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RETRACTED: ANOVA Analysis Applied on Factors Which Are Assumed To Be Related To Horizontal Directional Drilling Productivity

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Abstract

Horizontal Directional Drilling is considered as one of the most common trenchless technologies for the installation of pipes, conduits, and cables underground. This is can be refered to the high applicability of method in different soil conditions, high suitability for different zones (rural and congested urban areas). The installation of different services including cables and pipelines of different materials is another advantage of horizontal directional drilling. Also, the ease of mobilization, construction, and demobilization of horizontal directional drilling auxiliary and supporting machines compared with other trenchless technologies and methods. This research aims to apply a statistical methodology (analysis of variance, ANOVA model) for studying the factors expected to have an effect on the productivity of horizontal directional drilling operation, considering drilling time but not minor activities such as welding and coating of pipes or dismantling, or physical effects during horizontal directional drilling mechanism such as start or/and end of work, annulus removal and drilling fluid solidifying or liquefying, drilling fluid fracout, or the existence of rock formation in proposed uniform soil formation. Also activities such as building of job site, fencing of site, and detecting of existing services

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are not covered by the study. The research also divided horizontal directional drilling productivity factors into four main groups or conditions including soil, project, contractor, and machine conditions.

Introduction

Horizontal directional drilling was originated from oil fields industry in the 1970s and was developed by emerging technologies to be used in utilities and water well industries (Najafi, 2005). Horizontal directional drilling these days is applied widely for the installation of different material (HDPE, PVC, ductile iron, and steel pipe) serving as conveyants for water and wastewater pipelines, gas applications, power lines, and telecommunications. The method is applied in different soil commonly classified as soft, medium, and moderate hard, and project conditions (depth, length, and material) and sites in crossing most of the barriers (valleys, lakes, rivers, and highways) or special areas such as airport runways and buildings.

The number of horizontal directional drilling rigs manufactured and sold can show the quick growth of infrastructure installation using horizontal directional drilling technology; from 12 horizontal directional drilling operational units were manufactured in 1984, then a 2,000 horizontal directional drilling operational units in 1995 (Allouche et al., 2000), where as, 17,800 horizontal directional drilling unites were manufactured and sold during the period between 1992 and 2001 in North America (Baik et al., 2003), and finally the number of horizontal directional drilling rigs manufactured worldwide recently comes to 32,135 units in 2011, with 80% of these rigs manufactured in USA (Carpenter, 2011).

According to the North American Society for Trenchless Technology (NASTT) horizontal directional drilling Good Practice Guides (2008), horizontal directional drilling is the most widely used trenchless technology (TT) construction method, for the following reasons:

- Ability to accommodate large diameters.
- Ability to install pipes of different materials, including HDPE, PVC, steel and ductile iron pipe.
- Compatible with a variety of soil conditions, including not cemented sand and solid rock.
- Requires relatively little auxiliary equipment.
- Satisfies environmental guidelines (especially in wet lands).
- Minimal traffic disruption and associated social costs, considering the long installation drives (about 2,000 ft).
- Applicable to gravity, water and sewer pipelines.

Background

Adel and Zayed (2009) had utilized fuzzy approach (Sowell, 2003) in describing the factors expected to affect horizontal directional drilling operations using a fuzzy logic model. Qualitative inputs, such as soil type, pipe material, and quantitative inputs such as product pipe outside diameter, depth, and length were considered to affect productivity of trenchless operation. Initial arbitrary weights were assigned to inputs that adjusted by the network it self. The assigned value in the 1st iteration will be the new value in 2nd

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iteration plus the difference or error in estimation between target and estimated value. Conditions such as horizontal directional drilling rig specifics or categories, soil types, unseen obstacles, pipe diameter, pipe length, pipe depth, and pipe type were considered significant to productivity of operation.

Ali et al. (2007) divided the subjective factors that affect the productivity of trenchless technology of underground infrastructure into three categories: management, environmental, and physical factors. Management factors include managerial skills, safety regulations, mechanical conditions of equipment, and operator skills. Environmental factors include soil and site conditions, unseen soil obstacles, as well as groundwater level. Physical factors include pipe type, length, usage, and depth. The analytical hierarchy process (AHP) and fuzzy logic were utilized to develop the productivity index (PI) for efficiency of operation by considering the subjective effect of proposed factors on operation. The relative weight of factors *(SFE)* included in this study was calculated in Equation 1.

$$SFE = \sum_{i=1}^{i=n} W_i * E_i(x_i) \qquad (1)$$

Where, W_i is the decomposed weight of factor in operation. E_i (x_i) is the effect value of the factor in the project, and n is number of factors. The developed productivity index $PI = 1 - SFE$ represents time efficiency in productivity of operation.

According to Mahmoud (2009), horizontal directional drilling productivity factors were classified into managerial, mechanical as well as environmental and pipe physical conditions. Analytical hierarchy process (AHP) was utilized to rank factors according to their importance. Then, a Neurofuzzy Model was employed to develop horizontal

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directional drilling productivity values for clay, rock, and sand. The decision of neuron is based upon the sum of weights associated to the factors considered in operation. Management conditions include managerial skills, safety regulations, mechanical conditions, and operator skills, while environmental conditions include unseen soil obstacles, water table level, soil conditions, and site conditions, and physical conditions include pipe type, pipe usage, pipe length, and pipe depth.

In this study, drilling time was considered as the major activity duration in horizontal directional drilling operation, while durations of other activities such as pipe layout and connection, changing reamer, and setting of drilling angles were considered minor durations for auxiliary activities as they usually managed during site preparation in small projects. While in large projects; the duration of auxiliary activities becomes major compared to the drilling time that considered minor activity.

It was concluded that pipe diameter, soil type, and drilling rig capabilities were considered the most important factors that can affect productivity of horizontal directional drilling operation. While, factors such as site, weather, and fluid properties were considered minor factors in operation. Simply, because seasonal changes (i.e., weather) does not have direct effect on horizontal directional drilling productivity, groundwater table is said to have no effect on horizontal directional drilling productivity as the nature of the mechanical process. Also, slurry pumping rate and mixing ratio are functions of soil type. Although pipe material (HDPE, PVC, and steel pipe) affect productivity of pipe connection, during pull back, pipe material has no direct effects on horizontal directional drilling operation as most of pipe materials are floating in borehole.

