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Modeling of Productivity for Horizontal Directional Drilling (HDD) Operation and Applications

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Abstract

Horizontal Directional Drilling (HDD) is a growing method for installation of pipes in urban areas and where trenching is impossible or undesirable; such as in crossing rivers, lakes, railways, and runways in airports. This technique utilizes down-hole cutting heads to create a pilot borehole before it is enlarged with back reamers to allow pulling back of a product pipe. The utilization of HDD for the installation of underground infrastructure (i.e., water, wastewater, oil and gas pipes, telecommunication, and power conduits), has shown a rapid growth compared to other trenchless technologies. HDD can install a range of pipe diameters from 2 to 60 inches utilizing different pipe materials including steel, high density polyethylene (HDPE), polyvinyl chloride (PVC), and ductile iron pipe (DIP) with minimum surface and daily life disruptions. Estimation of HDD productivity, project duration, and quantity of materials required, is a difficult task due to variable productivity conditions such soil, project, contractor, and machine conditions involved in operation. This paper aims to introduce HDD productivity prediction model, and to present the HDD user interface as a planning tool for operation.

Introduction

Trenchless technology (TT) or No-Dig refers to the techniques for underground pipeline and utility construction, replacement, rehabilitation, renovation (renewal), repair, inspection, and leak detection with minimum or no excavation from the ground surface (Najafi, 2010). Over the years, TT methods have become more sophisticated (specialized) and more widely used in many fields and applications. Mainly, due to its environmental and social benefits, TT is considered to be one of the fastest growing technologies affecting the world's underground infrastructure installation and replacement (Liu et al. 2009).

Among TT techniques, Horizontal Directional Drilling (HDD) is the most versatile trenchless procedure available that can be widely used for underground telecommunications, electrical conduits, gas and oil pipeline installation, and public infrastructure (water and sewer) construction (Lawson and Najafi, 2003).HDD technique provides significant benefits for urban environments by decreasing disruption caused by streets excavations (Manacorda et al. 2010). In difficult situations such as deep pipeline laying or in case of crossing highways, rivers, or lakes, HDD can be not only more cost effective, but also more feasible and applicable than any other trenchless method (Atalah, 2009).

Horizontal Directional Drilling (HDD) is a steerable or a guided boring system for installation of pipes, conduits, and cables involving a surface drilling rig in digging operation. Generally, HDD is divided into three main divisions: large-diameter HDD (Maxi-HDD) in the range of 24-60 inches, medium-diameter HDD (Midi-HDD) in the range of 12-24 inches, and small-diameter HDD (Mini-HDD) in the range of 2-12 inches as presented in Table 1.

Table 1 HDD Main Features (Najafi. 2005)

HDD Size	Diameter (in.)	Depth (ft)	Drive Length (ft)	Torque (ft-Ib)	Thrust (lb)	Machine Weight (ton)
Maxi	24–60	≤ 200	≤6,000	≤ 80,000	100,000-1000,000	≤ 30
Midi	12–24	≤ 75	≤ 1,000	900–7,000	20,000–100,000	≤ 18
Mini	2–12	≤ 15	≤ 600	≤ 950	≤ 20,000	≤ 9

HDD is used to install different types of product pipes including Steel, HDPE, PVC, conduits, and flexible cables considering service type, soil type and severity, and pipeline diameter and depth (Barras and

Mayo, 1995). HDD involves at least two stages and can include multi stages of preream/ream operations depending on the final diameter of product pipe. The first stage involves drilling a pilot borehole using cutting head approximately of 2-6 inches in diameter in hard soils, but it can also be selected to start drilling at 12-16 inches in diameter in soft soils utilizing Midi- to Maxi-HDD rig size. Figure 1 illustrates drilling of pilot hole in HDD operation.

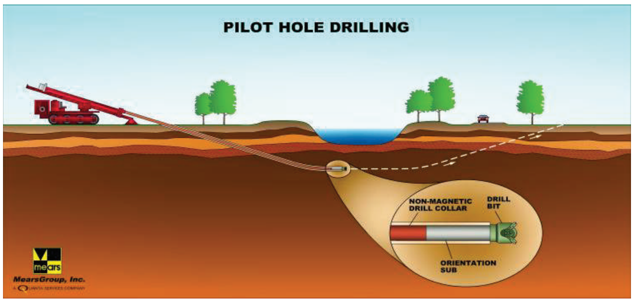


Figure 1 HDD Pilot-hole Stage (Najafi, 2010)

The second stage involves prereaming/reaming or enlarging of borehole using larger reamer diameter. The increments or jumps in diameters in soft soil are very large. While in hard soil, the increments are very small; in hard rock increments range from 2-4 inches, in medium rock increments range from 2-6 inches, in soft rock increment can be more. Prereaming/reaming stage continues until bore-hole diameter becomes 1.25 to 1.5 times the size of product pipe. Figure 2 illustrates prereaming/reaming stage in HDD operation. The last stage is the pulling back of product pipe in borehole and is shown in Figure 3.

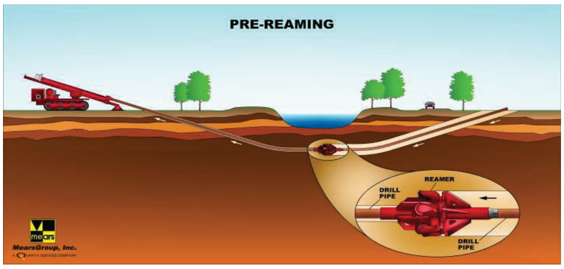


Figure 2 HDD Prereaming Stage (Najafi, 2010)

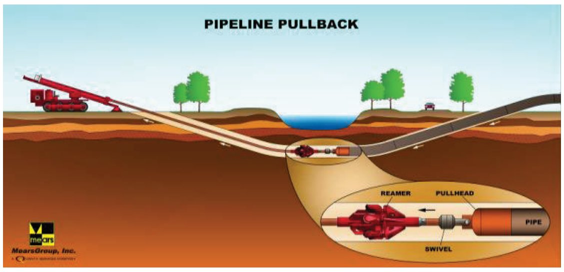


Figure 3 HDD Pullback Stage (Najafi, 2010)

Among trenchless technologies, HDD has a standing applicability in most of underground applications (Burman, 2009). Figure 4 illustrates utilization of HDD technique in installation of underground infrastructure utilities. HDD has a big share in underground construction including telecommunications, sewer and water, gas, and electric projects, in addition to environmental wells’ projects.

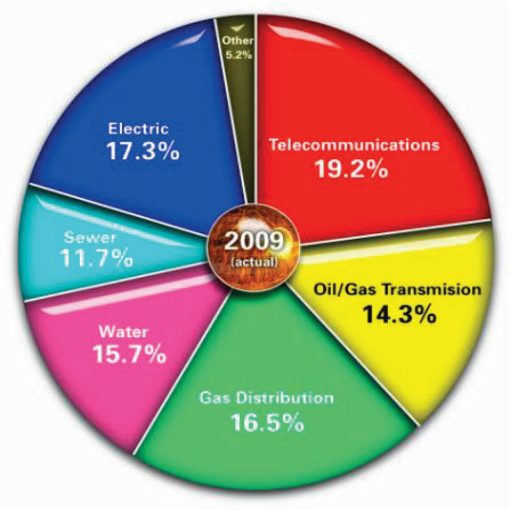


Figure 4 HDD Applications in Utilities Installations (Carpenter, 2010)

Background

Allouche et al. (2000) provided a study on HDD to consider company profile, type of project performed, duration, product pipe installed, bidding and estimating practices, and planning and operation control. The study concluded that HDD is favorable to most contractors, design engineers, and consultants in for the following reasons:

- No surface shafts required as drilling can commence from surface.
- HDD has relatively the shortest setup time.
- Straight alignment is not required, since HDD has the ability to change direction and grade.
- The long drive length installed using HDD compared to other trenchless technologies.

The most important results of the study were the productivity of HDD (ft/hr) associated to specific pipe diameters presented in Table 2, in clayey, rock, and sandy soils.

Table 2 HDD Productivity vs. Soil Type and Diameter (Allouche et al., 2000)

Diameter Range (in.)	Soil Type		
	Clay	Rock	Sand
2–4	74	42	55
6–8	53	28	41
10–12	42	19	37
>12	28	9.5	27

Allouche et al. (2001) studied HDD among other trenchless technologies including microtunneling, auger boring, pipe ramming, pipe jacking (hand excavation), tunneling (TBM), and tunneling (hand excavation). It was declared that HDD drillability in boulders, cemented soil, and in high specific weight soil is moderate. In flowing sand and in buried structure, HDD drillability is moderate to severe. In gravel and/or cobbles and in artesian aquifers is severe. Therefore, HDD has a standing drilling-ability compared to other TT methods in different soil conditions. In another study (Allouche et al., 2003), HDD operation was studied in terms of product pipe material, size, and applications.

Willoughby (2005) introduced prereaming values for HDD productivity (ft/hr) in clay, rock, and sand as presented in Table 3; it showed that sand and clay have large productivity compared to rock in different ranges of prereaming diameter.

Table 3 HDD Productivity in Soil Conditions (Willoughby, 2005)

Neam Diameter (in.)	HDD Productivity (ft/hr)		
	Clay	Rock	Sand
< 24	180	30–60	180
24–32	150	30	150
>32	120	18	120

According to Mahmoud (2009), HDD 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 HDD 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. Activity duration such as drilling time was considered as the major activity duration in HDD 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. In large projects, the duration of auxiliary activities becomes major compared to the drilling time that considered minor activity.

In clayey soil, HDD productivity was found to average 51.35 ft/hr, while HDD productivity predicted was 44.85 ft/hr with a validation of 87.34%. In rock, HDD productivity was found to average 35.01 ft/hr, while HDD productivity predicted was 31.07 ft/hr with a validation of 88.75%. In sandy soil, HDD productivity was found to average 37.5 ft/hr, while HDD productivity predicted was 33.5 ft/hr with a validation of 89.32%.

