2007

Evaluation of shear strength parameters of shale and siltstone using single point cutter tests

Mahendra Shewalla

Louisiana State University and Agricultural and Mechanical College, mshewa1@lsu.edu

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses

Part of the Civil and Environmental Engineering Commons

Recommended Citation
Shewalla, Mahendra, "Evaluation of shear strength parameters of shale and siltstone using single point cutter tests" (2007). LSU Master's Theses. 800.
https://digitalcommons.lsu.edu/gradschool_theses/800

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master's Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
EVALUATION OF SHEAR STRENGTH PARAMETERS OF SHALE AND SILTSTONE USING SINGLE POINT CUTTER TESTS

A Thesis
Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in The Department of Civil and Environmental Engineering

By
Mahendra Shewalla
B.E., Osmania University, India, 2005
December 2007
ACKNOWLEDGMENTS

I express my deep sense of appreciation to my advisor Dr. Radhey S. Sharma and Co – advisor Dr. John R. Smith for their immense support and invaluable suggestion. With their knowledge and experience, they continuously guided me towards my goal of completing this work. I express gratitude for their patience, time, help and support. I am grateful to Dr. Radhey S. Sharma for his selfless support and guidance bestowed during the course of my study. I am indebted to him for the encouragement he provided.

I thank Dr. George Z. Vojiadjis for being on my committee. Special thanks to Praneeth, Bratati, Sharbari and Sandeep for being my support throughout. I am also thankful to my lab mates Ananth and Sukanta for their enormous help and for the good times we spent together.

I am indebted to my parents for their help and support throughout my career. I was fortunate to have encouragement and support from all other family members and friends. Special mention is needed for my brother, Umesh and sister, Mridula for their love and support through my entire career.

Finally, I would like to thank everyone at LSU who played their role to make my program pleasurable and successful.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS..................................................................................................................... ii

LIST OF TABLES.............................................................................................................................. v

LIST OF FIGURES........................................................................................................................... vi

ABSTRACT.......................................................................................................................................... ix

CHAPTER 1. INTRODUCTION.............................................................................................................. 1
  1.1 Introduction .............................................................................................................................. 1
  1.2 Objectives .............................................................................................................................. 2
  1.3 Thesis Outline ......................................................................................................................... 3

CHAPTER 2. LITERATURE REVIEW.................................................................................................... 5
  2.1 Introduction .............................................................................................................................. 5
  2.2 Rotary Bits .............................................................................................................................. 6
  2.3 Friction...................................................................................................................................... 9
    2.3.1 Model of a Sharp Cutter ................................................................................................. 11
    2.3.2 Model of a Blunt Cutter ............................................................................................... 12
  2.4 Single Cutting Tests ............................................................................................................... 15
  2.5 Specific Energy ...................................................................................................................... 16
    2.5.1 Specific Energy - Volume ............................................................................................. 17
      2.5.1.1 Snowdon et al. (1982) ......................................................................................... 18
      2.5.1.2 Pessier and Fear (1992) ....................................................................................... 18
      2.5.1.3 Reddish and Yasar (1996) .................................................................................... 19
      2.5.1.4 Smith (1998) ......................................................................................................... 19
      2.5.1.5 Ersoy and Atici (2003) ......................................................................................... 21
      2.5.1.6 Ersoy and Atici (2005) ......................................................................................... 22
    2.5.2 Specific Energy - Surface Area ....................................................................................... 23
    2.2.3 Specific Energy – Detournay and Tan’s Approach ....................................................... 25

CHAPTER 3. SINGLE CUTTER EXPERIMENTS CONDUCTED ON SHALES AND SILTSTONE ............ 28
  3.1 Introduction ............................................................................................................................ 28
  3.2 Shales and Siltstone .............................................................................................................. 28
    3.2.1 Mancos Shale ................................................................................................................ 29
    3.2.2 Pierre Shale .................................................................................................................... 29
    3.2.3 Catoosa Shale ............................................................................................................... 29
    3.2.4 Twin Creeks Siltstone ................................................................................................. 30
  3.3 Single Cutter Tests ................................................................................................................. 30
    3.3.1 Steady State Range ...................................................................................................... 37
  3.4 Detournay and Tan Approach ............................................................................................... 40
  3.5 Friction Angle ....................................................................................................................... 43
CHAPTER 4. RESULTS AND DISCUSSION ...............................................................50
  4.1 Introduction ...............................................................................................50
  4.2 Variation of Specific Energy with Bore Hole Pressure ...............................50
  4.3 Calculation of m from Specific Energy ......................................................54
  4.4 Calculation of Interface Friction Angle from Force Ratio .........................58
  4.5 Assessment of Internal and Interface Friction Angles ...............................62
  4.6 Quantitative Assessment of m from Internal Friction, Interface Friction Angle and
      Back Rake Angles ..................................................................................62

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS ..............................66
  5.1 Conclusions ...............................................................................................66
  5.2 Recommendations ....................................................................................67