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Therefore, horizontal directional drilling productivity can be modeled using horizontal directional drilling rig capabilities, soil type, pipeline diameter, length, and depth.

Zayed et al. (2007) introduced major and minor factors of horizontal directional drilling productivity (i.e., rig capabilities, pipe material and diameter, soil type, contractor experience and weather conditions) to develop a deterministic model for duration of horizontal directional drilling operation, considering time required for pipe installation. The installation time was partitioned into two parts. First part was considered major, such as time for drilling, prereaming, and pullback. Second part was considered minor, such as time for adjusting drilling angle at entrance, time to connect drilling pipe segments, time to attach reamer with shackle for prereaming, mixing and pumping mud, and time to layout and connecting pipe or cable segments. It was concluded that total cycle time (major, such as drilling and prereaming operations, and minor, such as changing reamer or mixing drilling mud) usually have specific values for similar project conditions (soil, pipeline, and machine). However, in short drive (less than 600 ft) projects drilling activities are considered major or productivity deterrents, while in long drive (about 2,000 ft) projects changing parts become major time or productivity deterrent.

Two case studies were selected for horizontal directional drilling productivity in sandy soil; the first was for installation of 1.6-in. diameter polyethylene pipe for a distance of 880-ft, and the second was for installation of 2.36-in. diameter HDPE pipe. The cycle time was studied through the length of the borehole and was regressed for both to give a productivity of 123.4 ft/hr and 88.4 ft/hr, respectively. The results indicated that horizontal directional drilling productivity is a function of soil type, rig size, and pipe diameter. Horizontal directional drilling productivity can be lowered in sandy soil when it contains gravel or cobbles. Another conclusion was that horizontal directional drilling productivity is inversely proportional to diameter of borehole. A deterministic model for major time was developed to describe the cycle time as presented in Equation 2.

$$T_{major} = T_j = T_p + T_r + T_{pb} \quad (2)$$

where T_{major} or T_j is the total cycle time for the project; T_p is the pilot drilling time, T_r is the prereaming time, and T_{pb} is the pull back time.

The analysis presented in this paper forms a new methodology for studying productivity of horizontal directional drilling (ANOVA) analysis that will introduce for the productivity model by expecting a successful factors or conditions in operation. But, the large number of factors covered by the study and the insufficient data collected on part of them, makes it too difficult to design and analyze results by ANOVA.

Horizontal Directional Drilling Productivity Conditions and Factors

According to horizontal directional drilling contractors, engineers, and consultants, the author of this research presents the horizontal directional drilling conditions into four main groups including soil (soil type and ground water depth), project (diameter, length, depth, and pipe material), contractor (experience of contractor in years, and experience of horizontal directional drilling operator in years), and horizontal directional drilling machine conditions (machine thrust and torque force, drilling rod length, in addition to machine variables that include slurry mixing ratio and pumping rate). Data on soil type were received as sandy conditions (loose sand and cemented sand), clayey conditions (soft, medium, and hard), and rocky conditions (soft,

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medium, and hard). Depth was denoted for level of borehole at midpoint, but what is required in analysis to include entry and exit angle of drilling path and also the curved path of drilling, which were not considered, because it was impossible to collect detailed data on these items. Figure 1 shows HDD conditions and subconditions.

Depending on that data was collected by a questionnaire filled by contractors, engineers, superintendents, and consultants for a project they implemented, designed, or attended. Respondents replied describing the site, machine, project conditions, soil, and contractor conditions. It was noticed that there is a relation between machine capacity, soil type and strength, and project conditions (diameter, length, and depth). Detailed data from the questionnaire will be presented in a future research for productivity modeling in sandy, clayey, and rocky conditions. Capacity of machine (thrust and torque) is the main property considered in classifying data not the type or manufacturer. And this is nearly true as a specific size of machine will be used for a specific size of job and soil conditions. So, for rocky conditions, long drive length (about 2,000 ft), large pipeline diameter, or deep pipeline with high entry or/and exit angle, a high machine capacity or size (usually medi- to maxi-HDD) is employed.

The Analysis of Variance ANOVA Model in Testing Significance of Horizontal Directional Drilling Subconditions

The analysis of variance (ANOVA) model was utilized in testing the significance of factors that can affect the productivity of horizontal directional drilling operation. The analysis is not complete as other factors are not studied such as degree of hardness (or softness) of rock, drilling fluid design, and capacity on transporting annulus outside borehole. In this method a t-test is utilized to compare a pair of population means.

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However, if there are more than two population means, it is tedious to conduct t-test; also the experimentwise error is not easily controlled. Kinnear and Gray (2006) explained that the comparison between two population means, μ_1 and μ_2, is expected by the null hypothesis H_0: $\mu_1 = \mu_2$ versus the alternate hypothesis H_1: $\mu_1 \neq \mu_2$. Thus, if it is found that the t-test indicates significance, H_0 can be rejected, and then alternate hypothesis H_1: $\mu_1 \neq \mu_2$ is used to conclude that significant difference exists between the two population means. However, when there are more than two population means that need to be compared, testing the equality of means under the null hypothesis H_0: $\mu_1 = \mu_2 = \mu_3 = ... = \mu_n$. becomes cumbersome for t-test (Montgomery, 2007) and (Walpole et al., 2007).

Alternatively, One-Way ANOVA model is utilized efficiently to test the significance of difference in means of continuous random outcomes or dependent variables (e.g. horizontal directional drilling productivity) that it is affected by predictors or independent variables (e.g., soil type, pipe material, operator and contractor experience, machine size, and other subconditions). In this case, ANOVA model is applicable as a univariate model to explain how treatments affect a single outcome; i.e., horizontal directional drilling productivity. The general form of the ANOVA model is $Y_{ij} = \mu + \tau_i + \varepsilon_{ij}$, where μ is the grand mean, τ_i is the treatment effect, and ε_{ij} is the error (Bancroft and Han, 1981) and (Bird, 2004). This ANOVA model can bring consistency to outcomes of system or operation. When the treatment effect is significant, multiple comparisons can be used to determine which pair of means differ (Montgomery, 2007).

