait until the sensor reaches the desired point to obtain accurate positional data. Clearly there is the potential for the drill to deviate from the desired path and the operator must either withdraw the drill string and re-drill the bore or correct the position of the drill as it moves forward. The incorporation of deviations from line and level (known as dog-legs) has the potential to damage the drill string or the product pipe during subsequent installation. Royal et al. (2006, 2010) and Chapman et al. (2007) have argued for the need for research to improve the control of the position of down-hole assemblies if HDD is to become universally adopted, in place of open cut methods, and achieve long distances in continuous drives.

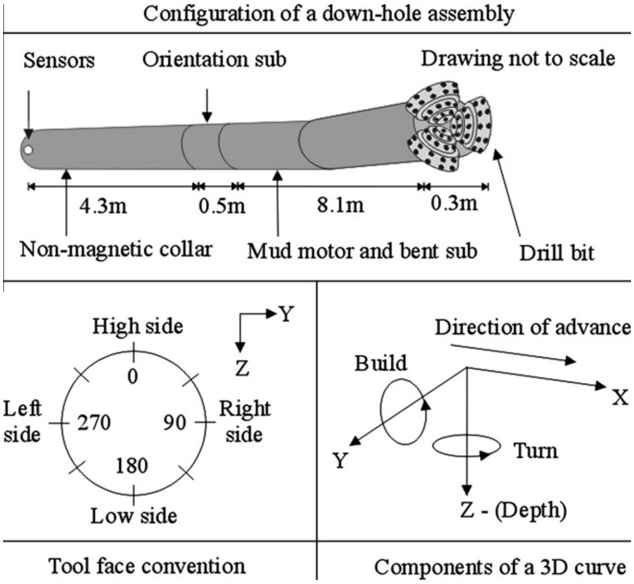


Fig. 2. Configuration of down-hole assembly, the tool face convention (looking from the surface down into the bore) and the components used to describe a 3-D curve (drawing not to scale).

5. Establishing the desired borepath during pilot drilling

Steering patterns are often developed by the HDD operators prior to pilot boring to guide the drillers, allow for the prediction of the location of the down-hole assembly at any point during the drive, and ensure that the desired borepath is established. These steering patterns are created in accordance with manufactures' technical data for the down-hole assembly in question. When developing steering patterns for curved sections within the borepath, HDD operators have traditionally utilised sequences of short alternating drive lengths of drilling and sliding in preference to continuous slide drilling. This is due to the concerns regarding the ability to accurately control the position of the down-hole assemblies whilst sliding over long distances.

Data collected from the sensors in the down-hole assembly can be compared to the steering patterns to monitor the down-hole assembly location; provided that the azimuth, inclination, distance to bit, distance to sensor and tool face angle are known. The frequency, and adopted strategy, of surveying the position of the down-hole assembly can lead to deviations from the desired borepath. Current practice is to take static surveys at set points (every time a new drill rod is introduced into the string, or after a set penetration distance; a maximum of 10 m between survey points is generally used in the HDD industry). Stockhausen and Lesso (2003a,b,c) undertook continuous surveying of oilfield boring and were able to illustrate that assuming the drill bit must cut a predictable bore between two surveyed points (approximate survey distance of 30 m) is invalid and can lead to significant deviations within the bore if the deviations are not identified and are allowed to combine over the length of the bore. It was recommended that a

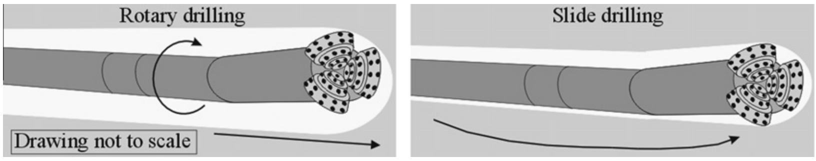


Fig. 1. Illustration of drilling (rotary drilling, left) and sliding (slide drilling, right) in HDD.

change in survey strategy is needed, i.e. to increase survey frequency or move towards continuous surveying, to improve the control of bit positioning. The authors of this paper believe that, whilst the surveying distance in HDD is less than in the oilfield industry (10 m intervals instead of every 30 m), continuous surveying, tied into static surveys every 10 m (or at the installation of a new drill rod into the drill string), would be equally applicable to HDD installations and would provide increased certainty in the positional control of the down-hole assembly.

6. Factors identified in oilfield drilling that impact upon the control of steering

Previous research undertaken in positional control of down-hole assemblies tends to refer to oilfield applications and focus upon the use of PDC bits, which is not felt to be directly relevant to the HDD industry. However, a number of factors have been identified that may be relevant to HDD installations and include; the compressive strength of the rock (Lesso et al., 1999; Hareland et al., 2000); changes in rock strength (both laminations and interbedding within the strata, Boualleg et al., 2006); the dip of the formation (Stockhausen and Lesso, 2003b); the type of down-hole assembly used (Lesso et al., 1999; Studer et al., 2007); the ROP (Ernst et al., 2007; Lesso et al., 1999), the WOB (Lesso et al., 1999; Studer et al., 2007); bit-walk (Liu and Shi, 2002); tool face angle (Lesso et al., 1999; Studer et al., 2007); stabilisers (that amplify the size of dog-legs created by migration away from line and level).

Lesso et al. (1999) and Studer et al. (2007) both developed approaches to investigate the relationship between the apparatus used (within the oilfield industry) and steering response. Lesso et al. (1999) investigated 4600 drives by averaging the steering performance for the drive and then undertaking a cluster analysis. Finite element models were created to predict the behaviour of 'typical' down-hole assemblies (based on the results of the cluster analysis) and the models were used to undertake a parametric study to identify important parameters on steering response (as described above). Studer et al. (2007) developed a program that can be used in post-analysis to investigate drilling performance. The model breaks a drive into segments and compares predicted performance (derived from user supplied variables) with actual performance.

In light of the previous research undertaken on steering control in oilfield drilling, the analysis of control of steering in HDD installations reported in this paper broadly follow the approach undertaken by Lesso et al. (1999) and Studer et al. (2007). The datasets were broken down into sections and the surveyed values were compared to theoretical values. The modified datasets were then used in a parametric study to assess the relative importance of various factors on the control the position of HDD down-hole assemblies. The parametric study included the length of slide drilled sections, the distance from the drilling rig to the down-hole assembly, the drill bit type and the stated performance of the down-hole assembly, the bend angle of the bent-sub. The methodology used to create the modelled data and the outcomes of the parametric study are reported in the following sections of the paper.

7. Analysis of steering HDD pilot bores

The data used in this study comprised three formats; drilling information (location, drilling conditions, drilling mud pressures and flow rates, down-hole assembly used, bit to sensor length, etc.), steering information (formalised description of operator's procedures throughout the installation) and the surveyed data. The data spans a 10 year period and describes HDD installations being undertaken in 13 countries by 20 companies. It is understood that in 10 years changes in technology or practice could have an effect upon the analysis. However, the data was included as a significant dataset was required to investigate which parameters have an effect on the control of steering and it was felt that HDD steering technology had not changed significantly within this period.