Factors such as pipe diameter, soil type, and drilling rig capabilities were considered the most important factors that can affect productivity of HDD 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 HDD productivity, groundwater table is said to have no effect on HDD productivity. Also, slurry pumping rate and mixing ratio are functions of soil type. Although pipe material (HDPE, PVC, and steel) affect productivity of pipe connection, during pull back, pipe material has no direct effects on HDD operation as most of pipe materials are floating in borehole. Therefore, HDD productivity can be modeled using HDD rig capabilities, soil type, pipe diameter, and depth.

HDD Productivity

Productivity of HDD rig is defined as the distance drilled, prereamed, or pulled back by HDD machine during a unit of time, denoted as (ft/hr) or (ft/day). Measuring productivity on hourly basis is more accurate than on daily basis. An hourly record allows considering subsurface conditions and changes as well as machine and worker efficiency in different time periods during operation.

HDD is utilized with multi- and interrelated-conditions including management, site, and product pipe (Ali et al., 2007), all of which affect HDD productivity and make HDD operation more critical and specific (Gelinas et al., 2000). Therefore, estimating of operation productivity, duration of project, and cost becomes all critical and specific too. Because the common practice in estimating these project parameters relied on previous project cases without considering significant subconditions in operation, a productivity prediction model is needed for more accurate results and calculations (Mahmoud, 2009).

HDD bore-path alignment usually continues in different soil conditions within the same project. These changes make the mission of the design engineer difficult when it comes to selecting cutting head, reamer, machine operational conditions including forces, slurry flow rate and mixing ratio. Therefore, considering project conditions, including soil investigations, and HDD machine abilities help engineers to design and implement HDD operation successfully (Royal et al. 2010).

Drilling using HDD is similar to any engineering operation, starts usually with preconstruction services including surface and subsurface survey or investigation, design, planning, drawings preparation, and specifying of materials to be used in operation (Najafi, 2005). The design and planning of HDD operation is performed to evaluate applicability of proposed work and to avoid or moderate problems such as instability of soil or potentiality of collapse of bore-hole during drilling, as well as to evaluate the opportunity of "frac-out" occurrence (Hair et al., 2005). Significant subconditions should be represented in HDD productivity prediction model to be acceptable and satisfying to contractors, consultants, and engineers. The outcomes of this study will help project parties estimate project parameters such as productivity in order to determine duration, planning, and scheduling. It will also help to bid the project successfully.

The productivity of HDD operation is very critical for contractors, engineers, and machine operators, also very important for owners and pipelines operators. According to the HDD operation conditions, contractor and/or engineer decide to select the size of HDD machine suitable to the type of soil encountered, the size of job. There are several challenges associated with HDD in marine environment and river installations. These challenges include construction restrictions such as mud control, expected frac-out, limited working area, seasonal restriction for aquatic habitats, and minimizing of disturbance for wet lands in project site and other adjacent sites expected to be affected. To prevent frac-out problems, lower pressure should be utilized and deep lay down of pipeline should be applied in alignment selection. An emergency plan must be in place if frac-out expected to happen. Also, casing is usually required for product pipe. Effective construction management will improve site accessibility and provision for material storage and fabrication.

HDD Productivity Data

For the purpose of this paper, data was collected through a questionnaire included HDD market (type of HDD rigs, size of HDD rigs, product pipes installed, soil information, and operational factors and conditions). The HDD data collected also included data related to HDD productivity (ft/hr) and factors expected to have an effect on productivity.

HDD Productivity Data in Clayey Conditions

As a mother of fact, HDD productivity data was sorted into three groups: data collected in clayey soil (condition), rocky soil (condition), and sandy soil (condition). Table 4 presents data collected in clayey soil.

Table 4 HDD Productivity Data in Clayey Conditions

Diameter (in.)	Depth (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	Productivity (ft/hr)
9	30	30	280	45	22
9.875	150	30	1200	100	56
12	6	10	25	11	120
16	70	30	130	25	76
20	22	30	215	25	77
22	30	30	280	45	276
24	120	30	230	25	183
26	148	10	260	35	27
26	125	30	40	4	238
28	22	30	215	25	79
28	70	30	130	25	76
34	150	30	1200	100	42
36	120	30	230	25	183
36	30	30	280	45	28
38	147	10	260	35	23
42	30	30	280	45	24

Figure 5 through Figure 10 illustrate HDD productivity data vs. prereaming diameter, pipeline depth, pipeline length, drilling rod length, thrust force, and torque force.

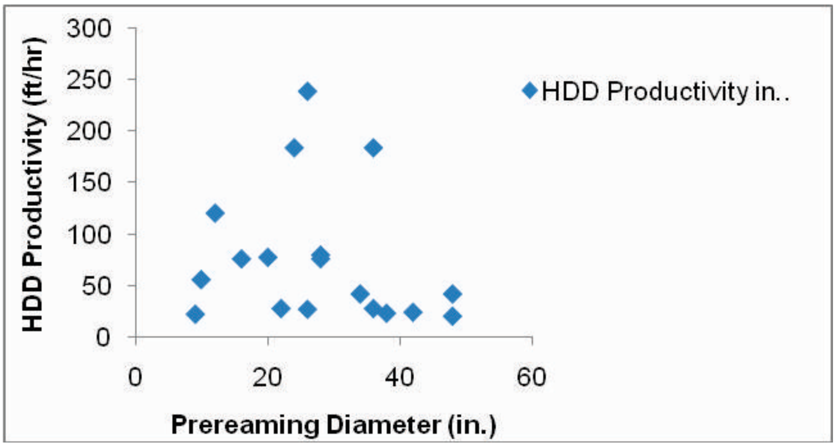


Figure 5 HDD Productivity vs. Diameter of Prereaming in Clayey Conditions

As it is illustrated in Figure 5, HDD productivity (ft/hr) decreases with the increase in prereaming diameter (in.), no matter the relation type (linear, power, or quadratic) used to describe this function.

Figure 6 illustrates HDD productivity in clayey conditions vs. depth of pipeline (ft). It is shown from the figure that HDD productivity shows a tendency to decrease with the increase of pipeline depth.

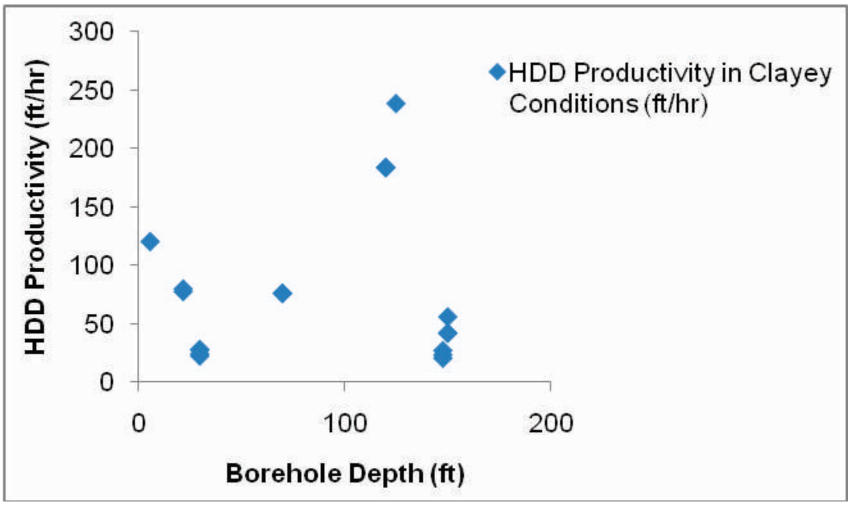


Figure 6 HDD Productivity vs. Pipeline Depth in Clayey Conditions

Figure 7 illustrates HDD productivity vs. length of bore-hole in clayey conditions. This figure shows that HDD productivity decreases as the length of bore-hole increases.

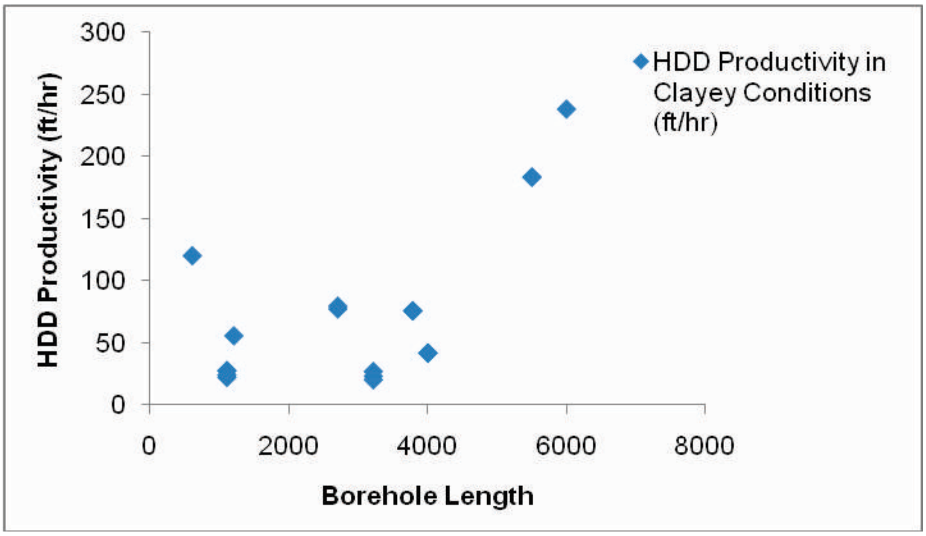


Figure 7 HDD Productivity vs. Borehole Length in Clayey Conditions

Figure 8 illustrates HDD productivity vs. drilling rod length. It shows that if contractors use short drilling rods (10–15 ft), HDD productivity will be in the range of 20–55 ft/hr. However, if full length of 30 ft drilling rod is used, productivity will be in the range of 20–180 ft/hr, considering the 3–4 minutes needed to remove or to add one drilling rod.