As mentioned earlier in this section, the ANOVA model is used to test the equality of several means. The test statistics is

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$$F_0 = \frac{SS_{Treatments}/(a-1)}{SS_E/(N-a)} = \frac{MS_{Treatments}}{MS_E},$$

which follows an *F-distribution* with $a-1$ and $N-a$ degrees of freedom where a is the number of treatments and N is number of total observations. The value of F_0 is compared with the *F-Value* in *F-distribution table* to determine if the test is significant.

In general, the Mean Squares Error (MS_E) is an unbiased estimator of σ^2, and under the null hypothesis, $MS_{Treatments}$ is unbiased estimator of σ^2. This implies that it is possible to reject H_0 and conclude that there is a difference in treatment means if $F_0 > F_{\alpha,a-1,N-a}$. Also, the same decision can be made using the *P-Value* associated to *F*- and F_0 - *Value* (Montgomery, 2007).

For a number of treatments, the term $y_{i.}$ represents the sum of observations in *ith* treatment for i = 1, 2,…, a_i; $\bar{y}_{i.}$ is the average of the *ith* treatment; $y_{..}$ is the total sum of observations; and $\bar{y}_{..}$ is the overall average for all observations. The sum of squares between treatments is defined as $SS_{Treatments} = \sum_{i=1}^{a} n_i (\bar{y}_{i.} - \bar{y}_{..})^2$; where, a is the number of treatments, and N is the total number of observations; in case of $n_1 = n_2 = ... = n_a$, then N= $n.a$.

The total sum of squares is equal to $SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij} - \bar{y}_{..})^2$ for all observations (y_{ij}) in the experiment. Now, it is possible to calculate SS_E, the error sum of squares as $SS_E = SS_T - SS_{Treatments}$.

The mean squares *(MS)* is computed as follows, the first is the treatments *MS*; $MS_{Treatments} = \frac{SS_{Treatments}}{a-1}$ with $a-1$ degrees of freedom (df), and the second is the error *MS*; $MS_E = \frac{SS_E}{N-a}$ with $N-a$ degrees of freedom. Then F_0 is calculated and compared with *F- Value* in *F-distribution* table with $a-1$ and $N-1$, the degrees of freedom as expected earlier.

Testing Significance of Horizontal Directional Drilling Subconditions in Horizontal Directional Drilling Model

Soil Conditions

Soil conditions are considered the most important factor especially in horizontal projects such as horizontal directional drilling as it changes in properties in the same project site. Soil type and groundwater level are included under soil conditions. Soil type determines size of horizontal directional drilling rig, type of cutting head or reamer, and type of material used in drilling fluid, mixing ratio, and pumping rate. Groundwater level is not expected to have significant effects on horizontal directional drilling productivity, based on conclusions in literature review, consulting horizontal directional drilling experts, and ANOVA results.

Soil Type Subcondition

A HDD pilot project is selected to collect data about HDD productivity through soil profile in one location. Table 1 presents details of pilot project that has other proposed conditions such as machine and contractor conditions, and borehole diameter and reamer.

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Table 2 presents horizontal directional drilling productivity data for preream in soil conditions encountered in the HDD pilot project. Maximum productivity was 180 ft/hr within soil No. 4 (silty clay). Minimum productivity was 25 ft/hr in soil No. 2 (sandy shale). Most of observations in middle of bore-path are very low, primarily due to soil type (shaly clay). To continue analysis of soil type impact on horizontal directional drilling productivity, a 2^2 ANOVA factorial design was conducted to test the effects of depth, length, and depth-length interaction during preream in pilot project. Therefore, the effects of soil on horizontal directional drilling productivity are considered to be major according to ANOVA analysis.

The results of variance analysis for horizontal directional drilling productivity samples in soil conditions are presented in Table 3.

Using ANOVA, it was obtained that F_0 value, i.e. $F_0 = \frac{MS_{Treatments}}{MS_E} = \frac{4{,}671}{961} = 4.86$. This F_0 was compared with $F_{\alpha,a-1,N-a} = F_{0.05,3,27} = 2.96$. Since $F_0 > F_{0.05,3,27}$, null hypothesis H_0 can be rejected and it can be concluded that there is a difference between population means (at least one pair of means is different). Therefore, it can be concluded to use different models for horizontal directional drilling productivity through bore-path or soil profile for the change in soil properties, as the means of productivity are different through the different soil profile.

When ANOVA test of treatments is significant within multi variables, it cannot be determined which pairs of means are different. Therefore, in this case, multiple comparisons should be considered. The comparison of means treatment effect has the null hypothesis $H_0: \mu_i = \mu_j$ for all $i \neq j$ and the alternate hypothesis $H_1: \mu_i \neq \mu_j$. For unequal sample sizes, Tukey-Kramer procedure (Montgomery, 2007) declares the two means are significantly different if the absolute value of their difference exceeds the value $T_\alpha = \frac{q_\alpha(a,f)}{\sqrt{2}}\sqrt{MS_E(\frac{1}{n_i}+\frac{1}{n_j})}$, where T_α is the critical value for significance level α, $q_\alpha(a,f)$ is the upper percentage point of the studentized range statistic with a treatments and f degrees of freedom, MS_E is the error mean squares, and n_i and n_j are the sample sizes. In this case the critical value is calculated as $T_{0.05} = \frac{q_{0.05(4,27)}}{\sqrt{2}}\sqrt{961*(\frac{1}{n_i}+\frac{1}{n_j})}$, and the upper percentage of studentized range statistic is found as $q_{0.05(4,27)} = 3.87$.

Table 4 presents the comparison of critical value and difference in means. It can be noticed that horizontal directional drilling productivity means of soil No. 2 and soil No. 4 conditions are significantly different as well as the horizontal directional drilling productivity means of soil No. 3 and soil No. 4 conditions.

While for other pairs, the difference in means is not significant. Therefore, ANOVA can determine if the difference in means is significant or not.

As means of horizontal directional drilling productivity values are not significantly different in soil conditions No. 1, 2, and 3 as shown in Table 5, it can be concluded that horizontal directional drilling productivity through these conditions should be modeled separately as we have relevant productivity data, but different depths and lengths through borehole.