8. Preparation of the dataset for use in the study

The majority of bits used in this study were TCR without stabilisers. Therefore datasets based on PDC, drag-bit, or stabilised down-hole assemblies were removed from the dataset used in the study. Data was also removed if the information provided was insufficient for the needs of the project. Occasionally, the drilling records would state that conditions encountered were 'difficult' or 'problematic', although further information providing insight as to why this may be the case were not supplied.

In these instances, the drilling records were also rejected from the dataset because it was not possible to quantify why the ground was 'problematic', nor how 'difficult' ground impacted upon steering control, and it was felt that it would be inappropriate to include such data within the analysis.

It is understood that 'difficult' ground conditions would be of interest to any investigation that considered the control of HDD steering; as such cases could result in extreme deviations from desired borepath. 'Difficult' ground is a term often used to describe when cavities, fractures, faults, boulders, and cobbles were encountered. Deviations caused by these structures are difficult to estimate without prior knowledge of their orientation relative to the drill alignment. Prediction of deviations in difficult ground is believed to be impractical without detailed mapping of the geological structures in which the borepath is being drilled. A potential method to compile such information would be to pull geophysical logging equipment through the completed borepath; something the authors are unaware of being undertaken in HDD, and certainly had not been undertaken in the installations investigated herein.

In total approximately 16 installations were removed as not being suitable for this study (72 installations, with 130 drives were initially investigated). The HDD project location, number of drives undertaken during the installation and approximate maximum drive length within the installation can be found in Table 1. For the purposes of analysis the installation data was tabulated and divided into sections describing changes in the drilling or sliding (informed by the driller's logs) during installation. The survey data (azimuth and inclination data) combines to form the 3-D borepath created during the installation, although for the purposes of this study the data was analysed in two planes (horizontal and vertical, termed turn and build respectively, Fig. 2). The sign convention for build and turn is defined herein as: build is positive when moving towards the high side and negative towards the low side; turn is positive turning to the right side and negative towards the left side.

The rate of curvature (°/m) was calculated in both planes (Table 2) for each section of drilling (drilling turn rate and drilling build rate; DTR and DBR, respectively) and sliding (sliding turn rate and sliding build rate; STR and SBR, respectively). The measured distance in Table 2 refers to the distance travelled during each phase of drilling and sliding (calculated from the change in distance from drilling rig to bit). The ability to achieve the desired curvature during the drive was assessed by dividing the curve rates achieved in each section (STR and SBR) by the predicted curve rate of the down-hole assembly in the turn and build planes. The predicted build and turn rates initially used the manufacturer's rate of curvature quoted in literature associated with each down-hole assembly (known as build up rate, BUR (°/m)). The resultant ratios

Table 1
HDD installations investigated in the study.

Project	Country	Drives	Approximate maximum drive length (m)	Stated geologic formation	Project	Country	Drives	Approximate maximum drive length (m)	Stated geologic formation
1	Belgium	3	420	Mudstone/clay	28	Spain	1	2101	Claystone
2	Denmark	1	155	Clay/gravel	29	Spain	3	368	Greywacke
3	France	3	1364	Clay/gravel/marl	30	Spain	1	368	Greywacke
4	France	1	1011	Sand/silt/clay	31	Spain	2	339	Greywacke
5	France	3	577	gravel/clay/marl	32	Spain	4	310	Claystone
6	France	3	557	Clay/gravel/rock	33	UK	3	1425	Mudstone/siltstone/clay
7	France	1	509	Sand/gravel/clay	34	UK	1	1038	London clay
8	France	1	394	Clay/chalk	35	UK	3	805	Clay/sandstone/mudstone
9	France	1	390	Sand/gravel/clay	36	UK	2	713	Mudstone
10	France	1	300	Clay/fill	37	UK	1	500	Stiff clay
11	France	1	280	Granite	38	UK	3	458	Mudstone
12	Georgia	1	714	Sandstone/mudstone	39	UK	4	442	Sand/limestone/clay
13	Germany	2	1237	Sandstone/claystone	40	UK	2	359	Sandstone
14	Germany	1	808	Compacted sand/marl	41	UK	1	234	Sand/clay/stone
15	Germany	1	748	Compacted sand/marl	42	UK	1	215	Sand/clay/stone
16	Germany	1	579	Gravel	43	UK	3	205	Sand/clay/stone
17	Germany	2	406	Sand	44	UK	1	95	Stiff clay
18	Germany	1	380	Sand/clay/gravel	45	Australia	2	1014	Sandstone
19	Germany	1	276	Sandstone/claystone	46	Brazil	1	1077	Sand/gravel/shale/clay
20	Germany	1	180	Sandstone	47	Canada	1	834	Clay/shale
21	Germany	1	112	Gravel/shale/quartzite	48	Canada	1	741	Sandstone
22	Germany	2	111	Gravel/shale/quartzite	49	India	1	511	Clay/weathered rock
23	Germany	1	46	Gravel/shale/quartzite	50	India	1	484	Clay/weathered rock
24	Germany	1	24	Sand/cobble/chalk	51	India	1	416	Rock
25	Italy	2	845	Folded siltstone	52	India	1	406	Rock
26	Italy	1	269	Sand/silt/gravel	53	India	1	235	Silty clay/rock
27	Romania	1	400	Sandstone	54	–	1	195	Schist/gneiss

Table 2
Definition of actual curve rate and curve effectiveness for the horizontal and vertical planes.

Plane	Turn component	Actual rate of curvature (between surveyed points)			Curve effectiveness	
		Definition (drilling and sliding)	Abbreviation		Definition (sliding only)	Abbreviation
			Drilling	Sliding		Sliding
Horizontal	Turn	Change in azimuth/measured distance	DTR	STR	Actual turn rate/predicted turn rate	STE
Vertical	Build	Change in inclination/measured distance	DBR	SBR	Actual build rate/predicted build rate	SBE

describe the 'sliding effectiveness' (dimensionless) for the drive, with the turn and build components termed: sliding turn effectiveness (STE) and sliding build effectiveness (SBE), respectively. The parametric study predominantly focused upon the relationship between SBE and STE values and the various parameters investigated, DBR and DTR were also considered. Equivalent drilling parameters to the sliding effectiveness were not derived as there should be no deviations from line and level when drilling, although such deviations do exist (as illustrated in a subsequent section of this paper).

9. Impact of the stated build up rate of the down-hole assemblies on prediction of sliding effectiveness

The HDD installations considered herein were undertaken using a variety of down-hole motors manufactured by different companies (although not all of the datasets included manufacturer' bit type information used in the installation). Each down-hole motor has an associated BUR, determined by the manufacturer, although the methods used to calculate the BUR vary and these were not necessarily made public. There is the potential for the manufacturer's quoted BUR to have an effect upon the prediction of steerage control within the ground. This has been difficult to assess as the majority of installations utilised down-hole motors from one manufacturer (although the type may change during the installation).