REFERENCES ....................................................................................................69

APPENDIX: NOTATIONS ..................................................................................73

VITA ..................................................................................................................74
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3.1: Descriptive data for Outcrop Shales</td>
<td>31</td>
</tr>
<tr>
<td>Table 4.1: Variation of specific energy with bore hole pressure for Mancos shale</td>
<td>51</td>
</tr>
<tr>
<td>Table 4.2: Variation of specific energy with bore hole pressure for Pierre shale</td>
<td>51</td>
</tr>
<tr>
<td>Table 4.3: Variation of specific energy with bore hole pressure for Catoosa shale</td>
<td>52</td>
</tr>
<tr>
<td>Table 4.4: Variation of specific energy with bore hole pressure for Twin Creeks siltstone</td>
<td>53</td>
</tr>
<tr>
<td>Table 4.5: Calculation of m for Mancos shale</td>
<td>55</td>
</tr>
<tr>
<td>Table 4.6: Calculation of m for Pierre shale</td>
<td>55</td>
</tr>
<tr>
<td>Table 4.7: Calculation of m for Catoosa shale</td>
<td>55</td>
</tr>
<tr>
<td>Table 4.8: Calculation of m for Twin Creeks siltstone</td>
<td>55</td>
</tr>
<tr>
<td>Table 4.9: Calculation of interface friction angle from force ratio for Mancos shale</td>
<td>60</td>
</tr>
<tr>
<td>Table 4.10: Calculation of interface friction angle from force ratio for Pierre shale</td>
<td>60</td>
</tr>
<tr>
<td>Table 4.11: Calculation of interface friction angle from force ratio for Catoosa shale</td>
<td>60</td>
</tr>
<tr>
<td>Table 4.12: Calculation of interface friction angle from force ratio for Twin Creeks siltstone</td>
<td>60</td>
</tr>
<tr>
<td>Table 4.13: Calculation of m for Mancos shale</td>
<td>63</td>
</tr>
<tr>
<td>Table 4.14: Calculation of m for Pierre shale</td>
<td>63</td>
</tr>
<tr>
<td>Table 4.15: Calculation of m for Catoosa shale</td>
<td>63</td>
</tr>
<tr>
<td>Table 4.16: Calculation of m for Twin Creeks siltstone</td>
<td>63</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2.1: Rolling cone bit ........................................................................................................... 7
Figure 2.2: PDC drill blanks ......................................................................................................... 8
Figure 2.3: PDC bit ....................................................................................................................... 9
Figure 2.4: Specifications of PDC bit .......................................................................................... 9
Figure 2.5: Sharp cutter (after, Detournay and Defourny 1992) .............................................. 13
Figure 2.6: Blunt cutter (after, Detournay and Defourny 1992) ............................................... 13
Figure 2.7: Frictional Forces on PDC cutter (after, Detournay and Defourny 1992) ............. 14
Figure 2.8: Effect of penetration on specific energy in Gregroy sandstone (after, Snowdown et al. 1982) .................................................................................................................. 19
Figure 2.9: Graph of specific energy against uniaxial compressive strength (after, Reddish and Yasar 1996) ............................................................................................................. 20
Figure 2.10: Specific energy for various bore hole pressure (after, Smith 1998) .................... 21
Figure 2.11: Graph of specific energy against uniaxial compressive strength (after, Ersoy 2003) .................................................................................................................................................. 22
Figure 2.12: Graph of specific energy against uniaxial compressive strength for all rock (granite, andesite, limestone) types (after, Ersoy and Atici 2005) .............................................. 23
Figure 2.13: Laboratory cutting rig (Ersoy and Atici, 2005) ...................................................... 24
Figure 2.14: Plot of Specific energy against bore hole pressure (after, Detournay and Tan 2002) .............................................................................................................................................. 27
Figure 3.1: Single cutter tester (after, Zijssling 1987) ............................................................... 32
Figure 3.2: Normal cutting load on Mancos shale (after, Zijssling 1987) ............................. 33
Figure 3.3: Tangential cutting loads on Mancos shale (after, Zijssling 1987) ......................... 33
Figure 3.4: Tangential cutting load on Pierre shale (after, Zijssling 1987) ............................. 34
Figure 3.5: Normal cutting loads on Pierre shale (after, Zijssling 1987) ............................... 34
Figure 3.6: Schematic of Single Cutter Apparatus ..........................................................36
Figure 3.7: Cutter for cutting rock samples (Smith, 1998) ........................................36
Figure 3.8: Variation of specific energy over time for WB pressure 9000 psi (Smith, 1998) ......37
Figure 3.9: Single cutter test apparatus (Smith, 1998) ..................................................38
Figure 3.10: Rock sample in sample holder (Smith, 1998) ..............................................39
Figure 3.11: Sample after the experiment (Smith, 1998) ..................................................39
Figure 3.12: Cutting process of a cutter ............................................................................40
Figure 3.13: Forces obtained from single cutter tests at a confining pressure of 9000 psi (Smith, 1998) ..................................................................................................................41
Figure 3.14: Example force data from a single cutter test showing the steady state range (after, Smith 1998) ..................................................................................................................41
Figure 3.15: Sketch of cutter under down hole conditions ..............................................42
Figure 3.16: Schematic drawing of the autonomous triaxial cell ....................................43
Figure 3.17: Plan and elevation views of the cutting device ............................................44
Figure 3.18: Direct shear apparatus ..................................................................................45
Figure 3.19: Direct shear apparatus for testing of rocks (Smith, 1998) ..........................46
Figure 3.20: Comparison of direct shear and triaxial tests on Catoosa shale (after, Smith 1998) ..................................................................................................................47
Figure 3.21: Catoosa shale sample after a direct shear friction test on a PDC cutter (Smith, 1998) ..................................................................................................................47
Figure 3.22: Lower blocks with matrix, polished and standard PDC cutters (Smith 1998) ....48
Figure 3.23: Comparison of friction coefficient for different fluids ...............................49
Figure 4.1: Plot of specific energy against bore hole pressure for Mancos shale ...............52
Figure 4.2: Plot of specific energy against bore hole pressure for Pierre shale .................52
Figure 4.3: Plot of specific energy against bore hole pressure for Catoosa shale ...............53
Figure 4.4: Plot of specific energy against bore hole pressure for Twin Creeks siltstone .......53
Figure 4.5: Plot of m against bore hole pressure for Mancos shale

Figure 4.6: Plot of m against bore hole pressure for Pierre shale

Figure 4.7: Plot of m against bore hole pressure for Catoosa shale

Figure 4.8: Plot of m against bore hole pressure for Twin Creeks siltstone

Figure 4.9: Comparison of interface friction angles calculated from force ratio to the interface friction angles calculated from direct shear tests for Catoosa shale and Polished cutters

Figure 4.10: Variation of interface friction angle with bore hole pressure for Mancos shale

Figure 4.11: Variation of interface friction angle with bore hole pressure for Pierre shale

Figure 4.12: Variation of interface friction angle with bore hole pressure for Catoosa shale

Figure 4.13: Variation of interface friction angle with bore hole pressure for Twin Creeks siltstone

Figure 4.14: Comparison of m with bore hole pressure for Mancos shale

Figure 4.15: Comparison of m with bore hole pressure for Pierre shale

Figure 4.16: Comparison of m with bore hole pressure for Catoosa shale

Figure 4.17: Comparison of m with bore hole pressure for Twin Creeks siltstone
ABSTRACT

Detournay and Tan (2002) performed experiments with a rock cutting device to measure the load required to fail the rock under confining stress. They proposed models describing the correlation between the specific energy and confining stress for shear dilatant rocks as a function of unconfined specific energy at failure, cutter rake angle (θ), internal friction angle (φ) of the rock and an assumed interface friction angle (ψ) between the rock and the cutter.