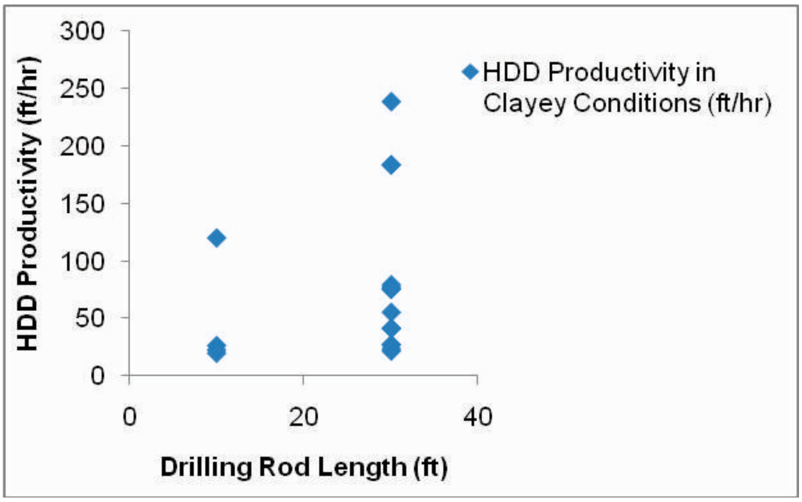


Figure 8 HDD Productivity vs. Length of Drilling Rod in Clayey Conditions

Figure 9 illustrates HDD productivity vs. thrust force (kip). This figure shows that as the thrust force increases, the productivity will decrease as Midi- and Maxi-HDD with large thrust force are used to drill or preream in hard clayey conditions.

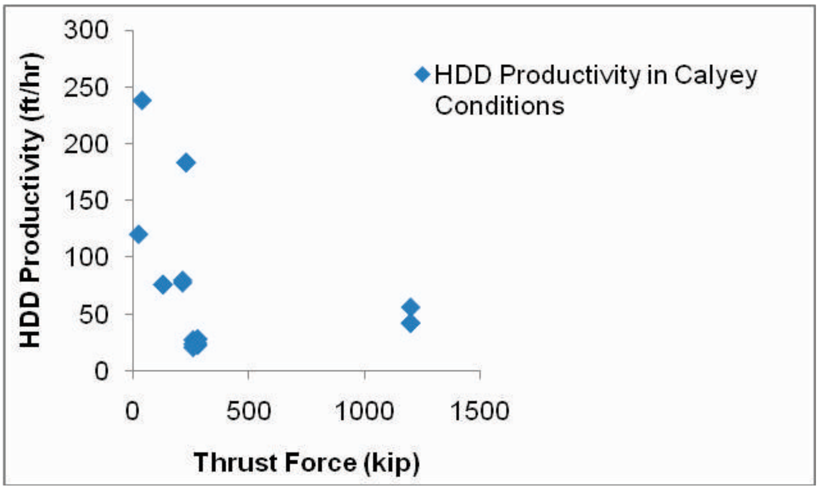


Figure 9 HDD Productivity vs. Thrust Force in Clayey Conditions

Figure 10 illustrates HDD productivity vs. torque force (ft-kip), confirming that torque force provides similar indication about HDD productivity in clayey conditions.

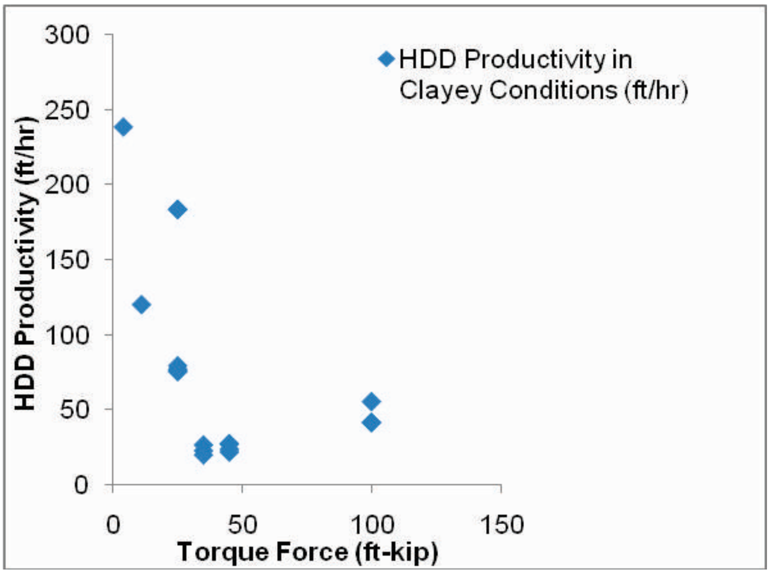


Figure 10 HDD Productivity vs. Torque Force in Clayey Conditions

A HDD productivity model was developed using data presented in Table 4 for clayey conditions considering significant factors as indicated and tested by the analysis of variance (ANOVA) model as presented in Table 5.

Table 5 ANOVA Significance for HDD Productivity in Clayey Conditions (Sarireh and Najafi, 2011)

HDD Conditions Main Group	HDD Sub Condition	Significance
Soil Conditions	Soil Type	Yes
	Groundwater Level (ft)	No
Project Conditions	Prereaming Diameter (in.)	Yes
	Pipeline Depth (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)	

After applying SPSS regression analysis, HDD productivity model has the following equation:

HDD PC = 110.68 – 0.315 (Diam.) + 0.309 (Depth) + 3.148 (DRL) + 0.408 (Th.F.) - 6.83 (Trq.F.)

Where: HDD PC is HDD productivity in clayey conditions (ft/hr), Diam. is prereaming diameter (in.), Depth is depth of borehole at midpoint (ft), DRL is drilling rod length (ft), Th.F. is thrust force (kip), and Trq.F. is torque force (ft-kip)

Appendix A1 through A2 represent for HDD productivity in clayey conditions the data sheet in SPSS, model summary, ANOVA analysis for sum of squared errors, mean squares, significance, and model coefficients.

HDD Productivity Model in Rocky Conditions

Table 5 presents data used for modeling HDD productivity in rocky conditions including reported HDD productivity and significant subconditions. The values of HDD productivity in rocky conditions are very low compared to clayey conditions. For example, at 24-in. prereaming diameter, productivity in rocky conditions is equal to 27 (ft/hr) at 30-ft depth, while HDD productivity is equal to 183 (ft/hr) for clayey conditions at depth of 120-ft. Another major difference between clayey and rocky conditions is that HDD machine force in rocky conditions including thrust and torque is very high especially in hard rock conditions compared to that used in clayey conditions.

Table 6 HDD Productivity Data in Rocky Conditions

Diameter (in.)	Depth (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	Productivity (ft/hr)
8.75	30	30	70	5	40
9	14	14	35	9	18
10	25	15	70	9	67
12	25	15	35	5	75
13	14	14	35	9	18
14	25	15	70	9	33
16	25	15	70	9	33
18	14	14	35	9	18
18	25	15	70	9	33
18	30	30	70	5	33
22	25	15	70	9	33
24	30	30	70	5	27
30	30	30	70	5	25
36	30	30	70	5	20

Figure 11 illustrates HDD productivity (ft/hr) for rocky conditions vs. diameter of prereaming (in.). This figure shows that HDD productivity decreases with the increase of reamer diameter as the contact surface between reamer and bore-hole increases.

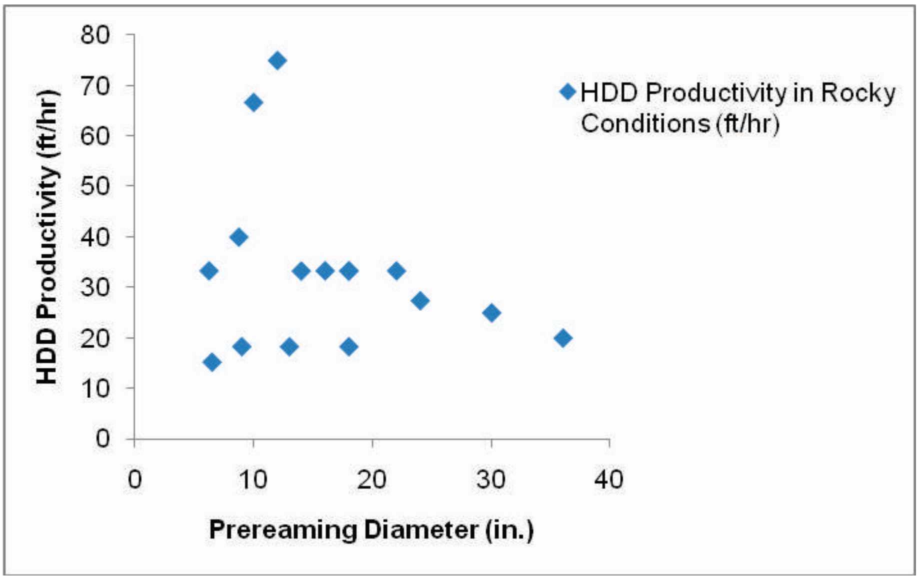


Figure 11 HDD Productivity vs. Prereaming Diameter

Figure 12 illustrates HDD productivity vs. depth of bore-hole, and shows that HDD productivity increases with the increase of depth. But, does not have good correlation, as the depth takes the value from 14-ft to 30-ft, which is a close range. Deeper bore-holes of installations, may cause HDD productivity to decrease.

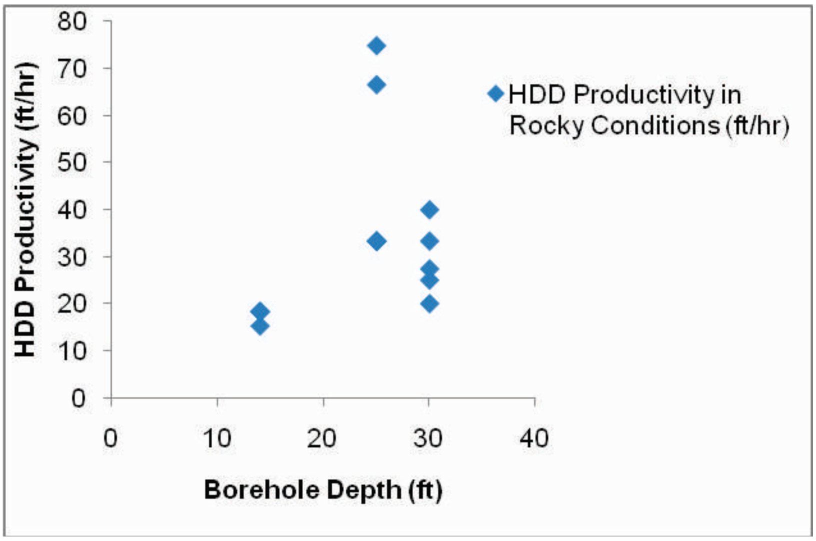


Figure 12 HDD Productivity vs. Borehole Depth in Rocky Conditions

Figure 13 illustrates HDD productivity vs. length of borehole. It shows that HDD decreases with the increase of the borehole length. Obviously, the increase in length increases friction force exerted by the bore-hole sides on the reamer. It should be noted that HDD productivity outlier of 75 (ft/hr) is achieved by a Midi-HDD rig with a 70 kip of thrust force, this case will be discussed in details in validation of research results.