One installation used two manufacturers' down-hole motors on one site that comprised several drives. Throughout the installation the operators did not record any difficult ground conditions; therefore this dataset was used to investigate how quoted BUR could have an impact upon this study. Fig. 3 illustrates the variance in SBE for the two motors using the manufacturer's quoted BUR and a generic BUR (definition of the generic BUR provided in the following section). The box plots used illustrate a number of parameters for the data set: the boxes describe 50% of the data with the mean value highlighted within and the error bars on the plots indi-

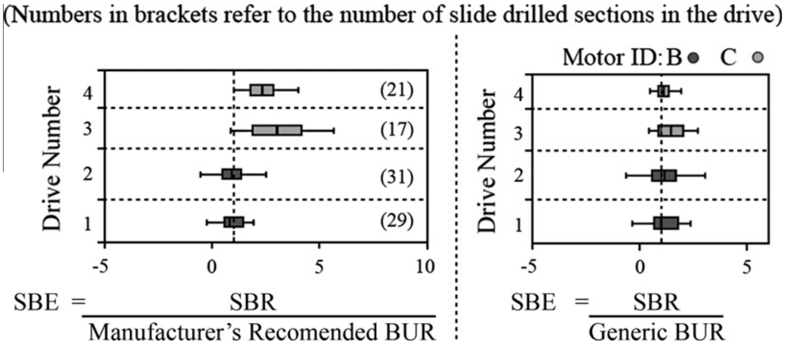


Fig. 3. Variation in SBE using both the manufacturers' and generic BUR.

Table 3
Impact of applying a generic BUR to the STE calculation instead of using manufacturers' recommended BUR.

Motor	Number of investigated drive sections	STE: (STR/manufacturers recommended BUR)		STE: (STR/generic BUR)	
		Mean	Standard deviation	Mean	Standard deviation
A	9	−0.73	2.78	−0.48	1.86
B	193	0.86	1.47	0.86	1.69
C	786	1.85	5.2	0.86	2.44
D	219	1.79	3.14	2.06	3.83
E	508	1.1	2.6	1.27	2.96
F	39	0.15	1.85	0.2	2.53

cate 100% of the variation. The values in brackets presented on the figures within this paper describes the number of slide drilled sections undertaken for a given condition, in the case of Fig. 3 the number of slide drilled sections in the given drive. The change in BUR only had a limited effect on the motor used on the initial drives, but a significant effect on the SBE for the second motor used on the later drives.

The impact of applying a generic BUR when calculating the STE can be found in Table 3 (the number of investigated drive sections represent the number of slide drilling sections undertaken in all of the HDD installations investigated for each motor). The use of the generic BUR does not universally relate to an improvement in the STE calculation. However, the increases in STE resulting from the adoption of a generic BUR was far less than the experienced decrease, and a common methodology was desired when creating SBE and STE values to allow the investigation of the impact of various parameters upon the steering response of HDD installations using down-hole motors. In light of this, the generically derived BUR was used in place of the manufacturer's data in the study. Therefore, for the remainder of this paper SBE and STE (with the exception of Fig. 3) will be based on generic BUR determined for each instillation. The installations that did not include manufacturer's data on the motors were also converted to using the generic BUR. If the down-hole assembly data (bend angle, distance to bit from sensor, etc.) was insufficient to calculate a generic BUR for the installation then it was rejected from the study.

10. Development of a generic build up rate for the down-hole assemblies

The generic BUR was developed from the three-point curvature BUR calculation method (Gabolde and Nguyen, 2006) that assumes the path of the slide drilled hole follows an arc through the centralised drilling assembly. For HDD the assembly is rarely centralised within the bore so the generic method assumes that the drill string is in contact with the surface of the bore at three locations on the low side of the bore. If the geometry of the down-hole assembly (angle of bent-sub, bit to sensor distance, bit diameter, etc.) is known the BUR can be calculated (Fig. 4). Thus, one value for the generic BUR was not adopted; instead it was determined for each installation using the manufacturer's quoted geometry for the down-hole assembly. The curved line in Fig. 4 represents the bore-path created by slide drilling and the BUR is described by the generation of an angle about the origin as the drill bit moves forward. BUR is conventionally expressed as degrees per 30 m, or 100 ft, of measured distance in HDD but will be displayed as degrees per metre herein.

Points 1–3 within the drill string (Fig. 4) are assumed to follow the same curvature. The radius of curvature (r) can be calculated using a relationship proposed by Avallone et al. (2006) (Eq. (1)). Eq. (2) illustrates the solution to this equation for the geometry of the down-hole assembly presented in Fig. 4. Providing that lengths A and B are known then lengths C and D along with angles c and d (Fig. 4) can be derived using Pythagoras' theorem and other simple trigonometric relationships. The BUR can be predicted for the down-hole assembly using Eq. (3) (where L refers to the length of arc and α the subtended angle of the arc (Avallone et al., 2006).

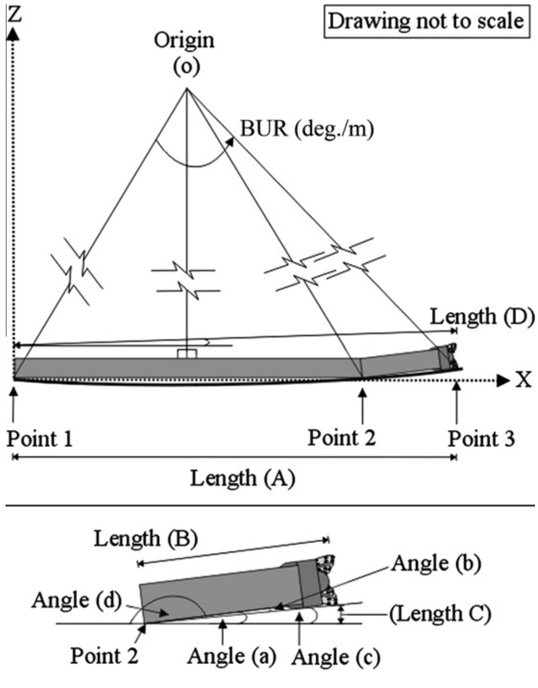


Fig. 4. Illustration of the generic BUR.

$$r = \frac{0.5D}{\sin(d)} \tag{1}$$

$$r = \frac{0.5[A^2 + (B\sin(c))^2]^{0.5}}{\sin(180 - c)} \tag{2}$$

$$\alpha = \frac{180L}{r\pi} \tag{3}$$

11. Deviations from desired line and level when drilling and sliding

Fig. 5 presents the distributions for DBR and DTR and SBE and STE respectively (an idealised SBE and STE should have the value of 1.0 and this value has been marked on the appropriate figures). The distributions for both datasets are leptokurtic (normally distributed curves have been superimposed in Fig. 5 to further illustrate the nature of the distributions), suggesting that the steering of HDD the pilot bore is controllable, which can invalidate the use of statistics more commonly associated with normally distributed datasets (Brown, 1997).

Fig. 5 illustrates that SBE and STE values greater than 10 are 'extreme' events and, for ease of viewing, subsequent SBE or STE plots are limited to a maximum range of −10 to 10 (with the exception of Fig. 8). The 'extreme' SBE and STE events were identified by applying three standard deviations either side of mean (in Gaussian distributions, the region within the range described by the application of the standard deviations contains at least 99% of the dataset). It is understood that the distributions in this study are leptokurtic, thus this model is not directly applicable. However, as leptokurtic curves exhibit far greater distribution of the dataset near mean than encountered in normally distributed curves, it was felt that despite the inaccuracies in applying the boundaries on the distributions with the use of standard deviations, the data outside the boundaries can still be considered 'extreme' occurrences. It is with this in mind that the 'extreme' limits for the datasets were applied.