The aim of this research is to evaluate the model proposed by Detournay and Tan (2002), which states that specific energy varies linearly with bore hole pressure and assumes that the interfacial friction angle (ψ) between the rock and the cutter is equal to the internal friction angle. Quantitative assessment of rate of change coefficient (m) of specific energy was accomplished to evaluate the assumption that m is constant for different bore hole pressures (p_m).

The data on Mancos shale and Pierre shale was obtained from Zijsling (1987) and for Catoosa shale and Twin Creeks siltstone, the data was obtained from Smith (1998). The analysis of results presented in this thesis show that the variation of specific energy with the bore hole pressure is non linear, whereas the conclusions of Detournay and Tan (2002) proposed a linear relationship. The results also show that the internal friction angle is not equal to the interface friction angle. The results show that rate of change coefficient (m) of specific energy estimated using Detournay and Tan’s proposed equation and an assumed internal friction is not representative of m obtained from known values of internal friction angle, interface friction angle and back rake angle.
CHAPTER 1. INTRODUCTION

1.1 Introduction

Behavior of rock under a range of confining pressures has a vital role in its applications to many engineering and scientific disciplines. The strength and stress - strain behavior of rock under confining stress is particularly important to geophysicists analyzing plate tectonics, earthquakes, and other fault movements. It is also useful to engineers designing deep foundations for buildings, off shore structures and dams on the rocks. It is significantly important for drilling engineers to understand the behavior of the rock under various confining stresses to understand the behavior of drill bits on different kinds of rocks and developing techniques for enhanced rate of penetration (RoP).

Detournay and Defourny (1992) developed a model that related the unconfined strength of a rock to the specific energy required to cut the rock. Richard et al. (1998) proposed a “scratch test” to measure the unconfined strength of the sedimentary rocks. They too related the unconfined strength to the unconfined specific energy. The proposed specific energy model by Richard et al. (1998) implies that the specific energy and the internal fiction angle of the rock can be calculated from two measurements made at different confining pressures of the specific energy used for cutting. Also, a Mohr-Columb failure model for rock allows determination of strength as a function of confining pressure if the unconfined strength and the internal friction angle of the rock are known. Therefore it is hypothesized that the Mohr-Columb strength parameters for a rock can be determined based on specific energies for cutting the rock measured at two different confining pressures.

Detournay and Tan (2002) also used a scratch test that measures the cutting load for failure of rocks under confining stress and used the measured load to calculate the specific
energy required to fail the rock. They proposed model for predicting the specific energy at failure for shear dilatant rocks as a function of the of the unconfined specific energy at failure, cutter rake angle, internal friction angle of the rock, an assumed interface friction angle between the rock and the cutter and the confining pressure. Based on the proposed models they have concluded that the specific energy ($\varepsilon$) required to cut a unit volume of the rock varies linearly with the bottom hole pressure ($p_m$) and they also suggested that the interfacial friction angle on the cutting face ($\psi$) can be assumed to be equal to the internal friction angle of the rock.

This research is intended to assess the hypothesis that a rock’s confined strength parameters can be determined based on confined cutting tests. The assessment will specifically evaluate the proposed models using data collected from literature. The data will be used to examine the assumptions made by various researchers including Detournay and Tan (2002) and to evaluate the proposed models.

1.2 Objectives

Following are the main objectives of this research:

1. To examine the validity of the assumption that specific energy varies linearly with confining pressure
2. To examine the assumption that interface friction angle equals internal friction angle.
3. To make a quantitative assessment of the theoretical relationship between interface friction angle, cutter force angle, and cutter rake angle.
4. To make a quantitative assessment of the theoretical model for calculating the rate of change coefficient for specific energy versus effective confining pressure

The aim of the research are be achieved by:
The variation of specific energy, internal and interface friction angles with bore hole pressure is examined by detailed analysis using data presented by Zijsling (1987) for Mancos shale and Pierre shale as well as data from Smith (1998) for the Catoosa shale and Twin Creeks siltstone.

The data obtained from direct shear strength tests and direct shear friction tests for the same rock samples is compared to evaluate the assumption that the internal friction angle (φ) is equal to the interface friction angle between the rock and the cutter face (ψ). The obtained results will be used for quantitative assessment of the theoretical relationship between interface friction angle, cutter force angle and cutter rake angle.

The single point cutter tests conducted at five different confining pressures ranging from 300 psi to 9000 psi will be used to quantitatively evaluate the assumption that the specific energy varies linearly with the confining pressure. Results from these evaluations will in turn be used in the quantitative assessment of the “theoretical rate of change” coefficient for specific energy versus confining pressure.

1.3 Thesis Outline

Chapter 2 of this thesis presents the literature on specific energy concepts of rock cutting and drilling. It presents the role of internal friction angle and interface friction angle in drilling process and various models for specific energy and friction. It also presents details of the PDC cutters and single point cutter tests.

Chapter 3 explains the data including the type of tests, materials and testing conditions.