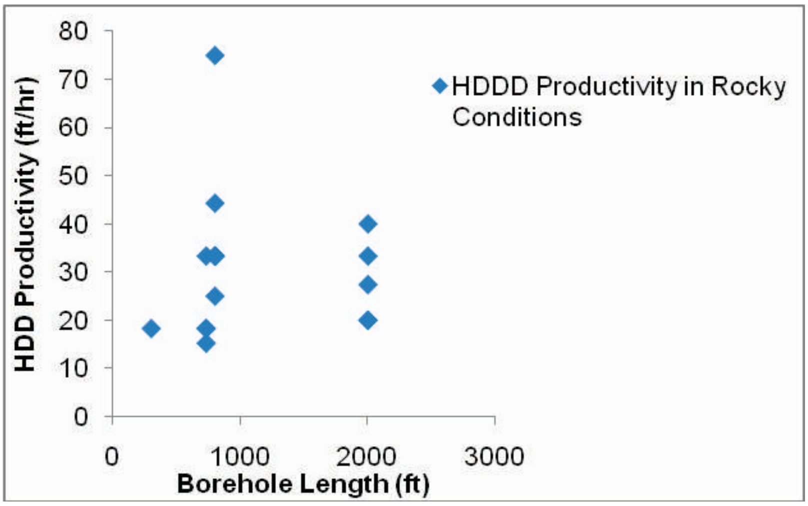


Figure 13 HDD Productivity vs. Borehole Length in Rocky Conditions

Figure 14 illustrates HDD productivity vs. drilling rod length. It seems that drilling rod length is inversely related to HDD productivity in rocky conditions, or at least it has some of constant value as drilling rod length takes the values of 15 ft and 30 ft. Also, productivity can be lower in more problematic soil conditions, such as hard rock. Preream in hard soil conditions such as rock, is detrimental to drilling bit, because large force must be used to maintain productivity.

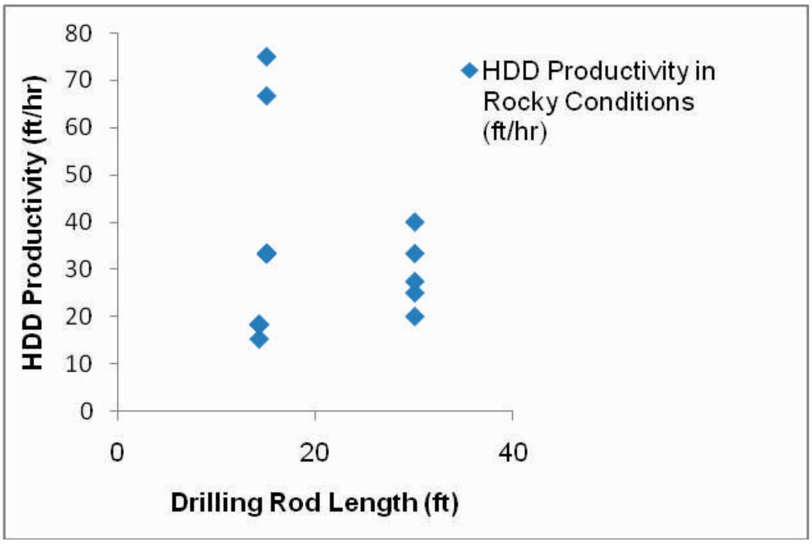


Figure 14 HDD Productivity vs. Drilling Rod Length in Rocky Conditions

Figure 15 shows that HDD productivity increases with increase of thrust force (kip).

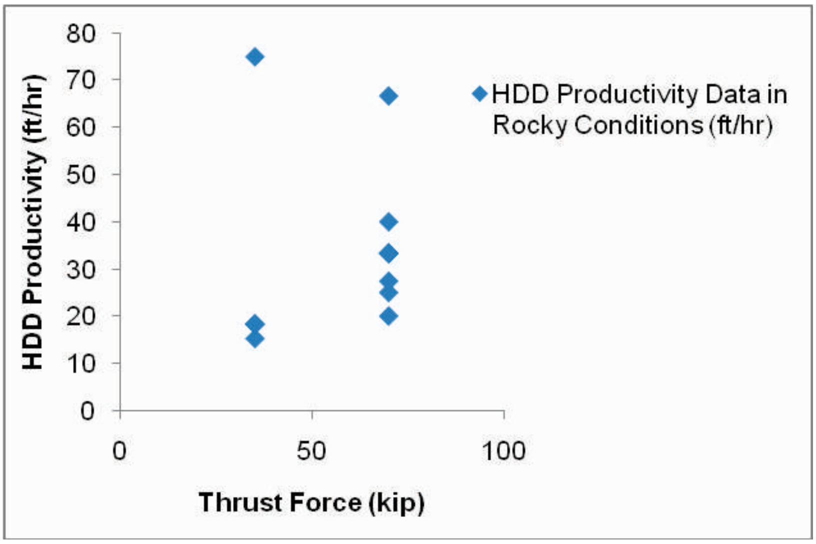


Figure 15 HDD Productivity vs. Thrust Force in Rocky Conditions

Figure 16 illustrates HDD productivity vs. torque force (ft-kip). It shows that HDD productivity in rocky conditions for torque force has similar trend as for thrust force. This is simply because thrust force and torque force are related in HDD machine size and design, job size, and soil type.

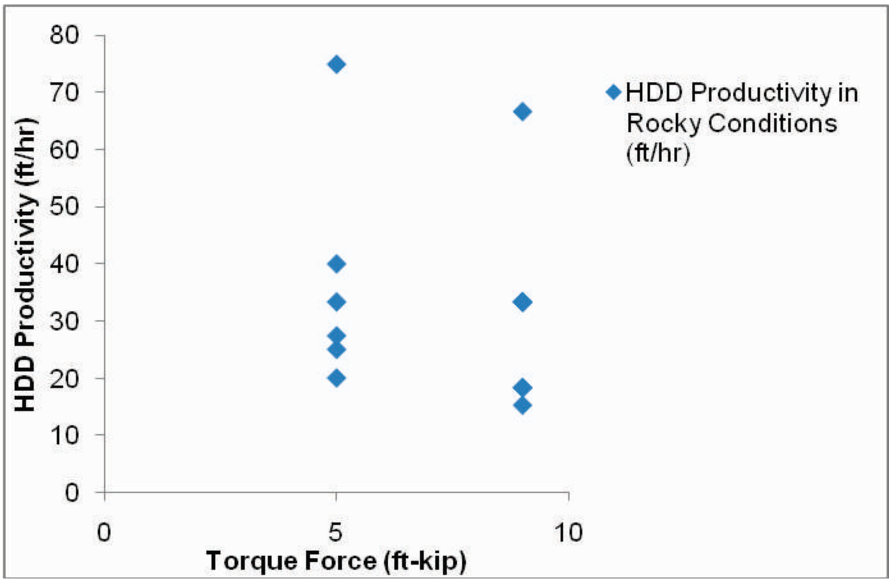


Figure 16 HDD Productivity vs. Torque Force in Rocky Conditions

The developed model for HDD productivity in rocky conditions includes prereaming diameter (in.), thrust force (kip), torque force (ft-kip), and drilling rod length (ft) and has the following equation:

HDD PR = 197.48 – 0.669 (Diam.) – 4.313 (DRL) + 0.755 (Th.F.) – 15.238 (Trq.F.)

Where: HDD PR is HDD productivity in rocky conditions (ft/hr), Diam. is prereaming diameter (in.), DRL is drilling rod length (ft), Th.F. is thrust force (kip), Trq.F. is torque force (ft-kip).

Appendix B1 to B2 represent SPSS analysis, model summary and significance.

HDD Productivity in Sandy Conditions

HDD productivity in sandy conditions comes in high values when sandy layers -that contains HDD pipelines- found at shallow depths, this results because sandy layers are loose. While values of HDD productivity comes in low values when goes through deep sandy layers because of the consolidation of the over burden and compaction weight make these layers dense. Table 7 presents HDD productivity data collected in sandy conditions. The minimum value was 54 ft/hr which happened at 30-in. diameter of prereaming, 35-ft depth, and 750-ft length. The maximum value of 220-ft/hr occurred at 16-in. diameter, 6-ft. depth, and 220-ft length. The average productivity value was 100 ft/hr. Although sandy conditions provides good drilling ability, but it may face bore-hole collapse that consumes more drilling fluid to remove cuttings and holding sides of borehole wall.

Table 7 HDD Productivity Data Collected in Sandy Conditions

Prereaming Diameter (in.)	Pipeline Depth (ft)	Pipeline Length (ft)	Drilling Rod Length (ft)	Thrust Force (kip)	Torque Force (ft-kip)	HDD Reported Productivity (ft/hr)
16	6	220	14	25	2.5	220
18	35	750	30	35	3	94
22	35	750	30	35	3	63
30	35	750	30	35	3	54
56	100	4,300	30	30	35	72
Average HDD Productivity in Sandy Conditions						100

HDD Productivity Model Prediction and Validation

In this section, developed HDD productivity model for clayey and rocky conditions shown above, are tested and validated using the whole set of collected data.