Fig. 6 illustrates the relationship between build and turn components for drilling and sliding for MT and TCI. An idealised relationship between SBE and STE should have coordinates of (1, 1) on the scatter plots, the greater the distance away from the ideal point the greater the deviation from the planned location. Rotational drilling ideally should return a value of zero for build and turn on Figs. 5 and 6, as the rotation of the drill string should result in a straight borepath. It is clear from Figs. 5 and 6 that a small degree of variation from level can be anticipated. To provide a context to the degree of curvature associated with rotary drilling the maximum, minimum, mean and standard deviations for the RBR and RTR along with the SBR and STR are presented in Table 4. It is clear that the maximum rates of curvature (approximately 0.14 °/m) are within the range that the HDD operators' will select when slide drilling a curve, although the average rate of curvature is almost an order of magnitude lower than that for slide drilling.

Fig. 7 illustrates the change in elevation from a datum with the distance from the commencement in slide drilling in an idealised case (the installation with an SBE of one is assumed to have a BUR of 0.06 °/m and a radius of curvature of 955 m) and Table 5 presents the difference in the elevation between the increased SBE values with respect to those for an SBE of 1. The distances considered from the commencement of slide drilling have been taken up to 10 m to reflect the maximum likely distance between survey

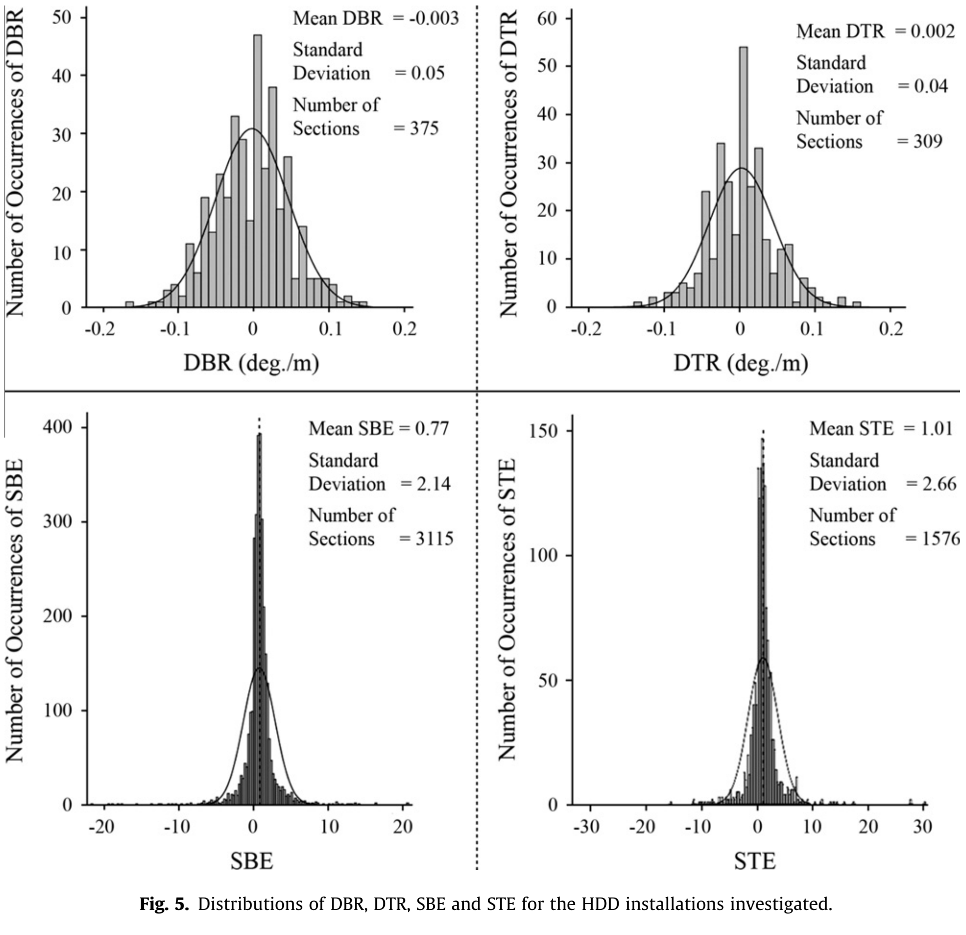


Fig. 5. Distributions of DBR, DTR, SBE and STE for the HDD installations investigated.

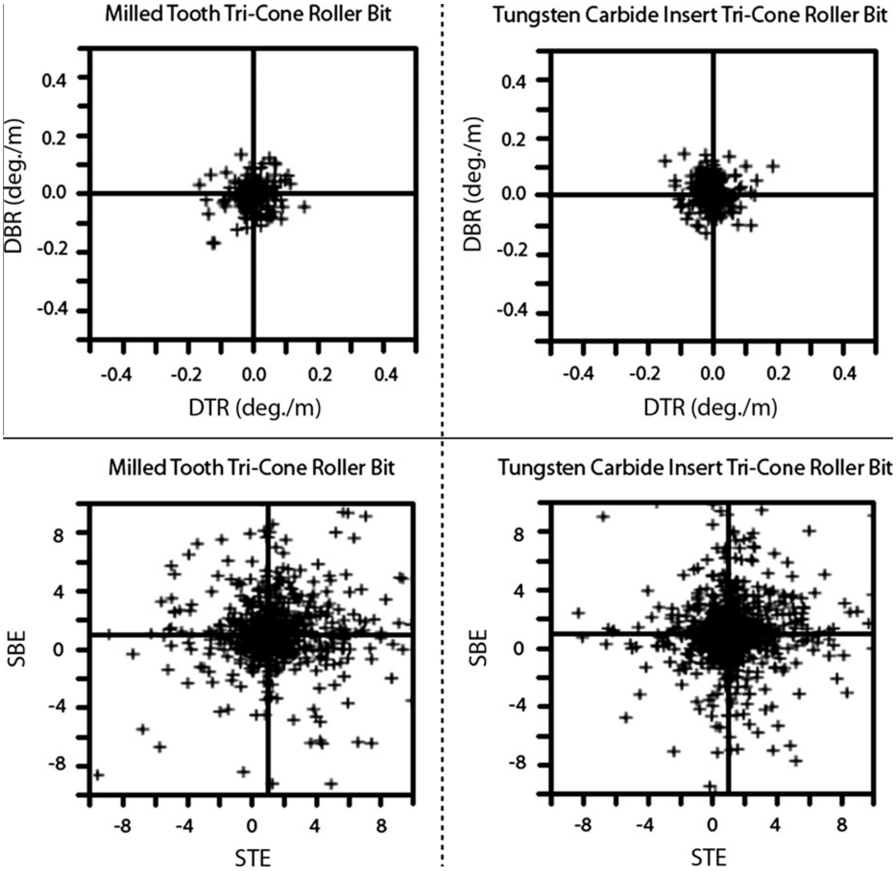


Fig. 6. Relationship between build and turn for drilling (top) and sliding (bottom) using TCR Bits (MT, left, and TCI, right).

Table 4
Build and turn rates for rotary and slide drilling.