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Depth-Length Effect Analysis in Pilot Project

To confirm the ANOVA results presented in Table 2 and Tukey-Kramer procedure comparison conducted in Table 3, the 2^2 *Factorial Design* (Montgomery, 2007) was conducted to test the effects of depth, length, and depth-length interactions on horizontal directional drilling productivity. For example, if the test is significant for any of these factors, it will be included in the horizontal directional drilling productivity model for the whole bore-path profile as the soil effect is significant. Table 5 presents the 2^2 *Factorial Design* organized table.

2^2 Factorial Design implies there is a 2-factor effect (A = length, and B = depth) distributed into two levels (low, and high). Calculations are presented as subtotal and total of horizontal directional drilling productivity observations in Table 6. Finally, results of ANOVA analysis are presented in Table 6. Results of ANOVA 2^2 *Factorial Design* are able to tell to include or not to include any of these subconditions or terms in horizontal directional drilling productivity model among the whole bore-path of soil profile in pilot project.

As said earlier, Table 7 presents the significance of depth, length, and depth-length interaction on horizontal directional drilling productivity in pilot project. The results obtained by 2^2 *Factorial Design* in Table 6 confirmed results obtained in soil subconditions discussed earlier (soil type condition) for significant effect of soil, depth, and length of borehole that were presented in Table 3, 4, and 5.

From *F-Distribution* table, for factor A = Length, and factor B = Depth, it was found that $F_{\alpha,\ (a-1),\ ab\ (n-1)} = F_{\alpha,\ (b-1),\ ab\ (n-1)} = F_{0.05,\ 1,\ 24} = 4.26$. Also, for the factor AB = Length - Depth Interaction, it was found that $F_{\alpha,\ (a-1)\ (b-1),\ ab\ (n-1)} = F_{0.05,\ 1,\ 24} = 4.26$.

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As for depth, length, and depth-length interaction $F_0 < F_{0.05,\ 1,\ 24}$, then the test fails to reject H_0, and concludes that the horizontal directional drilling productivity means through borehole (depth, length, and interaction in path profile) are not significantly different, i.e., horizontal directional drilling productivity means through the whole bore-path are affected by the change of depth and length. This result supports the results were obtained in previous section (soil type condition).

Groundwater Level Subcondition

Table 8 presents horizontal directional drilling productivity observations in rocky conditions through projects implemented within medium diameter and short drive length (less than 600 ft). The first projects had been implemented under 20 ft of groundwater above borehole, while the level of groundwater in the second projects is 0 ft.

Table 9 presents the ANOVA for horizontal directional drilling productivity observations that were distributed between projects implemented under 20 ft and 0 ft of groundwater.

From *F*- Distribution table, it is found that $F_{0.05,\ 1,\ 6} = 5.99$, and since $F_0 < F_{0.05,\ 1,\ 6}$ then the test fails to reject H_0 and concludes that the difference in horizontal directional drilling productivity means is not significant or means are the same. Also, similar decision can be made considering *P*-Value that is greater than $\alpha = 0.05$.

Project Conditions

Prereaming Diameter Subcondition

Borehole diameter has a major role in horizontal directional drilling through soil conditions. It was observed that in soft soil conditions (not cemented sand, soft clay); the

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increment in preream diameter is too large compared to that in hard soil conditions such as rock. Table 10 presents horizontal directional drilling productivity through different diameters classes in clayey conditions within large drive length.

Applying the ANOVA analysis to study the variation in means due to prereaming diameter effect, Table 11 presents results of the analysis.

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,2} = 18.51$, and as $F_0 > F_{0.05,\,1,2}$ then H_0 can be rejected and concluded that the difference in horizontal directional drilling productivity means is significant or horizontal directional drilling productivity means are different. Also, similar decision can be made considering *P*-Value which is less than 0.01 and less than $\alpha = 0.05$.

The last test on the effect of borehole diameter on horizontal directional drilling productivity was applied on rocky conditions. Table 12 shows horizontal directional drilling productivity observations in rocky conditions.

Table 13 presents the ANOVA for horizontal directional drilling productivity vs. prereaming diameter changes in rocky conditions.

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,2} = 18.51$, and as $F_0 >>> F_{0.05,\,1,2}$ then H_0 can be rejected and concluded that the difference in horizontal directional drilling productivity means is significant and that horizontal directional drilling productivity means are different. Similar decision can be made considering *P*-Value which is less than 0.01 and less than $\alpha = 0.05$ in this test.

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Pipeline Depth Subcondition

Depth of pipeline is expected to have a significant impact on horizontal directional drilling productivity. Designers may be able to select soft soil for bore-path alignment. But for some reasons such as existence of underground utilities, building foundations or basement barriers at that depth, designers may have to change the bore-path profile avoid these obstructions. This issue may force designers to select a different bore plan which encounters hard soils. Problematic entry/exit angles to/from borehole, machine setback requirements, and limited available working areas are examples of few problems related to pipeline depth. Table 14 presents horizontal directional drilling productivity observations for depth of borehole in clayey conditions in large diameter category. The ANOVA results are presented in Table 15.

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,3} = 10.13$, and as $F_0 >>> F_{0.05,\,1,\,3}$ then H_0 can be rejected and it can be concluded that the difference in horizontal directional drilling productivity means is significant; i.e., horizontal directional drilling productivity means are different. Similar decision can be made considering *P-Value* which is less than 0.01 and less than $\alpha = 0.05$.

Pipe Material Subcondition

Steel, HDPE, and PVC pipe are the most common pipe materials installed in horizontal directional drilling operation. Therefore, it is important to test the impact of pipe material on horizontal directional drilling productivity during pull-back of product pipe. Table 16 presents a comparison of horizontal directional drilling productivity observations for installation of steel and HDPE pipes in clayey conditions.

From *F*- Distribution table, it was found that $F_{0.05, 1, 4} = 7.71$, and as $F_0 < F_{0.05, 1, 4}$, the test fails to reject H_0 and concludes that the difference in horizontal directional drilling productivity means is not significant; i.e., horizontal directional drilling productivity means are the same. Similar decision can be made considering *P*-Value which is greater than $\alpha = 0.05$ and also greater than 0.25. The ANOVA is presented in Table 17. This test is related to the resultant of forces during pullback including thrust force, friction force between pipe and soil, product pipe and fluid unit weight, and buoyancy force. Therefore, more life data need to be collected for pipe material during pullback to do further analysis extensively in this area by comparing pullback productivity considering, pipe outside diameter, pipe material, borehole diameter, machine type and exerted force, type of soil conditions and annulus properties.