Chapter 4 presents the results and discussion. It presents the results of variation of specific energy with bore hole pressure, the interface friction angles were calculated from force ratio and checked with internal friction angle to check the equality of interface friction angle to internal
friction angle and rate of change (m) with bore hole pressure was also calculated. Main conclusions and recommendations for future research are presented in chapter 5.
CHAPTER 2. LITERATURE REVIEW

2.1 Introduction
The earliest hole in the earth was dug by land dwelling members of the animal kingdom in search of food, water, protection and in building places of abode. The history of drilling can be divided into four general categories according to the equipment used: hand dug, spring tool, cable tool and rotary. Each method was replaced by a better, new method because of the demand for deeper, faster drilling. Early man used hand tools such as sticks, bones and naturally shaped stones for digging. (McCray and Cole, 1986)

Hand dug wells were literally holes in the ground dug with common hand tools such as a pick and shovel. The size of the hole allowed people to work in the bottom of the hole. Earth was picked loose, scooped up with a shovel, and thrown out of the hole. Baskets suspended from ropes were used to remove earth from deeper holes. Hand dug wells seldom exceeded 20 to 30 ft in depth because of the slow method of digging and because of caving the earth from the sides into the hole. Spring pole drilling used a long, limber pole fixed at one end and supported near the other end with a forked pole or similar support. Drilling tools were suspended from the longer, limber end of the pole by rope or wooden rods. Iron rods were used on some late spring pole rigs. The tools were reciprocated by hand or by a foot sling to provide drilling action. The need to drill deeper, faster and more economically brought about the gradual evolution of the cable tool rig from the spring pole rig. By the 1850s, most rigs were modified spring pole units. Although both the types used the same basic drilling procedure, horse or mulepower replaced manpower. The development of steam power was a significant advancement, and this in turn was replaced by the more efficient internal combustion engine. Equipment, tools and operating techniques were also developed and improved.
The need to drill deeper and faster in a safe, economical manner led to the development of the rotary rig. The rotary rig first gained prominence when it drilled the discovery well in the prolific Spindletop field in the East Texas in the early 1900s. Although rotary rigs had been used before then, the Spindletop well was one of the first high productive well that gushed oil or gas. The first rotary rigs were known as “rotaries” or “steam rigs.” These, like the cable tool rigs, were powered by engines that converted steam into mechanical work. Well boring or drilling in America had its birth during 1800 – 1860. The first well to be drilled in America for the sole purpose of producing oil for commercial use was Drake well, drilled in 1859 to a depth of 69 ½ feet near Titusville, Pennsylvania under the supervision of Colonel Edwin L. Drake (McCray and Cole, 1986). By its completion time, crude stills had been built, and the value of petroleum products as illuminants and for lubrication was known. Since then, earth’s formation has been drilled using various tools to obtain resources such as, water, coal and oil.

2.2 Rotary Bits

Rotary bits drill the formation primarily using two principles:

i. Rock removal by exceeding its shear strength

ii. Rock removal by exceeding its compressive strength

Shear failure involves the use of a bit tooth to shear, or cut, the rock into small pieces for it to be removed from the area below the bit. The simple action of forcing a tooth into the formation creates some shearing action and results in cutting development. In addition, if the tooth is dragged across the rock after its insertion, the effectiveness of the shearing action will increase. Shearing of a rock can be accomplished only when the rock exhibits low compressive strength that will allow the insertion of the tooth. Rocks with high compressive strengths generally prevent the insertion of a tooth that would have initiated the shearing action. These rocks require compressive failure mechanism be used. Compressive failure of a rock segment requires that a
load be placed on the rock that will exceed the compressive strength of that given rock type. Drag bits are the oldest rotary tool used in drilling industry. These are primarily used for soft and gummy formations. Drag bits remove the rock by shearing mechanism. In 1909, the rolling cutter rock bit was designed, built and successfully used by Howard R. Hughes (Brantly, 1971). The rolling cutter bits remove the rock by exceeding the compressive strength of the rock and generally accounted for hard formations. Figure 2.1 shows rolling cone bits.

![Rolling cone bit](image)

Figure 2.1: Rolling cone bit

The use of diamond inserts in a special bit matrix is used for various drilling formations. Diamond bits are structured differently than roller cone bits. A matrix structure is embedded with diamonds and contains waterways from the bit throat to the exterior of the bit. The rock drilling mechanism with a diamond bit is slightly different than rolling bits. The diamond is embedded in the formation and then dragged across the face of the rock without being lifted and re-embedded, as would be the case with roller cone bits. This shearing mechanism can be used in soft, medium and hard rock. Polycrystalline Diamond compact (PDC) bits are now used more often than natural diamond bits. PDC bits have several significant design features that enhance their ability to drill:
• Since it fails the rock by shearing, less drilling effort is required than the cracking, grinding principles used in roller bits.

• The lack of internal moving parts reduces the potential of bit.

• High bit weights are not required.

PDC drill bits were first introduced by General Electric Company in 1973 under the trade mark of Compax. In 1976, the same company introduced drill blanks under the trade name of Stratapax which were particularly suited for rock drilling applications. After the pioneering start, PDC’s have been developed by many companies for rock drilling applications. A PDC cutter is made of layer of polycrystalline diamond on a tungsten carbide substratum which is produced as an integral blank. The bonding of diamond to diamond in the polycrystalline layer gives high strength and thermal conductivity. The tungsten carbide backing furnishes impact strength which puts the diamond layer in compression during the formation of the composite. As a result, wear and impact properties are greatly enhanced (McCray and Cole, 1986). Figure 2.2 shows drill bit blanks.

Figure 2.2: PDC drill blanks

PDC drill bits, see Figure 2.3 for an example can be usually used successfully in soft, soft to medium – hard, and medium – hard, non – abrasive formations. A sharp PDC bit will typically drill two to three times faster than the best rolling cone cutters, but the performance of PDC cutter will gradually decrease with increasing wear, so that a worn out PDC bit can be worse than a rolling cone bit (Feenstra, 1988).
The shearing action of the drill bits equipped with drag cutters during cutting generates friction and heat between the rock/cutter interface. Friction has a significant importance in the cutting operation of drag bits. Friction induced heat between the cutter/rock interface reduces the drill bits operational life.

2.3 Friction

Frictional forces on PDC cutters were first studied by Hibbs (1983). The measurements in the study were primarily intended to be representative of friction coefficients between the wear flat
on a PDC cutter and the rock being drilled. The tests were conducted at different ranges of speeds and axial loads that were intended to be representative of field drilling conditions. Friction coefficients measured on four types of rock in five different fluid environments ranged from 0.03–0.34.