	SBR (°/m)	STR (°/m)	DBR (°/m)	DTR (°/m)
Maximum	0.89	0.46	0.14	0.17
Minimum	−0.59	−0.43	−0.15	−0.14
Mean	0.04	0.02	0.003	0.002
Standard deviation	0.10	0.08	0.05	0.04

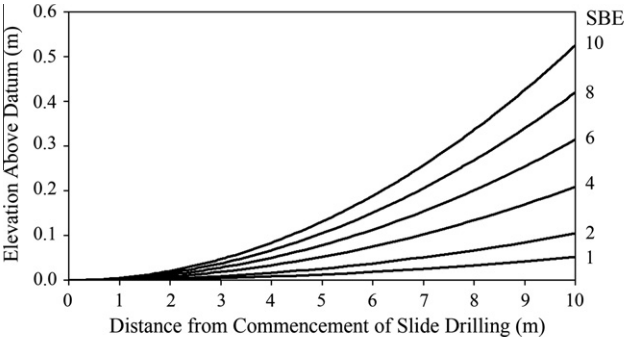


Fig. 7. Impact of increased SBE in Elevation from a datum with distance from commencement of slide Drilling (0–10 m range considered).

points in HDD. It can be seen that the more infrequently the location of the down-hole assembly is surveyed the greater the potential for significant deviations from the desired bore path, necessitating retraction of the drill string and redrilling of the bore, amendments within the bore path to allow for the localised change in position or corrective measures as the drill advances to restore the location of the down-hole assembly to the desired location.

12. Parameters considered in the parametric study

The difference between the datasets for rotary drilling and slide drilling indicates that when the drill sting is rotated, deviations from desired line and level are effectively minimal and the most significant deviations are associated with sliding. Therefore, rotary drilling will not be considered further within this study. The deviations from ideal illustrated for SBE and STE in Figs. 5 and 6 would appear to be a function of a number of parameters, including; drill bit, geology, relative slide length, distance from drilling rig, predicted BUR (discussed previously) and ROP, which is akin to the findings of the studies undertaken in oilfield drilling by Ernst et al. (2007) and Boualleg et al. (2006). The remainder of the paper will focus on the length of slide, distance from drilling rig to bit, drill bit and bend angle of the bent-sub used as well as the impact of geology on the control of steering in HDD installations.

13. Length of slide

The practice of repeatedly alternating between sliding and drilling over short distances to create curved sections of bore, instead of slide drilling the entire curve in one continuous motion, is commonplace as it is deemed to afford greater control over the position of the drill bit. This technique can utilise lengths of sliding that are far less than the distance between bit and sensor, and often less than a metre in length. The practice of incorporating such short slide drilled sections can be attributed to the large SBE and STE values within the investigated dataset. Fig. 8 illustrates the relation-

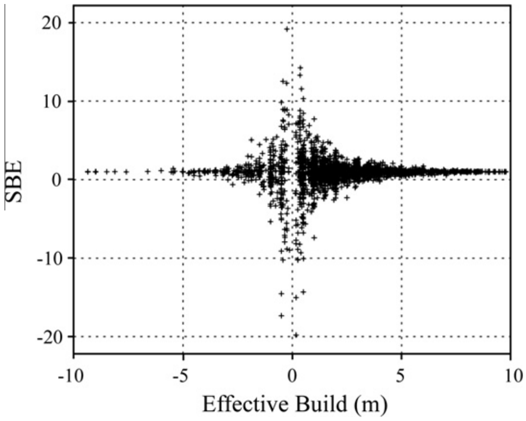


Fig. 8. SBE with length of section established by sliding.

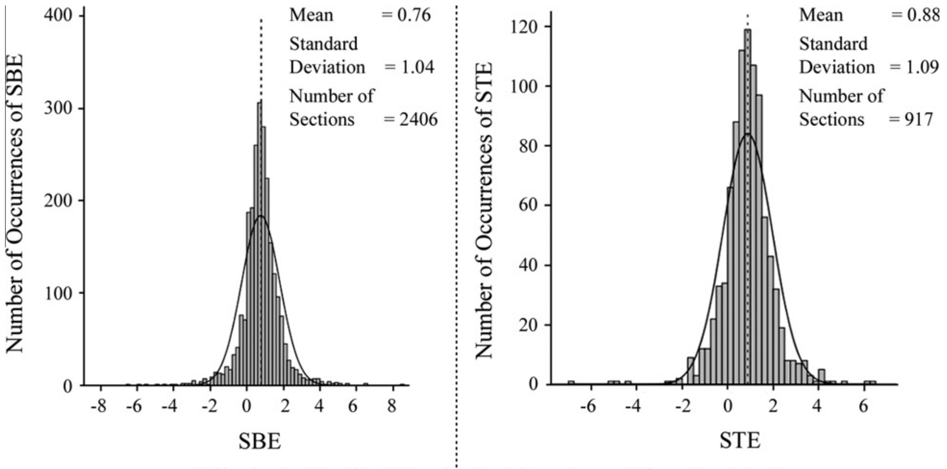
ship between SBE against effective build (length of curved section established via slide drilling) and there is a clear correspondence between effective build and improvement in returned SBE. Fig. 9 presents the distribution for SBT and STE for the dataset with the effective builds of 1 m or less removed. Whilst both distributions in Fig. 9 are still leptokurtic they are approaching a normal distribution. The distributions in Figs. 5 and 9 suggest that the occurrence of 'extreme' events, initially considered being of SBE or STE values over 10, would now appear to be for values of 4 or greater.

It is believed that the significant SBE and STE values with short slide distance are a function of two parameters. Firstly, the diameter of the pilot bore created via rotary drilling is greater than that for slide drilling (due to the inclusion of the bent-sub, Fig. 1). Unless there is significant WOB, there is no guarantee that the bit will not 'walk' within the borehole when the rotation of the drill string is terminated (changing from drilling to sliding) and the slide drilling will deviate from desired line and level. Secondly, the positional sensors incorporated within the down-hole assembly are a significant distance behind the bit (Fig. 2), thus these deviations are unlikely to be identified unless the static positional survey is undertaken at that point. If short sections of alternating drilling and sliding are used, then these deviations can very quickly accumulate and the driller has a very poor understanding of the actual borepath created (let alone the actual position of the down-hole assembly at any point between surveys) and the overall deviation from desired line and level can be considerable (as illustrated by Stockhausen and Lesso (2003a,b,c); although their study focused on the oilfield industry which takes static positional points less frequently than in HDD). It would be of interest to determine the impact of the repeated deviations introduced within a curved section has on the pull-in forces during the installation of the product pipe. It is also not fully understood if these deviations are actually smoothed out during backreaming or remain to have an impact upon the pull-in of the product pipe.