Contractor' Conditions

Contractor' conditions are important in terms of qualifications, abilities, and capabilities that usually come from years of experience. This main group includes contractor' experience and operator' experience in years.

Contractor Experience Subcondition

Level of knowledge and experience determine classes of jobs that contractors can bid and implement. Usually practices, techniques and means, as well as equipment and materials utilized are similar for most contractors. Therefore, the current research expects that contractor and operator experience will not have significant effect on horizontal directional drilling productivity. Part of the reason for this has to do with the volume of investment in horizontal directional drilling equipment and salaries paid for labor.

Table 18 presents horizontal directional drilling productivity observations vs. contractor experience in rocky conditions. From *F*- Distribution table, it was found that $F_{0.05,\,1,\,4}$ = 7.71, and as $F_0 < F_{0.05,\,1,\,4}$, so the test fails to reject H_0 and concludes that the difference in horizontal directional drilling productivity means is not significant; i.e., horizontal directional drilling productivity means are the same. Similar decision can be made considering *P*-Value which is greater than $\alpha = 0.05$ as the ANOVA shows in Table 19.

Horizontal Directional Drilling Operator' Experience Subcondition

It can be expected that horizontal directional drilling operator experience does not have effect on horizontal directional drilling productivity since most maxi and midi horizontal directional drilling operators receive an intensive training program by manufacturers or contractors. Therefore, horizontal directional drilling operators for these rigs will have similar level of knowledge and experience in operating horizontal directional drilling machine, safety instructions, and in trouble shooting. this issue will eliminate most of differences of experience effects on horizontal directional drilling productivity.

Table 20 presents horizontal directional drilling productivity observations vs. horizontal directional drilling operator experience in rocky conditions. The ANOVA is presented in Table 21. From *F*- Distribution table, it was found that $F_{0.05,\,1,\,6}$ = 5.99, and as $F_0 < F_{0.05,\,1,\,6}$, so the test fails to reject H_0 and conclude that the difference in horizontal directional drilling productivity means is not significant; i.e., horizontal directional drilling productivity means are similar. Similar decision can be made considering *P*-Value which is greater than 0.25.

Horizontal Directional Drilling Machine Conditions and Variables

Machine conditions (mainly abilities) play a big role in horizontal directional drilling as a specific horizontal directional drilling machine size (thrust and torque force) and drilling rod length must be selected to dig in specific soil and project conditions (diameter and depth). While machine variables in this group also include Bentonite and polymer mixing ratio, and drilling fluid pumping rate are the proposed subconditions in this group supposed to be highly related to soil conditions and soil specifics.

Thrust Force Subcondition

Thrust force (kip) is categorized according to machine size depending on soil condition encountered and project conditions. Table 22 presents horizontal directional drilling productivity observations vs. thrust force (kip) variation in rocky conditions within medium diameter and short drive length category (less than 600 ft), and results are shown in table 23.

From *F*- Distribution table, it was found that $F_{0.05,\,1,\,4} = 7.71$ and as $F_0 > F_{0.05,\,1,\,4}$ then it is able to reject H_0 and conclude that the difference in horizontal directional drilling productivity means is significant; i.e., horizontal directional drilling productivity means are different. Similar decision can be made considering *P*-Value which is less than 0.025 as it is presented in Table 23.

Torque Force Subcondition

It can be expected that torque force (ft-kip) is related to thrust force, and also related to horizontal directional drilling machine size and specific model. Therefore, it is assumed that horizontal directional drilling machine characteristics and performance are

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related to change of torque force. Table 24 validates this assumption, which contains pairs of thrust force and torque force.

Slurry Mixing Ratio Subcondition

Slurry or drilling fluid is composed mainly of Bentonite and water. It is used during drilling to help in facilitating cutting, reducing friction, cuttings' removal, stabilizing borehole sides, cooling drilling head, and lubricating installation of product pipe during pull back. Slurry mixing ratio (lb/100 gal) is a function of soil type, and it is not related to the horizontal directional drilling productivity because in hard rock the thrust force is high while the mixing ratio of the fluid is constant through the whole operation. Table 25 presents horizontal directional drilling productivity observations vs. slurry mixing ratio in rocky conditions.

From F- Distribution table, it was found that $F_{0.05,\ 1,\ 5} = 6.61$ and as $F_0 < F_{0.05,\ 1,5}$ and the test fails to reject H_0 and concludes that the difference in horizontal directional drilling productivity means is not significant; i.e., horizontal directional drilling productivity means do not differ on different slurry mixing ratio. Similar decision can be made considering P-Value that is greater than 0.05 as shown in Table 26.

Slurry Pumping Rate Subcondition

The volume of drilling fluid pumped (gpm) through cutting head or reamer nozzles is function of soil type, and volume of cuttings. Drilling fluid pumping rate can be assumed to be constant for a specific borehole size, and rarely is changed.

For example, in clayey conditions pumping rate during pilot hole drilling is around 400 gpm, while during preream operation, it is around 120 (gpm). During

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pullback, pumping rate is around 80 gpm. Table 27 presents horizontal directional drilling productivity observations vs. slurry pumping rate in clayey conditions within large diameter and large drive length category.

Table 28 presents ANOVA analysis for slurry pumping rate effect, it was calculated that $F_0 = 5.40 < F_{0.05,\,1,\,5} = 18.51$, and the test fails to reject H_0 and concludes that the difference in horizontal directional drilling productivity means is not significant. For example, horizontal directional drilling productivity means do not differ on different slurry pumping rate. Also, similar decision can be made considering *P*-Value that is greater than 0.10.

Drilling Rode Length Subcondition

Horizontal directional drilling machine uses different length drilling rods depending on rig and job size and pipe material and diameter. It takes horizontal directional drilling crew 3 minutes to change a rod of30 ft in ream/preream and pullback. However, it takes 6 minutes to change same rod in pilot hole. Therefore, if 10-ft drilling rod is used, it will add about 8-12 minutes to cycle time and drilling rod length can affect productivity of horizontal directional drilling operation. Table 29 presents horizontal directional drilling productivity observations vs. drilling rod length and Table 30 presents the ANOVA analysis with the required test in term of *F-Distribution* and *P-Value*.