Warren and Sinor (1986), Glowka (1989), Detournay and Defourny (1992), Kuru and Wojtanowicz (1995) and Ziaja (1997), have developed force models for bits with PDC, (polycrystalline diamond compact) cutters. A common research element that all the above researchers worked on was the forces on the bit relating to the frictional forces developed by relative movement at contacts between the bit and the rock. Drill fluid is used to reduce the temperature arising from the frictional forces, and consequently, increase the operational life of the drag bits. Kuru and Wojtanowicz (1995) reported that the drilling fluid flows around the cutter and reduces the temperature by providing convecting cooling, lubricating the contact between wearflat and the rock and removing rock chips and obstructions that reduce cutting efficiency.

Kuru and Wojtanowicz (1992) conducted friction tests between the sliding surface of a polycrystalline diamond cutter and the surface of a rock. They reported that friction forces were insensitive to any change in lithology and lubricants within the tested range of materials. The rock seemed to be the controlling mechanism of friction and measured friction coefficients were independent of normal forces. A study by Kuru (1992) measured friction between a standard cutter surface and rocks under atmospheric conditions. The study observed very low frictional coefficients under all the conditions tested. The measured friction coefficients ranged from 0.06 to 0.12.

Smith et al (2002) performed tests with polished cutters and standard cutters and reported that the friction coefficient for a polished cutter is significantly less than a cutter with standard
surface finish. He performed direct shear tests on Catoosa shale samples to determine the interface friction angle of polished PDC cutter on Catoosa shale. He also conducted direct shear tests on the shale using standard PDC cutter to identify the interface friction angle between the rock surface and the cutter surface.

2.3.1 Model of a Sharp Cutter

Detournay and Defourny (1992) model a perfectly sharp cutter tracing a groove of constant cross sectional area on a horizontal rock surface, as shown in Figure 2.5. The cutter has a vertical axis of symmetry, and its inclination with respect to the vertical direction is measured by the back rake angle (θ). During cutting, a force \( F_c \) is imparted by the cutter on the rock; \( F_{cs} \) and \( F_{cn} \) denote the force components that are parallel and normal to the rock surface and it is assumed they are proportional to cross sectional area \( A \) of the cut

\[
F_c^s = \varepsilon A \quad (2.1)
\]

\[
F_n^c = \zeta \varepsilon A \quad (2.2)
\]

\( \varepsilon \) is defined as the intrinsic specific energy and it characterizes the pure cutting action, without any loss of specific energy due to friction. \( \zeta \) is the ratio of vertical to horizontal force acting on the cutting face. The two quantities specific energy and drilling strength are defined as

\[
E \equiv \frac{F_c}{A} \quad (2.3)
\]

\[
S \equiv \frac{F_n}{A} \quad (2.4)
\]

Then, for a perfectly sharp cutter

\[
E = \varepsilon \quad (2.5)
\]

\[
S = \zeta \varepsilon \quad (2.6)
\]
Equation 2.5 and 2.6 represents the amount of total energy used to cut a unit volume of rock which is equal to the intrinsic specific energy. Figure 2.5 shows a sketch of sharp cutter and the forces it imparts on the rock.

**2.3.2 Model of a Blunt Cutter**

For a blunt cutter, additional frictional must be considered. The cutter force \( F \) is split into two vectorial components: \( F^c \) transmitted by the cutting face and \( F_f \) acting at the interface of the cutter wear flat and the rock, see Figure 2.6. It is assumed that the cutting components \( F^c_n \) and \( F^c_s \) obey the relations postulated for a perfectly sharp cutter. It is further assumed that a frictional process is taking place at the interface between the cutter and the rock; thus the components \( F^f_n \) and \( F^f_s \) are related by

\[
F^f_s = \mu F^c_n \tag{2.7}
\]

Sum of horizontal force component

\[
F_s = F^c_s + F^f_s \tag{2.8}
\]

Sum of vertical force component

\[
F_n = F^c_n + F^f_n \tag{2.9}
\]

Substituting \( F^f_n \) as \( (F_n - F^c_n) \) and using equation (2.8), \( F_s \) can be expressed as

\[
F_s = (1 - \mu \zeta) eA + \mu F_n \tag{2.10}
\]

Dividing the above equation by ‘\( A \)’, the specific energy and drilling strength are obtained as

\[
E = E_0 + \mu S \tag{2.11}
\]

where, \( E_0 = (1 - \mu \zeta) e \) \tag{2.12}

Figure 2.6 shows a sketch of blunt cutter with the forces acting it imparts on the rock.
Friction that acts on the face of the cutter is less recognized in the literature, which would cause the force shown as $F_{ff}$ in the Figure 2.7. This force stems from the contact of cutter face with both the rock being sheared in front of the cutter and the broken rock, or cutting, being pushed up the face of the cutter. In some cases, the cutting may continue to contact the bit structure supporting the cutter, such as the blade above the cutter, causing friction on that surface as well.

Figure 2.5: Sharp cutter (after, Detournay and Defourny 1992)

Figure 2.6: Blunt cutter (after, Detournay and Defourny 1992)
Laboratory experiments by Smith (1995) and Smith (2000) on full size bits and single cutter bits have demonstrated the effect of frictional forces on the face of the cutter and also documented the severity of the buildup of cutting on the face of the cutter for different cutter surfaces. The buildup of cuttings on the cutter face is termed as cutter balling. The presence of cutter balling is due to the friction on the cutter face and provides evidence of forces being transmitted from the cutter face through the cutter ball to the rock surface.

Smith et al. (2002) conducted direct shear tests to study the affect of frictional forces on the PDC cutter face. They measured the shear stresses and normal stresses between rock and the contact surface of the PDC cutter to obtain the friction on the cutters.