HDD Clayey Conditions Productivity Model

Table 8 presents the validation of HDD productivity model in clayey conditions by comparing reported and predicted HDD productivity values. Figure 17 shows a comparison between reported and predicted HDD productivity.

Table 8 Validation of HDD Productivity Model in Clayey Conditions

Reported Productivity (ft/hr)	Predicted Productivity (ft/hr)	% Difference	Validation Factor
22	19	16.16	1.19
56	55	1.08	1.01
120	75	37.25	1.59
76	104	-37.49	0.73
77	12	-58.91	0.63
28	14	47.82	1.92
183	158	13.96	1.16
27	47	-74.17	0.57
238	225	5.69	1.06
79	120	-51.19	0.66
76	100	-32.49	0.76
42	47	-13.66	0.88
183	154	16.03	1.19
28	10	63.85	2.77
23	43	-86.73	0.54
24	8	66.34	2.97
20	40	-97.71	0.51
42	43	-3.08	0.97
Average (74.57)	Average (76.87)	Average (-10.40)	Average (1.17)

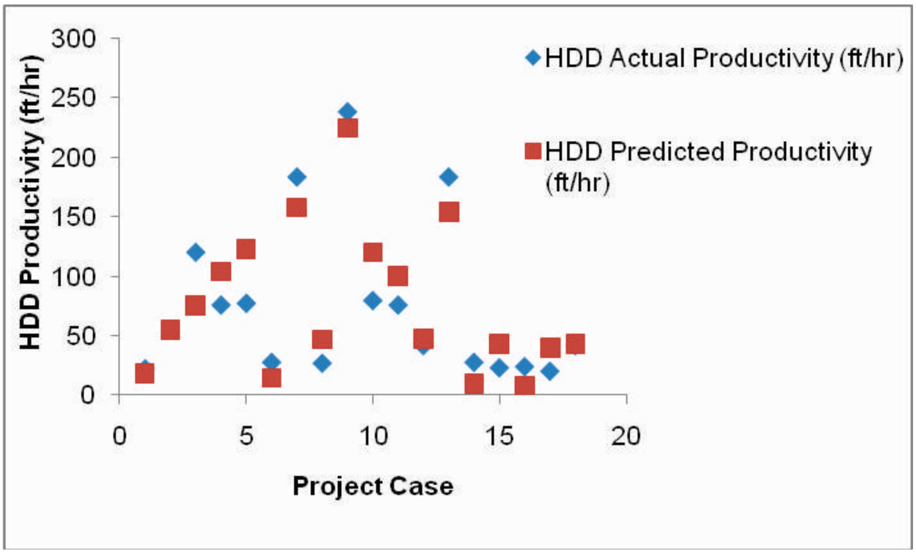


Figure 17 HDD Reported and Predicted Productivity for Clayey Conditions

HDD Rocky Conditions Productivity Model

Table 9 presents validation of HDD productivity model in rocky conditions. It is shown that validation factor is still high in this model averaging 105%, and the model is able to predict HDD productivity in rocky conditions. Figure 18 shows a comparison between reported and predicted HDD productivity.

Table 9 HDD Productivity Model Validation in Rocky Conditions

Reported Productivity (ft/hr)	Predicted Productivity (ft/hr)	% Difference	Validation Factor
40	39	0.03	1.03
18	19	-0.05	0.95
67	42	0.4	1.6
75	75	0.00	1.00
18	17	0.09	1.10
33	39	-0.18	0.85
33	38	-0.13	0.88
18	13	0.28	1.38
33	37	-0.09	0.91
33	33	0.02	1.02
33	34	-0.01	0.99
25	25	0.013	1.013
20	21	-0.03	0.97
27	29	-0.05	0.95
Average (34)	Average (32.77)	Average (0.02)	Average (1.05)

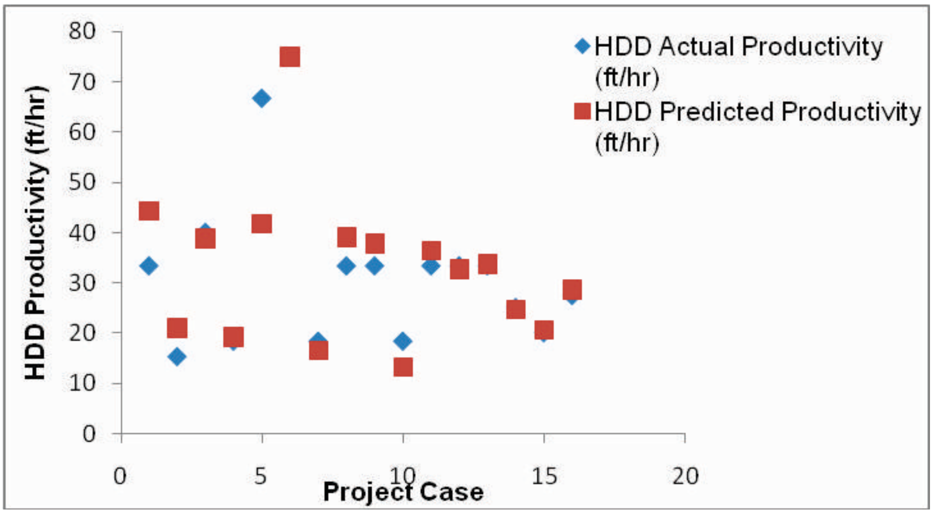


Figure 18 HDD Reported Productivity vs. Predicted in Rocky Conditions

Reality Validation for HDD productivity Models

Table 10 presents a comparison and summary of HDD productivity results obtained in the literature search and results obtained in current research.

Table 10 Comparison of Results for HDD Productivity Models (Sarireh and Najfi, 2011)

Soil Type	Allouche (2000)		Willoughby (2005)		Zayed (2007)		Mahmoud (2009)		Current Research (2011)	
	Actual	Model	Actual	Model	Actual	Model	Actual	Model	Actual	Model
Clay	44	NA	150	NA	NA	NA	51	45	75	77
Rock	25	NA	31	NA	NA	NA	35	31	34	33
Sand	40	NA	150	NA	123 and 88	NA	37.5	34	100	NA

Another reality check comes with the results of previous studies in considering significant subconditions in HDD productivity operation and other trenchless operations. Table 11 and 12 present the results obtained by previous studies conducted on HDD and other trenchless construction operations regarding HDD's significant subconditions.

Table 11 Significant Conditions in Trenchless Operations (Sarireh and Najafi, 2011)

Study	Significant Subconditions
Tunneling, Touran (1997)	Soil type, job environment, and equipment abilities (force)
TBM, Arachchige (2001)	Soil Type
Auger Boring, Salem (2003)	Soil type, length, obstruction, and diameter
Microtunneling Hegab and Salem (2004)	Soil type and conditions, drive length, diameter, no. of driven pipes, and jacking force
Continuous Flight Auger (CFA) Zayed (2005)	Soil type, obstructions, depth, diameter, and machine abilities (force)
Microtunneling Hegab and Salem (2010)	Soil type and soil conditions, diameter, length, and shear force

Table 12 Significant Conditions in HDD Operations (Sarireh and Najafi, 2011)

Study		Significant Subconditions
HDD Adel and Zayed (2009)		HDD rig capabilities (thrust and torque), soil type and unseen conditions, pipe diameter, length, and depth
HDD Zayed et al. (2007)		Soil type, pipeline diameter, and machine size
HDD Mahmoud (2009)	Significant Factors	Soil type, pipeline diameter, and machine capabilities (thrust and torque)
	Insignificant Factors	Season, weather, groundwater level, fluid ratios, and fluid pumping rate

Application of HDD Model in HDD User Interface

By estimating productivity using developed models' in clayey, rocky and sandy conditions, a HDD user interface is developed as a planning tool for HDD prereaming operations. During the research, also modified productivity model is introduced. The following formula provides modified productivity by factoring non-productive time in model productivity:

HDD Modified Productivity (ft/hr) = HDD Model Productivity (ft/hr) x (1 – Non-productive time %).

Table 13 shows some parameters in HDD operation such as HDD crew cost ($/hr), bentonite mixing ratio, polymer mixing ratio, fluid pumping rate, and non-productive time for clayey projects, rocky projects, and in sandy projects.

Table 13 HDD Prereaming Operation Parameters (Sarireh and Najafi, 2011)

Soil Conditions	**Data Collected by HDD Questionnaire (Average)**				
	HDD Crew Rate ($/hr)	**Bentonite Mixing Ratio (lb/100 gal)**	**Polymer Mixing Ratio (lb/100 gal)**	**Fluid Pumping Rate (gpm)**	**Non-Productive Time %**
Clayey Conditions	169.7*	12	2.5	180	13
Rocky Conditions		29	40	145	10
Sandy Conditions		20	3.25	62	15

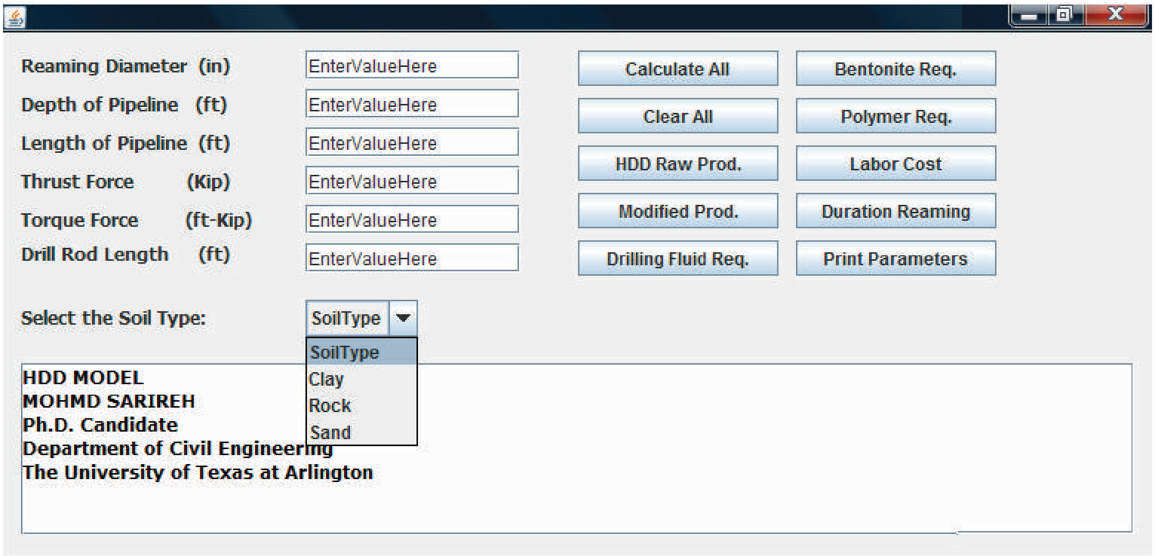
* Details of HDD crew cost ($/hr) presented in Table 14

Table 14 shows calculations of HDD crew cost ($/hr) for a crew of 7 workers including foreman.