If a curve of a specified radius forms part of the desired borepath in an installation, and the driller chooses to establish this using alternating sections of drilling and sliding then the angle of the bent-sub must be greater (and hence BUR will be greater) than that if the curve was created purely by sliding; the shorter the sections of sliding the greater the angle of the bent-sub required. Fig. 8 illustrates that the use of short lengths of slide drilling results in large SBE and STE values. It is understood that the deviations created by extreme SBE values over short distances may be relatively minor (Fig. 7 and Table 5), but the repeated inclusion of such deviations would have the potential to increase the frictional forces and bending moments acting on the product pipe during pull-in. However, the authors contend that using greater lengths of sliding (necessitating lower BUR) when creating curved sections of bore will result in reduced SBE or STE values when changing from drilling to sliding (for the reasons outlined above). Hence, increasing the slide length reduces the potential for the number of deviations included within the borepath, reduces the severity of SBE/STE (Fig. 8) and provides a greater understanding of the actual bore created. However, increasing the length of sliding increases the risk for the amplification in severity of dog-legs (Fig. 7) if the down-hole assembly deviates.

Table 5
Difference in elevation from a datum with distance from commencement of slide drilling with increasing SBE from SBE equal to 1.

Distance from commencement in slide drilling (m)	Elevation above datumn (m)					
	SBE = 1	SBE = 2	SBE = 4	SBE = 6	SBE = 8	SBE = 10
2	0.00	0.00	0.01	0.01	0.02	0.02
4	0.01	0.02	0.03	0.05	0.07	0.08
6	0.02	0.04	0.08	0.11	0.15	0.19
8	0.03	0.07	0.13	0.20	0.27	0.33
10	0.05	0.10	0.21	0.31	0.42	0.52



(Effective builds of less than 1m have been removed from the dataset)

Fig. 9. Distributions of SBE and STE for the HDD installations with the effective build lengths less than 1 m removed from the dataset.

Therefore, it is suggested that the length of slide should be chosen carefully so that it is long enough to avoid the accumulation of multiple unrecorded deviations in the borepath, whilst short enough to minimise significant for deviation from line and level. Of course this situation could be avoided in its entirety if real time positional monitoring (in conjunction with static monitoring) was undertaken using sensors that can be positioned directly behind the bit.

14. Distance to bit

Length of slide is clearly an important parameter when controlling the position of the bit, but the relationship presented in Fig. 8 does not account for the position of the drill bit in relation to the drilling rig. In ideal conditions the drill string would remain in the centre of the bore and the frictional losses would be due to fluidic drag (Cheng and Polak, 2007), resulting in relatively minor losses, and hence the reduction in WOB would be small. In reality the drill string will be in contact with the bore wall (if only in certain sections of the bore path) and frictional losses will be substantially higher, than for fluidic drag alone (Royal et al., 2010), thus the WOB will be reduced. TCR bits require WOB to operate efficiently and there is the potential for loss of steering control with increasing distance from the drilling rig as the frictional losses mount.

Grouping the sliding data into ranges of measured distance from the entry point (Fig. 10) allows for the relationship between measured distance and steering response to be investigated. Fig. 10 presents the data in a box plot format, akin to that in Fig. 3 (50% data within the boxes, mean indicated within the box, 100% within the error bars), and it is apparent that the variance within the dataset is such that it is difficult to derive any specific trends. This is compounded by the limited data set after a measured distance of 1000 m (only eight installations exceed this distance and only one of these extends past 1500 m). However, examining the mean values for each range of measured distances, it is suggested that there is a decrease in steering response with distance.

15. Drill bits, bend angle and geology

Isolating the steering control behaviour due to the down-hole assembly or the geology is problematic as the geological conditions for the installations were not fully characterised. The majority of installations utilised one type of down-hole assembly and, where multiple drives were undertaken the geological conditions were approximately constant.

Data relating to changes in down-hole assemblies within individual installations are limited; TCI and MT are selected for specific conditions (TCI are used in harder rock formations than MT) and bent-subs are not usually changed unless the conditions necessitate it. Fig. 11 illustrates the 95% confidence intervals from mean for three installations that changed either the bent-sub angle or cutting bit. The impact due to changes in either the drill bit type or angle of the bent-sub would not appear to be significant. There does not appear to be a correlation between the severity of the bent-sub angle and steering response. Clearly the dataset resulting from the three installations is small and further study would be required before conclusive findings can be reported upon the impact bent-subs of given angles or validity of bit types in given conditions. Such a study may be undertaken in the laboratory or, potentially more successfully, in controlled, and accurately monitored, HDD installations.

Fig. 11 illustrates that geology has an impact upon the steering ability (specifically the mixed ground conditions and the mudstone), particularly on the ability to turn. Investigations on the impact of ground conditions on HDD have been undertaken previously, but these tend to principally focus upon the stability of the bore (for example Xia and Moore, 2006; Ariaratnam et al., 2004, and Wang and Sterling, 2007). However, the authors have been unable to identify investigations reported in the literature that investigates the steering response in different geological conditions. Fig. 12 presents the SBE for stated geological conditions and provides the confidence intervals (95% from mean). A number of the confidence intervals quoted are for small datasets and, with additional data, the current outer limits included within the confidence interval may well prove to be ‘extreme’ events, increasing the predicted distance from mean.

Motor driven bits are rarely used in superficial soil deposits, as jet-cutting bits can be successfully used to establish the bore, although it is apparent that using down-hole motors in ‘soil’, ‘fill’, sand and gravel, steering is difficult (which concurs with anecdotal evidence). Mudstones, shale and chalk also appear to be problematic when sliding and it is presumed that this is due to the comparatively weak strength of the rock type and/or the potential for laminations or interbedding within the strata. Sliding in sandstone, siltstone, and more surprisingly claystone, returns predictable results when drilling with HDD and it its presumed that this is due to the lack of laminations commonly associated with these formations. This is also true in the case of clay formations (although no additional data was provided on what clays were bored through).

The SBE behaviour with primary lithology presented in Fig. 12 could be used to suggest that the argument for increased slide lengths (raised in the length of slide section of the paper) as a method to reduce the magnitude of SBE and STE encountered dur-

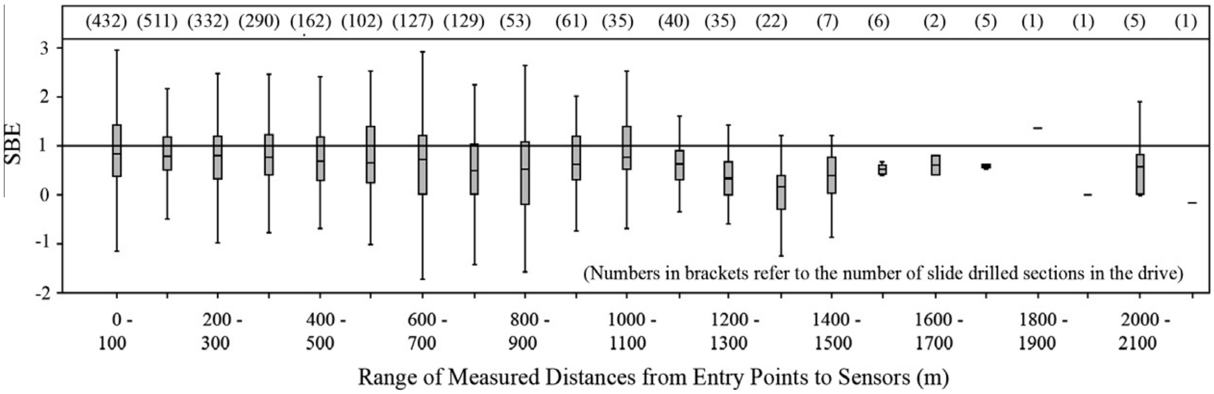


Fig. 10. SBE for intervals of measured distance.