Figure 2.7: Frictional Forces on PDC cutter (after, Detournay and Defourny 1992)

The impact of PDC cutter wear has been investigated using single cutters (Glowka (1982), Hibbs and Sogoian (1983), Lee and Hibbs (1979), Zijssling (1987), Smith (1998)), laboratory experiments with full scale prototype bits (Warren and Armagost (1986), Hoover and Middleton (1987)) and field tests with full scale bits (Cheatham and Leob (1987), Sinor and Warren (1987), Cortez and Besson (1981)).
2.4 Single Cutting Tests

A single cutter apparatus is a powerful research tool for studying the cutting process of PDC cutter under simulated downhole conditions and providing input for PDC bit development (Zijsling, 1987). Single cutter tests on the rock samples enable the operating conditions and the simulated downhole conditions during the cutting test to be controlled to a higher degree of precision than field testing methods. Under these conditions, high quality information regarding the cutting process can be generated, such as normal and tangential forces and the cutting depth. The data acquisition generated from single cutter testing can serve as a key input in developing models for field testing methods (PDC cutters). Zijsling (1987) used single cutter tester on Mancos shale and Pierre shale for a depth of cut of 0.15 and 0.3 mm with a back rake angle of 20˚. He conducted the tests to study the effect of downhole pressures on the cutting process in shales. He concluded that only the total bottomhole pressure was influencing for the cutting process in Mancos shale.

Cheatam and Daniels (1979) performed single cutter tests at high depth of cut, but only in oil based fluid at atmospheric conditions and at moderate confining pressures, and at a slow cutter speed of 0.78 inch/second. They employed Mancos shale and Pierre shale. They conducted experiments to define conditions wherein these kinds of shales can be effectively drilled, to determine causes of difficulty in drilling under adverse conditions.

Smith (1998) performed single cutter testing on Catoosa shale. The single cutter test apparatus was similar to the one described by Zijsling (1987). He used single cutter tests to identify the slow drilling problems in shales. He concluded that global bit balling is the major cause of the problem. He measured the normal and tangential forces acting on the cutter in his experiments. The measured normal and tangential forces were used to calculate the energy used to cut the rock, generally known was specific energy.
2.5 Specific Energy

Specific energy is a significant measure of drilling performance, especially of the cutting efficiency of bits and rock hardness. Specific energy quantifies a complex process of rock destruction and generally depends on various factors, such as rock type, the rake angle of the cutter, the cutter material, and pressure on the rock surface. In rotary drilling, specific energy is defined as the amount of work done for cutting a unit volume of rock, and in percussive drilling, specific energy is calculated by considering the surface area of the broken rock and left over rock during pounding. Many researchers have formulated equations to calculate the specific energy for a known volume of cut.

The concept of specific energy in rotary drilling was first introduced by Teale (1965). He suggested that the work done per unit volume of broken rock relates the process to the physical properties of rock, such as compressive strength of the rock. After Teale (1965), research in this area has been carried further by Peshalov (1973), Pessier and Fear (1992), Reddish and Yasar (1996), Smith (1999), Detournay and Tan (2002), and Ersoy and Atici (2005).

In the literature the specific energy is defined in two ways:

- As, the energy required to remove a unit volume of rock (Teale 1965)
- As, the energy required to generate a new surface area (Paithankar and Misra 1976)

Teale (1965) defined the specific energy required to remove a unit volume of the rock in rotary drilling. Scholars (Snowdon et al. 1982, Reddish and Yasar 1996, Smith 1999, Ersoy and Atici 2005) also related the specific energy to remove a unit volume of the rock. Paithankar and Misra (1976) accounted the definition of specific energy in terms of surface area, as the energy consumed to generate a new surface area in percussive drilling. The new surface area generated was obtained from the difference of the total surface area of particles after pounding and the total
surface area of chunks used. The concept of obtaining specific energy from surface area is generally applied in percussive drilling.

None emphasized on attaining the specific energy in terms of new surface area created in rotary drilling. The specific energy is an independent property and it does not depend solely on the properties of the rock per Snowdon et al. 1982. However, Reddish and Yasar 1996, Smith 1999, Detournay 2002 and Ersoy 2003 have found the correlation of the specific energy to the rock properties such as compressive strength and hardness of the rock. In the following sections specific energy defined in terms of volume of the rock cut, surface area of the rock is discussed. An approach presented by Detournay and Tan (2002) is emphasized.

### 2.5.1 Specific Energy - Volume

Teale (1965) introduced the concept of minimum specific energy required to remove a volume of rock in rotary drilling of rocks. The total amount of work done for excavating a volume \((Au)\) of rock is \((Fu + 2\pi NT)\). Specific energy is obtained by dividing the work done by the volume and is given as:

\[
e = \frac{F}{A} + \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right)
\]  

(2.13)

where, \(e\) is the specific energy, \(F\) is the thrust, \(T\) is the torque, \(N\) is the rotation speed, \(u\) is rate of penetration and \(A\) is the area of hole or excavation.

He used \(t\) and \(r\) as subscripts of \(e\) to denote the thrust and rotary components.

\[
e_t = \frac{F}{A}
\]  

(2.14)

\[
e_r = \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right)
\]  

(2.15)

Equation 2.12 can be rewritten as:
\[ \mathcal{E} = \mathcal{E}_t + \mathcal{E}_r \]  

(2.16)

He concluded, the specific energy cannot be represented by a single, accurate number since the drilling process is characterized by wide fluctuations of the drilling variables due to its complex dynamics and the heterogeneous nature of rock.

2.5.1.1 Snowdon et al. (1982)

Snowdon et al. (1982) performed single disc cutter tests on blocks of sandstone, limestone, dolerite and granite. The tests investigate the mechanical cutting characteristics of the rocks. They related the specific energy required to cut a rock in tunnel drilling to the ratio of disc spacing of the cutter and penetration of the cut. The formula used for specific energy calculation is given as:

\[ \text{Specific energy} = \frac{(\text{Mean rolling force } \times \text{length of cut})}{(\text{weight of debris / rock density})} \]  

(2.17)

They concluded, as the penetration increased the specific energy decreased asymptotically indicating that there is a critical penetration value beyond which there will be no significant improvement in specific energy, see Figure 2.8.

2.5.1.2 Pessier and Fear (1992)

Pessier and Fear (1992) modified the equation proposed by Teale (1965), as

\[ \varepsilon_s = \frac{WB}{A_B} + \frac{120\pi NT}{A_B R} \]  

(2.18)

\( \varepsilon_s \) is the specific energy; WB is the weight of the bit; R is rate of penetration; T is torque on bit; N is revolutions per minute; \( A_B \) is the area of the bit.