Table 14 HDD Crew Cost Rate ($/hr), (Sarireh and Najafi, 2011)

HDD Crew Description	**Crew Rate ($/hr)**	**No.**	**Rate Sum ($/hr)**	**Total Rate ($/hr - Crew)**
Foreman	30	1	30	169.7
HDD Driller	23	1	23	
Backhoe Operator	19.5	1	19.5	
Mechanical Operator	19	1	19	
Mud Recycling Worker	16.2	1	16.2	
Pump Worker	16	2	32	
HDD Worker	15	2	30	

A HDD user interface is developed by Java application. The HDD user interface is able to conduct HDD productivity calculations in clayey, rocky, and sandy conditions. Figure 19 illustrates the screen of HDD user interface.


Reaming Diameter (in) EnterValueHere
Depth of Pipeline (ft) EnterValueHere
Length of Pipeline (ft) EnterValueHere
Thrust Force (Kip) EnterValueHere
Torque Force (ft-Kip) EnterValueHere
Drill Rod Length (ft) EnterValueHere
Select the Soil Type: SoilType

HDD MODEL
MOHMD SARIREH
Ph.D. Candidate
Department of Civil Engineering
The University of Texas at Arlington

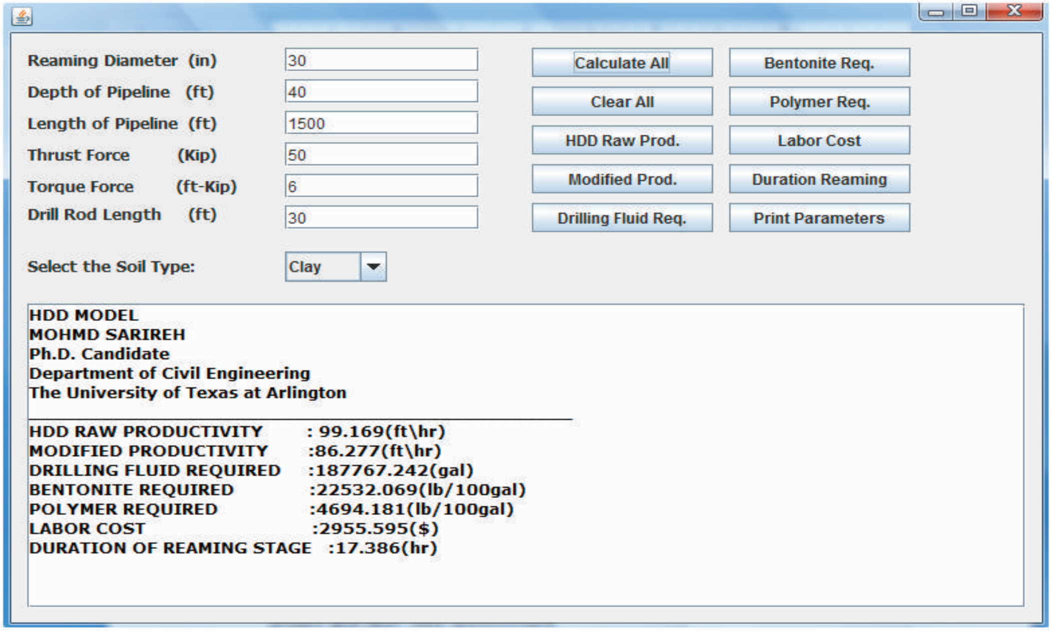
Figure 19 HDD Productivity User Interface (Sarireh and Najafi, 2011)

The calculations of the HDD user interface are organized as follow:

- Calculating HDD model productivity (ft/hr) using developed models in clayey, rocky conditions and sandy conditions.

- Calculating HDD modified productivity considering non-productive time percentage using aforementioned formula.
- Calculating duration of preream operations (hr) using the following formula:
  HDD Prereaming Duration (ft/hr) = Drive Length of Project (ft) / HDD Modified Productivity (ft/hr)
- Calculating drilling fluid required for total prereaming pass (gal) using the following formula:
  Fluid (gal) = [Fluid Pumping Rate (gpm) x 60 (min/hr) x Drive Length (ft)] / Modified Productivity (ft/hr)
- Calculating required bentonite quantity (lb) using the following formula:
  Bentonite (lb) = Drilling Fluid Required (gal) x [1/Bentonite Mixing Ratio (lb/100 gal)]
- Calculating quantity of polymer required (Ib) using the following formula:
  Polymer (lb) = Drilling Fluid Require (gal) x [1/Polymer Mixing Ratio (lb/100 gal)]
- Calculating labor cost ($) using the following formula:
  Labor Cost ($) = Labor Rate ($/hr) x [Drive Length (ft) / Modified Productivity (ft/hr)]

Figure 20 illustrates an example of HDD user interface calculations for prereaming operation using a 30 inch reamer. Clayey subconditions inputs, as well as all calculation output are shown in Java screen.



Reaming Diameter (in) 30
Depth of Pipeline (ft) 40
Length of Pipeline (ft) 1500
Thrust Force (Kip) 50
Torque Force (ft-Kip) 6
Drill Rod Length (ft) 30

Select the Soil Type: Clay

```
HDD MODEL
MOHMD SARIREH
Ph.D. Candidate
Department of Civil Engineering
The University of Texas at Arlington
________________________________________________
HDD RAW PRODUCTIVITY       : 99.169(ft\hr)
MODIFIED PRODUCTIVITY      :86.277(ft\hr)
DRILLING FLUID REQUIRED    :187767.242(gal)
BENTONITE REQUIRED         :22532.069(lb/100gal)
POLYMER REQUIRED           :4694.181(lb/100gal)
LABOR COST                 :2955.595($)
DURATION OF REAMING STAGE   :17.386(hr)
```

Figure 20 Example on HDD User Interface Calculations (Sarireh and Najafi, 2011)

Conclusions and Discussion

The main target of this paper was achieved in modeling HDD productivity for clayey and rocky conditions. For sandy conditions, only 5 cases are available to be used specifically for the related pipeline diameter, depth, length, and HDD machine force (thrust and torque). Modeling process was extended on two levels, the pilot project level and HDD questionnaire level, which resulted in a detailed analysis to refine subconditions that have significance to be used in HDD model. Mainly, five subconditions showed significant effect on HDD productivity. These subconditions included diameter of prereaming (in.), depth of borehole (ft), drilling rod length (ft), thrust force (kip), and torque (ft-kip).

Predicted HDD productivity for clayey conditions was found to be 77 ft/hr compared to average reported HDD productivity of 75 ft/hr with a validation factor of 117%. Predicted HDD productivity in rocky conditions was found to be 33 ft/hr compared to average reported productivity of 34 ft/hr with a validation factor of 105%. Average HDD productivity reported in the questionnaire in sandy conditions was calculated to be 100 ft/hr.

Modified productivity is calculated using non-productive time percent as reported in projects visited or information collected by questionnaire or interviews.

Soil conditions have the largest impact on the HDD productivity. Therefore, HDD productivity operation was first modeled on soil conditions, in addition to other subconditions.

HDD user interface is a good screen for productivity calculations using models developed for clayey and rocky conditions, and the average value for sandy conditions.