ing drilling is inappropriate in weak, laminated or stratified ground conditions. The authors of this paper suggest that this is not the case, that increasing minimum slide lengths beyond a metre is still an important practice if 'extreme' SBE or STE are to be avoided, indeed in 'problematic' ground conditions the occurrence of extreme events is more likely to occur unless measures are taken to prevent them. It is suggested that when attempting to bore though such conditions with motor driven bits (instead of jet-cutting bits, which are more appropriate for the conditions) the potential for deviations are great and the down-hole assembly position surveying strategy must be optimised to ensure that any deviations from desired position are identified early and corrective action is taken before it becomes a significant issue. It is also suggested that a balance must be adopted, when developing the lengths of slide in the steering patterns for an installation, between the slide lengths that are long enough to prevent the accumulation of unrecorded deviations from desired bore, whilst short enough to prevent significant deviation for the desired borepath. The authors of this paper also believe that this is another compelling reason for the adoption of sensing technologies that can be positioned directly behind the motor driven bit that allows real time positioning (in conjunction with traditional static surveying).

Approximately a third of the data analysed in this study is not attributable to specific geological conditions (this was either not identified or was returned as a generic identifier such as 'rock'). This is a reflection of the level of site investigation commonly associated with HDD installations. The confidence interval associated with this condition would suggest that not understanding the geological conditions will not have a detrimental impact upon the ability to control the position of the cutting bit. The authors of this paper are uncomfortable with this notion; HDD installations are effectively driven 'blindly', and until forward sensing cutting tools are developed (such as those been developed in the Orpheus project, Manacorda et al., 2008) this will continue to be the case. Not understanding the conditions in which a HDD installation is being undertaken must have implications upon the ability to predict and control the steering of the pilot bore as well as on the overall success of the installation. This is particularly true in mixed ground conditions, or when drilling in interbedded or laminated strata (assuming that the broad findings of Boualleg et al., 2006, can be applied to HDD conditions), or in strata containing discontinuities or buried structures (especially reinforced concrete).

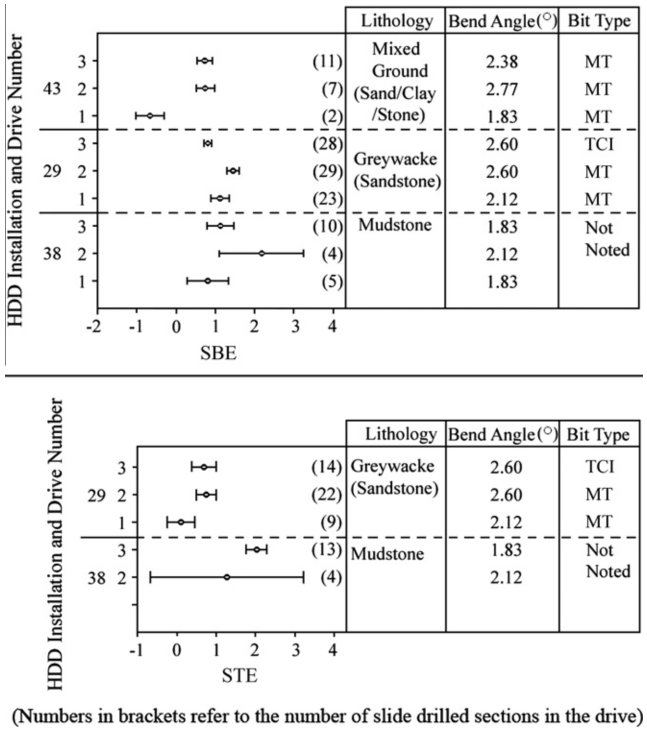


Fig. 11. Confidence intervals (95%) from mean for three HDD installations experiencing changes in bent-sub angle or bit type in various geological formations.

Site location data from five of the installations within the UK was sufficient to allow the use of geological information held by the British Geological Survey (BGS, 2008), and other sources, to identify the geological formations more precisely than stated in the drilling logs. The formations on the sites included tidal flat deposits, glacial till, Sherwood Sandstone, Mercia Mudstone, Kimmeridge Clay, London Clay and Bembridge Marl (details regarding four clay formations encountered in the five installations are presented in Table 6). SBE and STE behaviour for each of the geological formations, from the five installations, can be found in Fig. 13. There does not appear to be a correlation between the behaviour of SBE and STE in both the glacial till and tidal flats and it is presumed that this is due to the stratification of the two formations as both are likely to be anisotropic and heterogeneous in composition. However, the dataset for these formations are small and thus additional data is required before conclusive relationships between SBE and STE could be formulated. It is believed that the stratification of the marl, mudstone and clays can be used to explain why there is also disparity between the SBE and STE behaviour. The formations containing laminations or are interbedded (Mercia Mudstone, Kimmeridge Clay and Bembridge Marl) experience greater variation in STE response than in SBE. Conversely, the London Clay, which is not recorded as containing such features, returns a more uniform response between SBE and STE. The Sherwood Sandstone also appears to have similarly predictable behaviour to the London Clay, although it is interesting to note that the mean SBE for this formation is less than that for the overall mean for sandstones presented in Fig. 12. These findings would concur with those of Boualleg et al. (2006) who illustrated that vertical boreholes will deviate when drilling through laminated strata, and that drilling response was difficult to predict when driving through interbedded strata because when exposed to a differential in stiffness across the cutting face (such as at the interface in interbedded strata) the bit will deviate towards the softer ground.

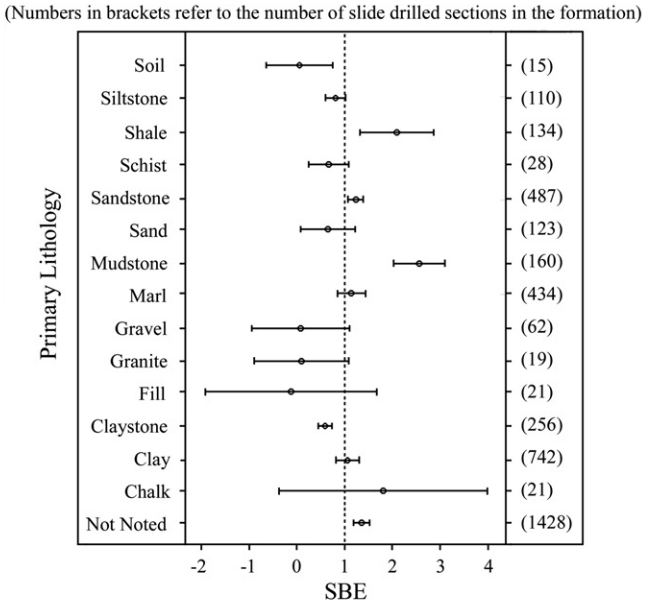


Fig. 12. Confidence intervals (95%) from mean of SBE in various ground conditions.

Table 6
Geological information for the London clay, Mercia mudstone, Kimmeridge clay and Bembridge marl.