As presented in Table 30 that $F_0 = 433.79 > F_{0.05,\,1,\,3} = 10.13$, and H_0 can be rejected and it can be concluded that the difference in horizontal directional drilling productivity means is significant; i.e., horizontal directional drilling productivity means differ by different drilling rod length. Similar decision can be made considering *P*-Value which is less than 0.01.

Conclusions and Recommendations

In this section, significant and non significant subconditions in horizontal directional drilling operations are listed in Table 31 depending on ANOVA model test that was applied for horizontal directional drilling productivity subconditions. Only significant subconditions will be used to model horizontal directional drilling productivity in clayey and in rocky conditions. Other conditions or effects that were not detected or studied in current research such as hardness (or softness) of rock, drilling fluid design, drilling fluid fracout, and transport capacity of annulus may be studied separately in a future research.

It is clear from Table 31 that soil type will be used as a category to distinguish between horizontal directional drilling productivity models (i.e. separate model for horizontal directional drilling productivity will be used in each soil type). Also it can be noticed that subconditions such as prereaming diameter, pipeline length, depth, thrust force, torque force, and drilling rod length are significant to be used in horizontal directional drilling productivity models that will be developed and presented in future work.

An extended horizontal directional drilling productivity model will be presented in a future research for types of soil encountered in the study, in addition to the user interface that will be developed as a field calculator for predicting horizontal directional drilling productivity in the field and required parameters such as quantity of drilling fluid, and average pumping rate of fluid.

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References

Adel, M., and Zayed, T. (2009). "Productivity analysis of horizontal directional drilling." *Pipelines 2009 Conference, Pipelines 2009: Infrastructure's Hidden Assets, August 15, 2009 - August 19*, American Society of Civil Engineers, San Diego, CA, United states, 835-843.

Ali, S., Zayed, T. and Hegab, M. (2007). "Modeling the effect of subjective factors on productivity of trenchless technology application to buried infrastructure systems." *J. Constr. Eng. and Manage.* 133(10), 743-748.

Allouche, E. N., Ariaratnam, S. T., and Lueke, J. S. (2000). "Horizontal directional drilling: profile of an emerging industry." *J. Constr. Eng. and Manage.,* 126(1), 68-76.

Bancroft, T.A. and Han, Chien Pai (1981). "Statistical theory and inference in research." Marcel Dekker, NY.

Bird, K. D. (2004). "Analysis of variance via confidence intervals." SAGE Publications Ltd, London.

Carpenter R. (2011). "13th Annual directional drilling survey: Mixed market recovery for horizontal directional drilling." Underground Construction, 66 (6), 24-28.

Horizontal directional drilling Consortium. (2008). "Horizontal directional drilling good practice guides."3rd Edition. © 2008 by North American Society for Trenchless Technology.

Hyeon-Shik Baik, D. M. A., and Gokhale, S. (2003). "A decision support system for horizontal directional drilling." *Tunneling and Underground Space Technology* 18(1), 99–109.

Kinnear, P. R. and Gray, C. D. (2006). "SPSS 14 made simple." Psychology Press, New York.

Mahmoud, M. A. (2009). "Productivity analysis of horizontal directional drilling," Dissertation, presented to Concordia University, Montreal, Quebec, Canada, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Montgomery, D. C. (2007). "Design and analysis of experiments."John and Welly Sons, Inc., Danvers.

Najafi, M. (2005). "Trenchless technology: pipeline and utility design, construction, and renewal." McGraw-Hill, New York.

Sowell, T. E. (2003). "Fuzzy logic tutorial." http://www.fuzzy-logic.com/, accessed on September 09, 2010.

Walpole, R. E., Myers, R. H., Myers, S. L., and Ye, K. (2007). "Probability and statistics for engineers & scientists." Pearson Prentice Hall, NJ.

Zayed, T., Amer, M. I., and Gupta, M. (2007). "Deterministic productivity model for horizontal directional drilling." *Twelfth International Colloquium on Structural and Geotechnical Engineering*, Ain Shams University Faculty of Engineering Department of Structural Engineering. http://icsge2009.com/2007/icsge/GE/GTE007.pdf, accessed on September 25, 2010.

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Figure Caption List

Figure Caption

Figure Number	**Figure Caption**
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Figure 1

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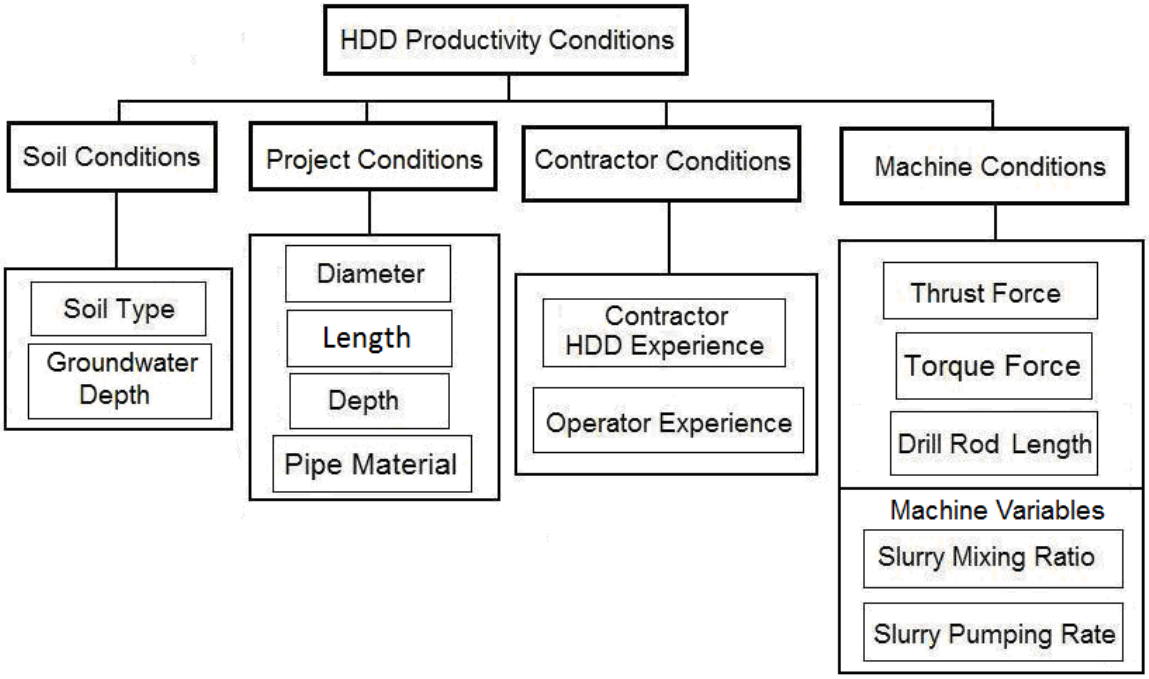