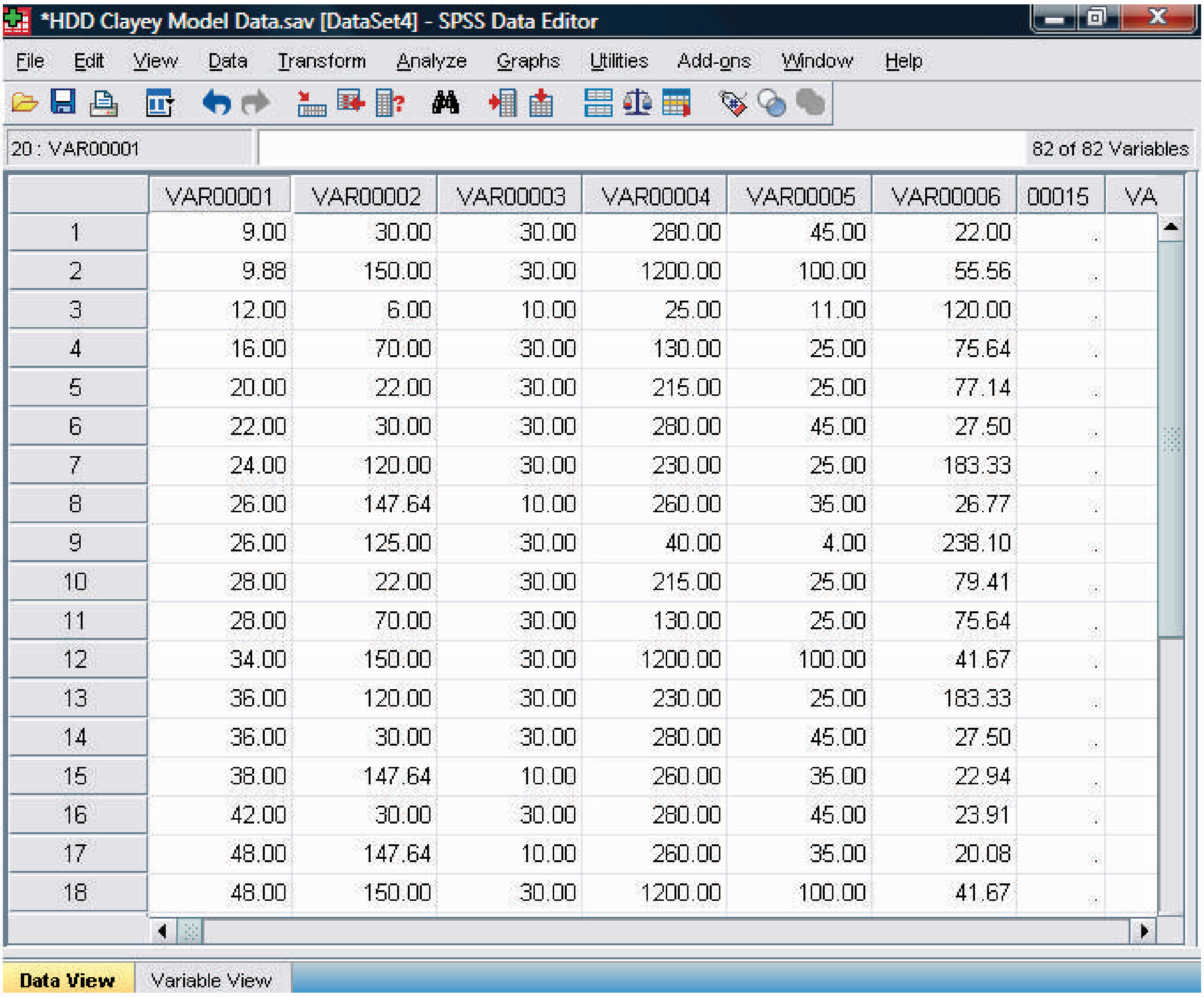
Acknowledgement

The author would like to thank Dr. Mohammad Najafi , CUIREI and construction engineering management Director at The University of Texas at Arlington for his help and guiding. Also, the thanks are directed to Tafila Technical University and staff for their support and encourage. Grate thanks are directed to the following industry professionals: Mr. Frank Canon of Baroid Industrial Drilling Products, Dr. Lawrence Slavin of Otside Plant Consulting Servies (OPCS), Mr. Eric Skonberg of Trenchless Engineering Corp., Mr. Robert Carpenter of Underground Construction Magazine, Mr. Daniel Applegate and Mr. Eric Grant of Conatser Construction, Mr. Cletus, R. Martin of Alan Plummer Associates, Inc., Mr. Bradley King of Underground Solutions, Inc., Mr. Gregg Wilder of Comtran Group, Mr. Clay Winnard of Wyo-Ben, Inc., Mr. Wesley Dunks of Atlantic Boring Company, Mr. Terry Williamson of A & L Underground, Inc., Mr. Bryan Dolan of Dolan Directional Drilling, Mr. Jonathan Faughtenberry of Chesapeake Energy, Mr. David McCallum of Trenchless Inc., Mr. Craig Danielson of Danielson Incorporated, Mr. Perry Crouse of Valley Directional Drilling, Mr. Bueler Hwang of Trans Asia Consulting & Trade Co. Ltd., Mr. Duane Brooks of Brooks Co., Mr. Charles Webb of Southwest Horizontal Drilling Services, Inc., and Mr. John Parton of Strega Company Limited.

Appendices

Appendix A1

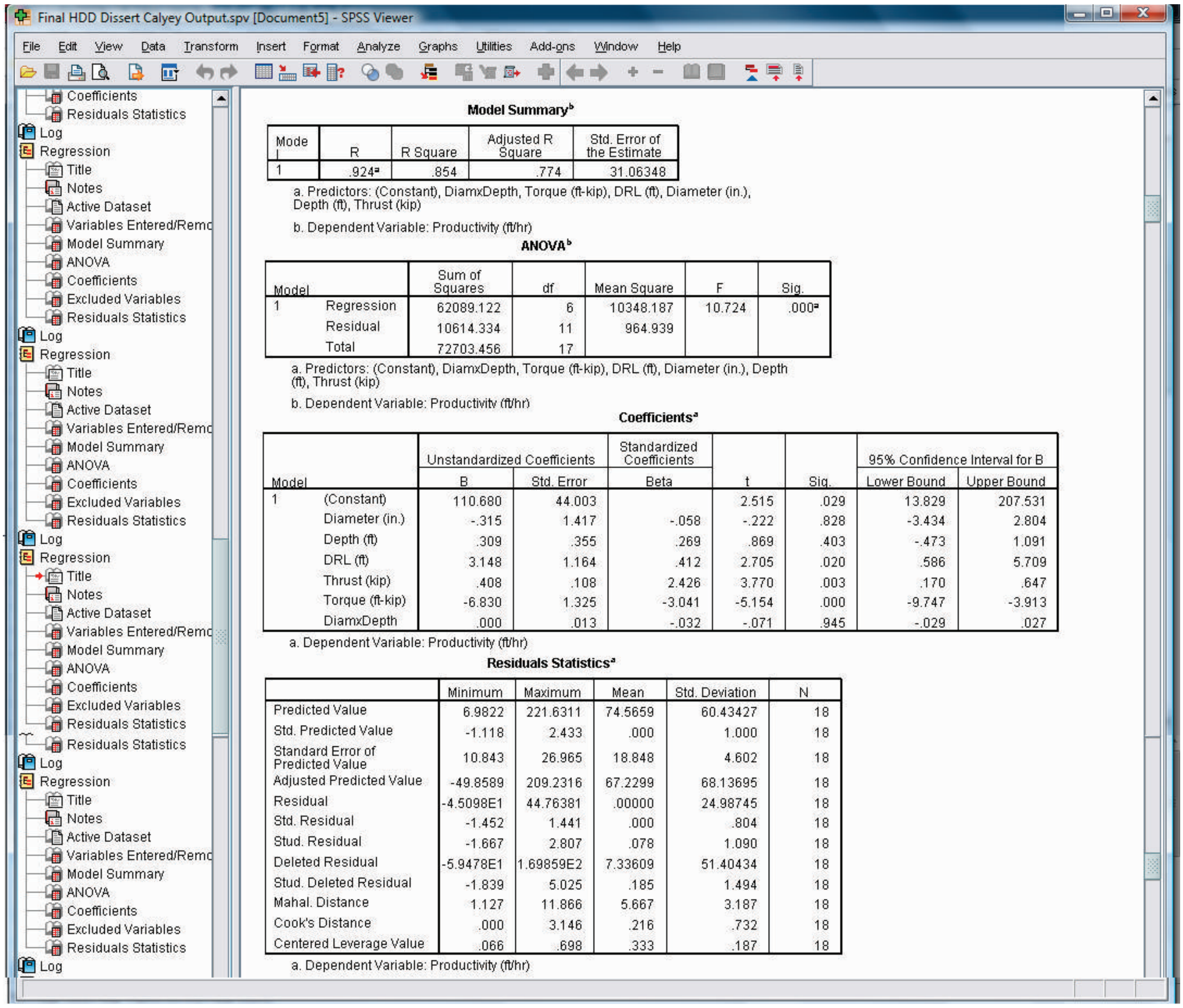
HDD PRODUCTIVITY DATA – CLAYEY CONDITIONS



	VAR00001	VAR00002	VAR00003	VAR00004	VAR00005	VAR00006	00015	VA
1	9.00	30.00	30.00	280.00	45.00	22.00	.	
2	9.88	150.00	30.00	1200.00	100.00	55.56	.	
3	12.00	6.00	10.00	25.00	11.00	120.00	.	
4	16.00	70.00	30.00	130.00	25.00	75.64	.	
5	20.00	22.00	30.00	215.00	25.00	77.14	.	
6	22.00	30.00	30.00	280.00	45.00	27.50	.	
7	24.00	120.00	30.00	230.00	25.00	183.33	.	
8	26.00	147.64	10.00	260.00	35.00	26.77	.	
9	26.00	125.00	30.00	40.00	4.00	238.10	.	
10	28.00	22.00	30.00	215.00	25.00	79.41	.	
11	28.00	70.00	30.00	130.00	25.00	75.64	.	
12	34.00	150.00	30.00	1200.00	100.00	41.67	.	
13	36.00	120.00	30.00	230.00	25.00	183.33	.	
14	36.00	30.00	30.00	280.00	45.00	27.50	.	
15	38.00	147.64	10.00	260.00	35.00	22.94	.	
16	42.00	30.00	30.00	280.00	45.00	23.91	.	
17	48.00	147.64	10.00	260.00	35.00	20.08	.	
18	48.00	150.00	30.00	1200.00	100.00	41.67	.	