Installation	Formation	Details	Stiffness
34	London clay	Grey/brown to grey fissured silty clay with siltstone inclusions[a]	Firm, stiff to very stiff[a]
35	Mercia mudstone	Red brown mudstone with and without gypsum veins and grey marl[b]	–
37	Kimmeridge clay	Mudstone (calcareous or kerogen-rich or silty or sandy); thin siltstone and cementstone beds; locally sands and silts[c]	Firm to stiff[c]
39	Bembridge marls	Interbedded silty clay with varying amounts of shell fragments and limestone & siltstone fragments[d]	Stiff, very stiff to hard[d]

[a] BGS borehole TQ87NE/24 BGS (2008).

[b] Le Brecht and Broom (2006).

[c] Serridge (2006).

[d] Site investigation boreholes associated with installation.

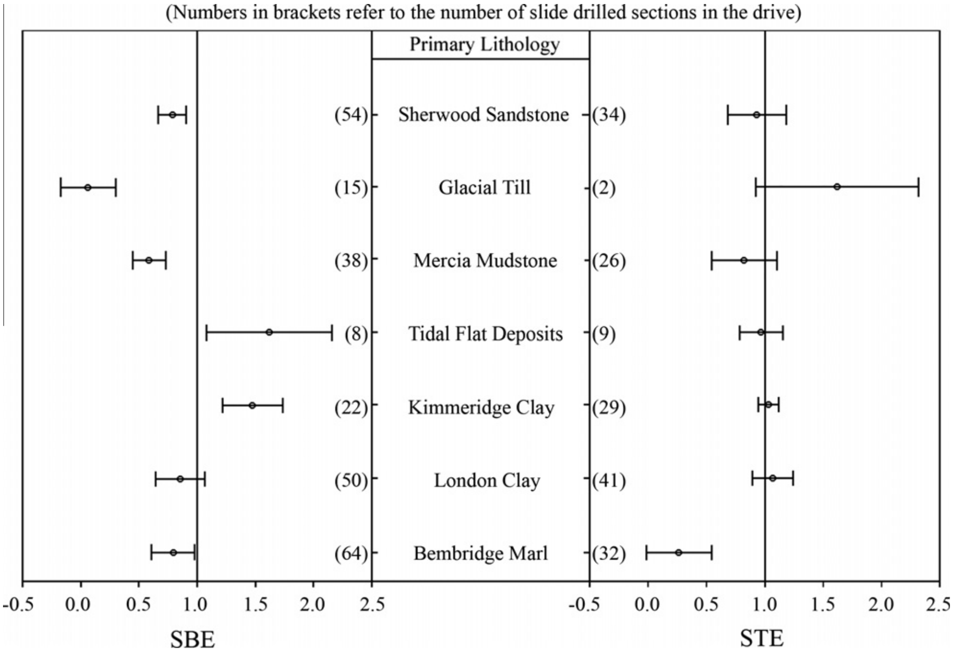


Fig. 13. Confidence intervals (95%) from mean of SBE and STE in known ground conditions.

Hareland et al. (2000) propose a relationship that states that the strength of the ground is inversely proportional to ROP, which can be used in real time, and the ability to accurately control PDC bits would appear to be inversely proportional to ROP (Ernst et al., 2007). Plotting the inverted ROP against SBE (Fig. 14) produces behaviour similar to SBE with measured distance in that the dataset is small and the distributions of the box plots make it difficult to derive anything definite from the data. However, the behaviour of the mean values of SBE with inverted ROP would suggest that there is a slight increase in drilling response with increasing stiffness. Very weak ground conditions, where high ROP would be expected, were not available in the study as jet-cutting bits would tend to be used in these conditions, and locations identified as being 'difficult' in the drilling logs were rejected in this study as the term difficult is subjective and can apply to several situations. The inclusion of this data could give further insight into the relationship between ROP (or inverted ROP) and control of steering, although the 'difficult' conditions would require careful quantification before being included in a future study.

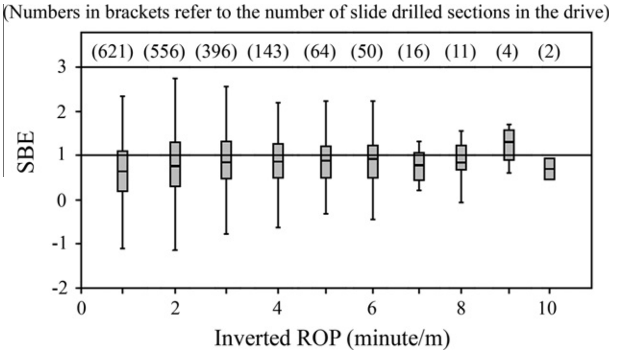


Fig. 14. SBE for inverted ROP.

16. Conclusions

Datasets from 54 HDD installations have been studied to try to develop an understanding of the parameters that impact upon the ability to control the steering response of HDD. The data comprised the site based data, the operators' drilling records and the survey data. Organising the HDD installation data into sections of rotary drilling and slide drilling (drilling and sliding), and determining the ratio of actual steering performance against predicted performance, has allowed identification of several factors that impact upon HDD installations. The outcomes of the study illustrate that deviations from desired line and level will occur in both drilling and sliding and it is believed that the deviations are due to a number of factors including the selection of drilling equipment, the calculation of the drilling response prior to drilling, the drilling practices utilised during the installation and the geology in which the bore is being established.

HDD operators utilise BUR data supplied by the manufacturers for the various down-hole assemblies when predicting the drilling performance before undertaking the installation and it is clear that there is the possibility for these recommendations not to reflect reality (although the majority of those investigated in this study did so) and care must be taken when utilising this data. Drilling practice accounts for a great deal of the extreme instances of loss of steering control, particularly when drilling and sliding alternating sections to create curved sections of bore, rather than sliding the entire curve. When adopting this strategy care must be taken when selecting the length of slide as this can result in high SBE and STE values. A simple solution to this would be to increase the length of slide drilled sections within the curved section of bore, or utilise drilling equipment that allows for the sensors to be located directly behind the bit.

Increasing the length of the drill string results in increased frictional losses due to increased contacts between the drill string and the bore wall, thus reducing the effective WOB applied to the TCR drill bit. TCR bits require WOB to effectively drill the bore and it is suggested that as the distance between the drilling rig and the down-hole assembly increases there is a reduction in ability to control the position of the drill bit due to a reduction in WOB acting on the TCR.

The geological formation within which the bore is being drilled clearly has an impact on the drillers' ability to control the position of the drill bit. The lithology, and particularly the stratigraphy, of the formation must be considered as the drill bit is likely to deviate in interbedded or laminated formations. The interface between strata must also be understood when drilling across boundaries between formations of different strengths as there is the potential for dill bit deviation at these instances. Formation stiffness (approximated by inverting the ROP) would also appear to have an impact on the ability to control the position of the drill bit, with the bit more likely to deviate in weaker formations. It is believed that monies invested in site investigation before the commencement in drilling would forewarn the HDD operators of any potential issues (discontinuities, interbedded or laminated strata, weak or 'difficult' ground, etc.) and allow for the development of an informed drilling strategy. Once again, the adoption of drilling equipment that allows for the incorporation of sensors directly behind the bit would help prevent deviation from the desired borepath.

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