Figure 1 HDD Conditions and Subconditions

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Table 1 HDD Pilot Project Specifics

Item	Description
Project Name	Village Creek Reclaimed Water Eastern Delivery System
Project Location	Highway 360, Trinity Boulevard, Fort Worth, Texas, USA
Pipe Type and Diameter	Steel Pipe, 30 in. Outside Diameter (OD)
HDD Machine Type	Vermeer D 330 x 500
Crew	1 HDD Operator, 2 HDD Workers, 1 Mud System Worker, 1 Trackhoe Operator, 1 Oiler and Mechanical, 1 Water Truck Operator, 1 Pump Worker
Pipeline Length and Depth	1,100 ft, 50 ft at midpoint
Type of Soil Conditions (starting from exit pit side)	Shaly Clay, Sandy Shale, Shaly Clay, and Silty Clay
Preparation Period (days)	4
Equipment and Tools	HDD Rig, Backhoe, Loader, Forklift, Recycling Unit, Pumps, Trailer, welding equipment, and Water Tank
Working Area	Machine Side (150 ft x 220 ft)
	Product Pipe Side (50 ft x 110 ft)
Drilling Fluid Collection Pool Size	35 ft x 35 ft x 5 ft
Entry Pit Size	18 ft x 20 ft x 6 ft

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Table 2 HDD Productivity in Soil Conditions

Soil Type*	Productivity Sampling (ft/hr)										Total	Average
	1	2	3	4	5	6	7	8	9	10	$y_{i.}$	$\bar{y}_{i\cdot}$
1	150	150	90	64	75	82	53	46	62	64	836	84
2	75	75	64	60	38	25	44	48	---	---	429	54
3	82	75	51	49	43	58	56	64	---	---	478	60
4	106	67	69	150	180	---	---	---	---	---	572	114
$y_{..} = 2315$												$\bar{y}_{..} = 75$

* 1: shaly clay; 2: sandy shale; 3: shaly clay; 4: silty clay

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Table 3 ANOVA Analysis for Soil Type

Source of Variation	Sum of Squares	Degree of Freedom (df)	Mean Squares	F_0	P-Value
Soil Type	14,014	3	4,671	4.86	< 0.01
Error	25,955	27	961	--	--
Total	39,969	30	--	--	--

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Table 4 Comparison of Studentized Range and Absolute Means Difference for Soil Type

Pairs of Means	$T_{0.05}$ Value	Means Difference $\left\|\bar{y}_{i}. - \bar{y}_{j}.\right\|$	Significance
$\bar{y}_{1.} - \bar{y}_{2.}$	40	30	No
$\bar{y}_{1.} - \bar{y}_{3.}$	40	24	No
$\bar{y}_{1.} - \bar{y}_{4.}$	47	31	No
$\bar{y}_{2.} - \bar{y}_{3.}$	42	6	No
$\bar{y}_{2.} - \bar{y}_{4.}$	48	61	Yes
$\bar{y}_{3.} - \bar{y}_{4.}$	48	55	Yes

Table 5

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Table 5 2^2 Factorial Design for Depth-Length of HDD Bore-path

Factor		B = Depth		Calculations	
		Low	High	Sum	Average
A = Length	Low	(1) Obsern<u>s</u> Sum	(b) Obsern<u>s</u> Sum	(1)+(b)	---
	High	(a) Obsern<u>s</u> Sum	(ab) Obsern<u>s</u> Sum	(a)+(ab)	---
Calculations	Sum	(1)+(a)	(b)+(ab)	Total	---
	Average	---	---	---	Overall Average

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Table 6 2^2 Factorial Design for Depth-Length Effect

Factor	Depth (ft)				
Length (ft)	Level of Factor	Low	High	Sum	Average
	Low	150	62		
		90	64		
		64	75		
		75	75		
		82	64		
		53	60		
		46	38		
	Sum	560	438	998	71
	High	58	25		
		44	44		
		48	48		
		106	82		
		67	75		
		69	51		
		150	43		
Sum		542	368	910	65
Total Sum		1,102	806	1,908	---
Average		69	50	---	68

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Table 7 ANOVA Analysis for 2^2 Factorial (Depth-Length)

Source of Variation	Sum of Squares	Degree of Freedom	Means Square	F_0	P-Value
Length	277	1	277	0.35	> 0.25
Depth	3,129	1	3,129	4	> 0.05
Length-Depth	97	1	97	0.12	> 0.25
Error	19,034	24	793	---	---
Total	22,537	27	---	---	---

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Table 8 HDD Productivity vs. Groundwater Level

Groundwater Level (ft)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\bar{y}_{i.}$
20	67	33	33	133	44
0	18	18	18	54	18
$\sum y_{j.}$	85	51	51	$y_{..} = 188$	$\bar{y}_{..} = 31$

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Table 9 ANOVA Analysis for Groundwater Level

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Groundwater Level	1027	1	1027	5.5	> 0.05
Error	741	4	185	---	---
Total	1,768	5	---	---	---

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Table 10 HDD Productivity in Clayey Conditions

Diameter Range (in.)	HDD Productivity Observations (ft/hr)			
	1	2	$y_{i.}$	$\bar{y}_{i.}$
20–28	77	79	156	78
38–48	23	20	43	22
$\sum y_{j.}$	100	99	$y_{..} = 199$	$\bar{y}_{..} = 50$