They performed constant penetration tests on Mancos shale. They drilled a selected length at a constant rate of penetration and bore hole conditions. They concluded, that for most cases, the
specific energy $\varepsilon_s$ increased with increasing rate of penetration. They also reported that the increase in specific energy was proportional to the increase in bottom hole pressure.

### 2.5.1.3 Reddish and Yasar (1996)

Reddish and Yasar (1996) analyzed the relation of the uniaxial compressive strength to the specific energy of cut for various rocks and proposed Equation 2.19 relating the specific energy (S.E) to the uniaxial compressive strength (U.C.S) of the rock.

$$S.E = 9.9278 \times (U.C.S) - 73.791 \quad (2.19)$$

They reported a linear increase of specific energy with an increase of uniaxial compressive strength. They stated that the efficiency of drilling depends on power and thrust, physical size, mode of breakage, bit geometry and bit sharpness. Of these factors, the bit sharpness and available power have most influence on the tests conducted.

### 2.5.1.4 Smith (1998)

Smith (1998) wrote an equation for specific energy in terms of the forces acting on a cutter to remove a unit volume of rock. The work done is given by $(F_N D + F_T \pi d)$ and the volume of rock is $(\pi d D w)$. Dividing work done by volume of rock gives:

![Figure 2.8: Effect of penetration on specific energy in Gregroy sandstone (after, Snowdown et al. 1982)](image-url)
Figure 2.9: Graph of specific energy against uniaxial compressive strength (after, Reddish and Yasar 1996)

\[
\varepsilon_s = \frac{F_N}{\pi dw} + \frac{F_T}{Dw}
\]  

(2.20)

\(\varepsilon_s\) is the specific energy, \(F_N\) is normal force, \(F_T\) is the tangential force, \(d\) is the diameter of the path of cutter, \(D\) is depth of cut, \(w\) is the width of the cutter.

He performed single cutter tests on Catoosa shale to study the cause of poor PDC bit performance in deep, overpressured shales. The study was performed to describe the slow drilling shale problem and to identify the characteristic symptoms of the actual problem in the field and to match them to the symptoms resulting from different possible causes in controlled tests. The tests allowed differentiation of the possible causes of slow drilling and it was observed that the global bit balling was the principal cause of the slow drilling shale problem.

He conducted the experiments on a 3.5 inch diameter sample. The normal and tangential loads were recorded and used to calculate the specific energy. He also obtained a correlation between the specific energy and confining pressure (well bore pressure). He increased the well bore pressure in increments to know its affect on the specific energy. He concluded that specific
energy $\varepsilon_s$ increases with well bore pressure. The increase in specific energy with well bore pressure reflects the importance of well bore pressure on bit performance. Figure 2.10 shows the variation of specific energy against bore hole pressure.

![Figure 2.10: Specific energy for various bore hole pressure (after, Smith 1998)](image)

**2.5.1.5 Ersoy (2003)**

Ersoy (2003) evaluated the optimum performance of polycrystalline diamond compact (PDC) and Tungsten carbide (WC) bits using a criterion based on maximum feed rate at minimum specific energy required to drill. Various coal–measure rock types were drilled using PDC and WC bits using a fully instrumented and automatic drilling rig at six different rotational speeds and an over range of thrust applied to the bit. A constant level of power was maintained at the bit in order to maximize the feed rate and minimize the rate of bit wear. During drilling; thrust, rotating speed, the feed rate and the torque was monitored and were used with Equation 2.21 to obtain the specific energy.

$$S.E = \frac{F}{A} + \frac{2\pi NT}{AR}$$  \hspace{1cm} (2.21)
F is the thrust; T is the torque; N is the revolutions/min; A is the area of the hole; R is the feed rate.

![Graph of specific energy against uniaxial compressive strength](image)

**Figure 2.11:** Graph of specific energy against uniaxial compressive strength (after, Ersoy 2003)

**2.5.1.6 Ersoy and Atici (2005)**

Ersoy and Atici (2005) performed cutting tests on rocks with diamond disk saws, see Figure 2.13, with different feed rates and cutting depths at constant velocity. The relationship between the specific cutting energy of the saw blade operating parameters and rock properties was established. Multivariable linear regression analysis was applied to obtain the predictive model of specific energy based on rock property data.

The specific energy was calculated based on the amount of energy required to remove a given volume of rock. The specific energy of cutting was calculated from Equation 2.22.

\[
SE_{cut} = \frac{P_c}{Q_w} = \frac{F_T V_p}{H_c W_M V_f}
\]  (2.22)

Where \(P_c\) is the required motor power for cutting rock; \(Q_w\) is the cutting volume (rate/time); and \(W_M\) is the segment width, \(F_T\) is the tangential force on the cutter, \(V_p\) is the peripheral velocity, \(V_f\) is the feed rate, \(H_c\) is the cutting depth.
They concluded that the results from the diamond saw cutter trials showed that increase in the cutting depth decreases specific energy down to some point. However, a further increase in the cutting depth causes constant or little decrease or even increases specific energy in some cases. They also concluded a good relationship between the cutting performance in terms of specific energy and physical and mechanical rock properties, like, compression resistance, relative abrasion resistance and abrasivity factor F. The use of statistical multivariable linear regression analysis to evaluate the combined effects of rock characteristics on cutting performance gave a feasible method for predicting the cuttability or rocks by circular diamond saws.

![Graph of specific energy against uniaxial compressive strength for all rock (granite, andesite, limestone) types (after, Ersoy and Atici 2005)](image)

**Figure 2.12**: Graph of specific energy against uniaxial compressive strength for all rock (granite, andesite, limestone) types (after, Ersoy and Atici 2005)

### 2.5.2 Specific Energy - Surface Area

The application of surface area concept to the specific energy has seen little progress in the past. Specific energy in terms of surface area was obtained only in percussive drilling and no emphasis was made on obtaining the specific energy in terms of the new surface area generated in rotary drilling (Paithankar and Misra 1976).
Protodyakonov (1962) proposed to evaluate the mechanical properties of rocks by means of relative strength coefficient, also called Protodyakonov index (f). It is a simple rock characteristic for predicting rock drillability in percussive drilling.