Appendix A2

HDD PRODUCTIVITY MODEL – CLAYEY CONDITIONS



Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.924[a]	.854	.774	31.06348

a. Predictors: (Constant), DiamxDepth, Torque (ft-kip), DRL (ft), Diameter (in.), Depth (ft), Thrust (kip)

b. Dependent Variable: Productivity (ft/hr)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	62089.122	6	10348.187	10.724	.000[a]
	Residual	10614.334	11	964.939		
	Total	72703.456	17			

a. Predictors: (Constant), DiamxDepth, Torque (ft-kip), DRL (ft), Diameter (in.), Depth (ft), Thrust (kip)

b. Dependent Variable: Productivity (ft/hr)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	110.680	44.003		2.515	.029	13.829	207.531
	Diameter (in.)	-.315	1.417	-.058	-.222	.828	-3.434	2.804
	Depth (ft)	.309	.355	.269	.869	.403	-.473	1.091
	DRL (ft)	3.148	1.164	.412	2.705	.020	.586	5.709
	Thrust (kip)	.408	.108	2.426	3.770	.003	.170	.647
	Torque (ft-kip)	-6.830	1.325	-3.041	-5.154	.000	-9.747	-3.913
	DiamxDepth	.000	.013	-.032	-.071	.945	-.029	.027

a. Dependent Variable: Productivity (ft/hr)

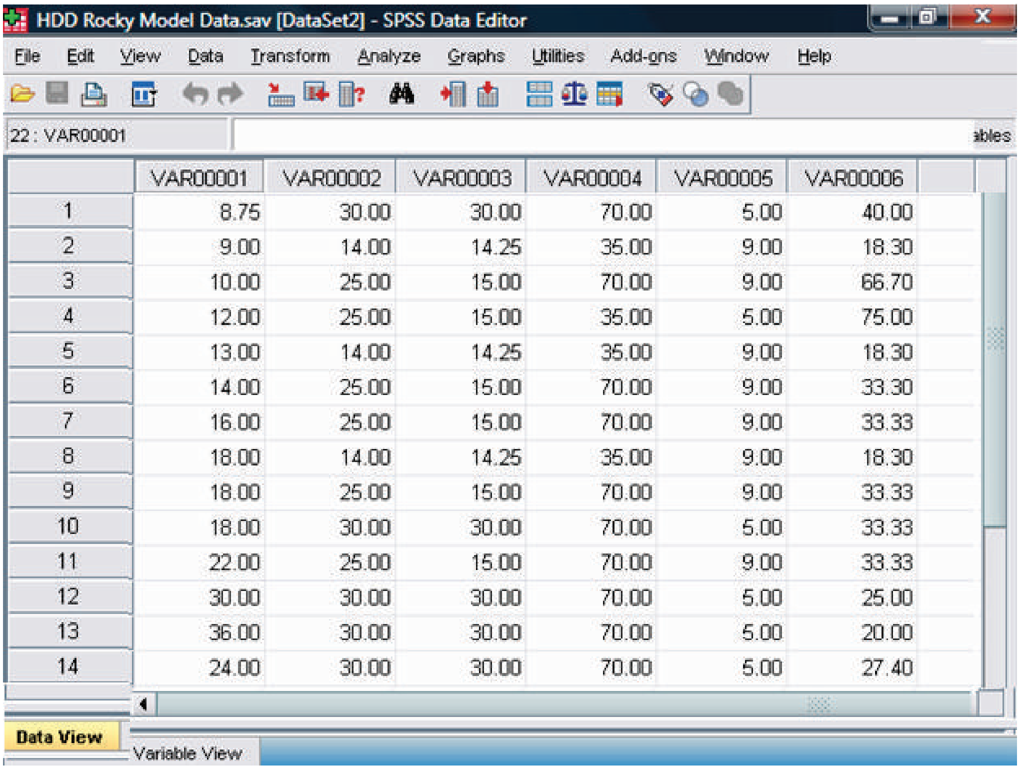
Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	6.9822	221.6311	74.5659	60.43427	18
Std. Predicted Value	-1.118	2.433	.000	1.000	18
Standard Error of Predicted Value	10.843	26.965	18.848	4.602	18
Adjusted Predicted Value	-49.8589	209.2316	67.2299	68.13695	18
Residual	-4.5098E1	44.76381	.00000	24.98745	18
Std. Residual	-1.452	1.441	.000	.804	18
Stud. Residual	-1.667	2.807	.078	1.090	18
Deleted Residual	-5.9478E1	1.69859E2	7.33609	51.40434	18
Stud. Deleted Residual	-1.839	5.025	.185	1.494	18
Mahal. Distance	1.127	11.866	5.667	3.187	18
Cook's Distance	.000	3.146	.216	.732	18
Centered Leverage Value	.066	.698	.333	.187	18

a. Dependent Variable: Productivity (ft/hr)

Appendix B1

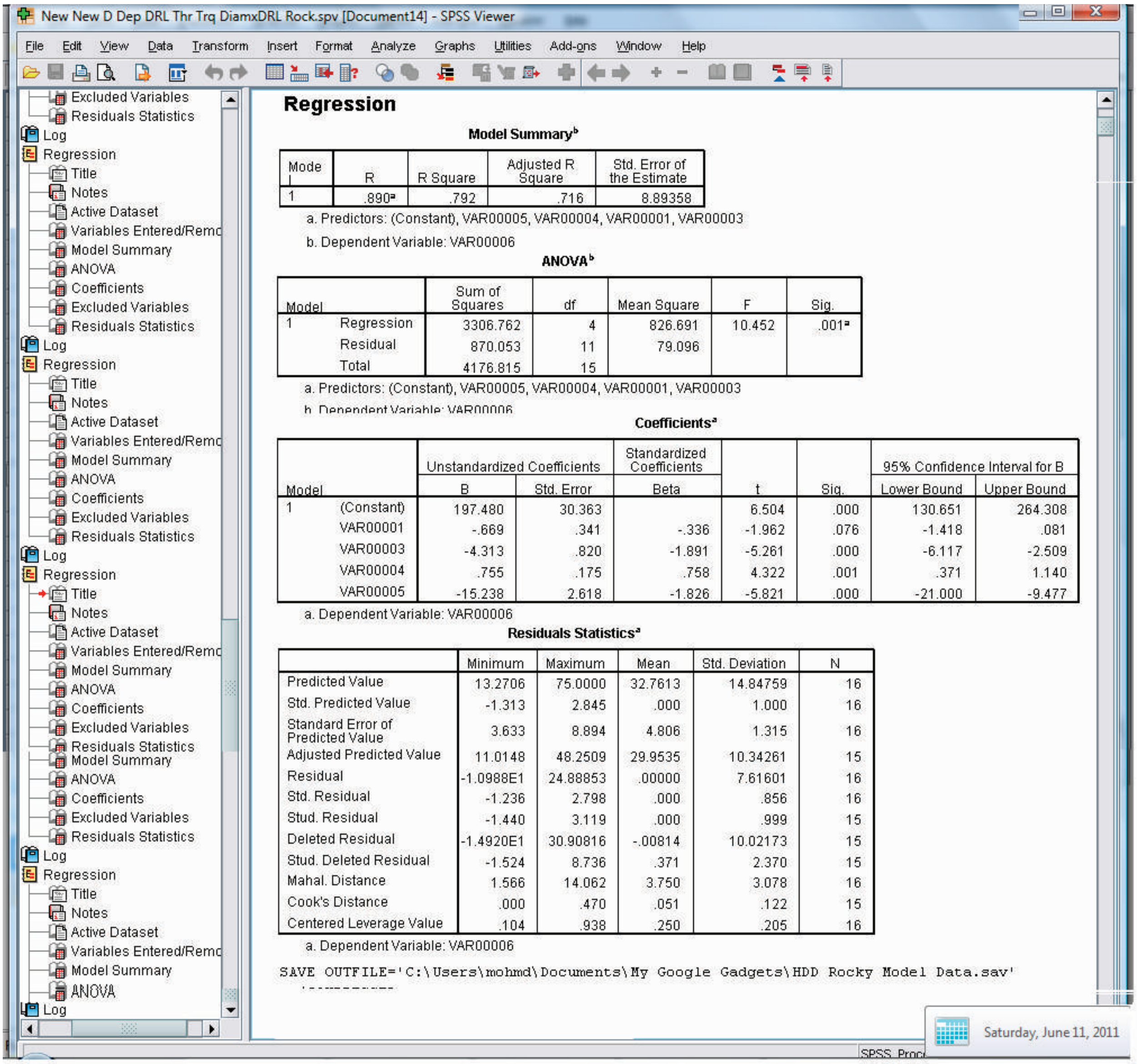
HDD PRODUCTIVITY DATA – ROCKY CONDITIONS



	VAR00001	VAR00002	VAR00003	VAR00004	VAR00005	VAR00006
1	8.75	30.00	30.00	70.00	5.00	40.00
2	9.00	14.00	14.25	35.00	9.00	18.30
3	10.00	25.00	15.00	70.00	9.00	66.70
4	12.00	25.00	15.00	35.00	5.00	75.00
5	13.00	14.00	14.25	35.00	9.00	18.30
6	14.00	25.00	15.00	70.00	9.00	33.30
7	16.00	25.00	15.00	70.00	9.00	33.33
8	18.00	14.00	14.25	35.00	9.00	18.30
9	18.00	25.00	15.00	70.00	9.00	33.33
10	18.00	30.00	30.00	70.00	5.00	33.33
11	22.00	25.00	15.00	70.00	9.00	33.33
12	30.00	30.00	30.00	70.00	5.00	25.00
13	36.00	30.00	30.00	70.00	5.00	20.00
14	24.00	30.00	30.00	70.00	5.00	27.40

Appendix B2

MODELING HDD PRODUCTIVITY – ROCKY CONDITIONS



Regression

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.890[a]	.792	.716	8.89358

a. Predictors: (Constant), VAR00005, VAR00004, VAR00001, VAR00003

b. Dependent Variable: VAR00006

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3306.762	4	826.691	10.452	.001[a]
	Residual	870.053	11	79.096		
	Total	4176.815	15			

a. Predictors: (Constant), VAR00005, VAR00004, VAR00001, VAR00003

b. Dependent Variable: VAR00006

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	197.480	30.363		6.504	.000	130.651	264.308
	VAR00001	-.669	.341	-.336	-1.962	.076	-1.418	.081
	VAR00003	-4.313	.820	-1.891	-5.261	.000	-6.117	-2.509
	VAR00004	.755	.175	.758	4.322	.001	.371	1.140
	VAR00005	-15.238	2.618	-1.826	-5.821	.000	-21.000	-9.477

a. Dependent Variable: VAR00006

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	13.2706	75.0000	32.7613	14.84759	16
Std. Predicted Value	-1.313	2.845	.000	1.000	16
Standard Error of Predicted Value	3.633	8.894	4.806	1.315	16
Adjusted Predicted Value	11.0148	48.2509	29.9535	10.34261	15
Residual	-1.0988E1	24.88853	.00000	7.61601	16
Std. Residual	-1.236	2.798	.000	.856	16
Stud. Residual	-1.440	3.119	.000	.999	15
Deleted Residual	-1.4920E1	30.90816	-.00814	10.02173	15
Stud. Deleted Residual	-1.524	8.736	.371	2.370	15
Mahal. Distance	1.566	14.062	3.750	3.078	16
Cook's Distance	.000	.470	.051	.122	15
Centered Leverage Value	.104	.938	.250	.205	16

a. Dependent Variable: VAR00006

```
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```

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