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Table 11 ANOVA for Prereaming Diameter in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Diameter	3,207	1	3,207	1,049	< 0.01
Error	6	2	3	---	---
Total	3,213	3	---	---	---

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Table 12 Productivity Observations in Rocky Conditions

Diameter Range (in.)	HDD Productivity Observations (ft/hr)			
	1	2	$y_{i.}$	$\bar{y}_{i.}$
9–13	18	18	36	18
24–30	27	25	52	26
$\sum y_{j.}$	46	43	$y_{..} = 89$	$\bar{y}_{..} = 22$

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Table 13 ANOVA Analysis for Prereaming Diameter in Rocky Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	P-Value
Diameter (in.)	63	1	63	44	< 0.01
Error	3	2	1.5	---	---
Total	66	3	---	---	---

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Table 14 Productivity Observations for Pipeline Depth in Clayey Conditions

Depth (ft)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\bar{y}_{i.}$
148	27	23	20	70	23
22	77	79	---	156	78
$\sum y_{j.}$	104	102	20	$y_{..} = 226$	$\bar{y}_{..} = 45$

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Table 15 ANOVA Analysis for Pipeline Depth in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Depth (ft)	3,632	1	3,632	434	< 0.01
Error	25	3	8	---	---
Total	3,657	4	---	---	---

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Table 16 HDD Pullback Observations for Pipe Material in Clayey Conditions

Pipe Material	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\bar{y}_{i.}$
Steel	373	201	275	300	1149	287
HDPE	275	220	---	---	495	248
$\sum y_{j.}$	648	421	275	300	$y_{..} = 1644$	$\bar{y}_{..} = 273.93$

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Table 17 ANOVA Analysis for Pipe Material Pullback in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Pipe Material	2,095	1	2,095	0.5	> 0.25
Error	16,626	4	4,157	---	---
Total	18,721	5	---	---	---

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Table 18 HDD Productivity Observations for Contractor' Experience

Contractor Experience (year)	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\overline{y}_{i.}$
24	33	27	25	20	105	26
11	18	18	---	---	36	18
$\sum y_{j.}$	51	45	25	20	$y_{..} = 141$	$\overline{y}_{..} = 24$

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Table 19 ANOVA Analysis for Contractor' Experience

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Contractor Experience (year)	89	1	89	4	> 0.25
Error	92	4	23	---	---
Total	181	5	---	---	---

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Table 20 HDD Productivity for Operator' Experience

HDD Operator Experience (year)	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\bar{y}_{i.}$
4	33	27	25	20	105	26
8	18	18	18	75	129	32
$\sum y_{j.}$	51	45	43	95	$y_{..} = 234$	$\bar{y}_{..} = 29$

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Table 21 ANOVA Analysis for Operator' Experience

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
HDD Operator Experience (yr)	73	1	73	0.18	> 0.25
Error	2,505	6	418	---	---
Total	2,578	7	---	---	---

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Table 22 HDD Productivity Observations for Thrust Force in Rocky Conditions

Thrust Force (kip)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\overline{y}_{i.}$
70	33	27	25	85	28
35	18	18	18	54	18
$\sum y_{j.}$	51	45	43	$y_{..} = 139$	$\overline{y}_{..} = 23$

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Table 23 ANOVA Analysis for Thrust Force in Rocky Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Thrust Force	159	1	159	18	< 0.025
Error	37	4	9	---	---
Total	196	5	---	---	---

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Table 24 Thrust Force and Torque in HDD Rigs

Thrust Force (kip)	Torque Force (ft-kip)
>260	30–100,000
200–220	20–30
30–40	2–6

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Table 25 HDD Productivity Observations for Slurry Mixing Ratio

Slurry Mixing Ratio (lb/100 gal)	HDD Productivity Observations (ft/hr)					
	1	2	3	4	$y_{i.}$	$\overline{y}_{i.}$
50	33	27	25	20	105	26
40	18	18	18	---	54	18
$\sum y_{j.}$	51	45	43	20	$y_{..} = 159$	$\overline{y}_{..} = 23$

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Table 26 ANOVA Analysis for Slurry Mixing Ratio in Rocky Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Slurry Ratio	114	1	114	6.3	> 0.05
Error	92	5	18	---	---
Total	206	6	---	---	---

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Table 27 HDD Productivity for Slurry Pumping Rate in Clayey Conditions

Pumping Rate (gpm)	HDD Productivity Observations (ft/hr)			
	1	2	$y_{i.}$	$\overline{y}_{i.}$
300	76	76	152	76
88	77	79	156	78
$\sum y_{j.}$	153	155	$y_{..} = 308$	$\overline{y}_{..} = 77$

Table 28

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Table 28 ANOVA Analysis for Slurry Pumping Rate in Clayey Conditions

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Slurry Ratio	7	1	7	5	> 0.1
Error	3	2	1.5	---	---
Total	10	3	---	---	---

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Table 29 HDD Productivity Observations for Drilling Rod Length

Drilling Rod Length (ft)	HDD Productivity Observations (ft/hr)				
	1	2	3	$y_{i.}$	$\bar{y}_{i.}$
10	27	23	20	70	23
30	77	79	---	156	78
$\sum y_{j.}$	104	102	20	$y_{..} = 226$	$\bar{y}_{..} = 45$

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Table 30 ANOVA Analysis for Drilling Rod Length

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F_0	*P*-Value
Drilling Rod Length (ft)	3,632	1	3,632	434	< 0.01
Error	25	3	8	---	---
Total	3,657	4	---	---	---

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Table 31 ANOVA Significance for HDD Productivity Conditions

HDD Conditions Main Group	HDD Sub Condition	Significant
Soil Conditions	Soil Type	Yes
	Groundwater Level (ft)	No
Project Conditions	Prereaming Diameter (in.)	Yes
	Pipeline Depth (ft)	
	Pipeline Length (ft)	
	Material (Pullback)	No
Contractor Conditions	Contractor Experience (yr)	No
	Operator Experience (yr)	
Machine Conditions	Thrust Force (kip)	Yes
	Torque Force (ft-kip)	
	Drilling Rod Length (ft)	
Machine Variables	Slurry Mixing Ratio (lb/100 gal)	No
	Slurry Pumping Rate (gpm)	