He established an empirical relation between strength of the rock at uniaxial compression in percussive drilling and the Protodyakonov index as:

\[ \sigma \equiv 1050 \frac{f}{\sqrt{(154/h) - 1}} \]  \hspace{1cm} (2.23)

![Figure 2.13: Laboratory cutting rig (Ersoy and Atici, 2005)](image.png)

Protodyakonov index (f) \equiv \frac{20n}{1} \hspace{1cm} (2.24)
where \( n \) is number of impacts of the drop weight on each sample, \( h \) is the shore hardness, determined by the rebound of the hammer head of the shore scleroscope from a polished surface of rock lump.

However, the accuracy of the protodyakonov index is susceptible to the duration of sieving and degree of compaction of the fines in the volumometer which depends on the number of blows. Also, it varies with the number of blows for the same rock depending on the hardness of the rock, as in the case of soft rocks, there may be regrinding of fines while in hard rocks the energy may be utilized in elastic deformation and cracking of particles without generating enough fines. Due to these defects in measurement of Protodyakonov index, Paithankar and Misra (1976) accounted for establishing a more reliable index such as specific energy. They defined specific energy in terms of surface area, as the energy consumed to generate a new surface area in percussive drilling. The new surface area generated was obtained from the difference of the total surface area of particles after pounding and the total surface area of chunks used. Specific energy was then calculated by dividing the total energy of pounding by the total new surface area produced. They concluded that the specific energy offers itself as a more consistent rock strength index over protodyakonov index, since it gives a constant value irrespective of mass of assay, size of chunks and number of poundings over a wide range.

Wootton (1974) observed that in drop hammer tests the relationship between energy input and new surface area produced is always linear. However for slow compression tests, it was reported that energy input against new surface area generated predicted a slight curved decrease.

2.2.3 Specific Energy – Detournay and Tan’s Approach

Detournay and Tan (2002) proposed an equation relating the specific energy for cutting a rock to the bore hole pressure and the unconfined compressive strength of the rock as implied from specific energy at atmospheric conditions as
\[ \varepsilon = \varepsilon_0 + m(\theta, \phi, \psi)(p_m - p_b) \quad (2.25) \]

\( \varepsilon_0 \) denotes the specific energy under atmospheric conditions; \( p_m \) is the bore hole pressure (confining pressure), \( p_b \) is the virgin pore pressure and \( m(\theta, \phi, \psi) \), see Equation 2.26 is a function of cutter rake angle (\( \theta \)) of the cutter, internal friction angle (\( \phi \)) of the rock and friction angle (\( \psi \)), see Equation 2.28 at the cutting face/failed rock interface and is given as

\[ m = \frac{2 \sin \phi \cos(\theta + \psi)}{1 - \sin(\theta + \phi + \psi)} \quad (2.26) \]

where,

\[ \psi = -\tan^{-1}\left(\frac{F_y}{F_x}\right) - \theta \quad (2.27) \]

Where \( F_y \) is the normal force component and \( F_x \) is the tangential force component.

He reported that the specific energy is independent of the differential pressure (\( p_m - p_b \)) for shale, as \( \varepsilon \) is independent of \( p_b \) under conditions of shale being shear dilatant and is only dependent on the bore hole pressure(\( p_m \)). The above equation is reduced to

\[ \varepsilon = \varepsilon_0 + m(\theta, \phi, \psi)p_m \quad (2.28) \]

The above condition may not be true for all rocks. He concluded that the increase in confined compressive strength increases the specific energy required to remove the rock. He assumed that the internal friction angle (\( \phi \)) is equal to the friction angle between the cutter and the rock surface (\( \psi \)). Figure 2.14 shows the variation of specific energy for well bore pressure as measured by Detournay and Tan (2002).

It was observed that interface friction angles calculated from Equation 2.27 were negative, so Equation 2.27 was rewritten as:

\[ \psi = -\tan^{-1}\left(\frac{F_y}{F_x}\right) - \theta \quad (2.29) \]
Figure 2.14: Plot of Specific energy against bore hole pressure (after, Detournay and Tan 2002)
CHAPTER 3. SINGLE CUTTER EXPERIMENTS CONDUCTED ON SHALES AND SILTSTONE

3.1 Introduction
Single cutter experiments are full scale laboratory tests used to study the performance of PDC cutter in field. This chapter describes the experiments done by Zisjsling (1987) and Smith (1998) that were used for this study. Zisjsling (1987) conducted single cutter tests on Mancos shale and Pierre shale to understand the drilling process of PDC cutters on these shales. Smith (1998) conducted single cutter experiments on Catoosa shale and Twin creeks siltstone to identify the slow drilling with PDC bits in deep shales. The methodology of these cutting experiments on different kinds of shales and siltstone will be discussed in detail in this chapter. The data obtained from their results is used to achieve the objectives of this research. Detournay and Tan’s (2002) approach of defining the specific energy and friction tests conducted by Smith (1998) are also discussed in this chapter.

3.2 Shales and Siltstone
Shale is a fine grained sedimentary rock which is formed due the compression of clays or mud. It is characterized by thin laminae breaking with an irregular curving fracture, often splintery and usually parallel to the often-indistinguishable bedding plane. This property is called fissility. Potter (1980) defined shale as the major class name for fine grained terrigenous rock. Terrigenous rocks are generally obtained from the breakdown of crystalline igneous rocks. He also defined shales as sediment composed of clays and a variety of other fine grained compounds. Sedimentary rocks that are predominantly fine grained (grain size less than 75 micrometers) are termed as shale. These definitions include the full spectrum of fine grained clastics from siltstones to claystones and the more common rocks that are fissile or laminated and include both clay and silt fractions.
Siltstone is a hardened sedimentary rock that is composed primarily of angular silt-sized particles and that is not laminated or easily split into thin layers. Siltstones, which are hard and durable, occur in thin layers that are rarely thick enough to be classified as formations. They are intermediate between sandstones and shales but are not as common as either. Siltstone is primarily composed of silt sized particles, ranging from 3.9 to 62.5 micrometers. Siltstones have smaller pores compared to sandstones and contain a significant clay fraction.

3.2.1 Mancos Shale

Mancos shale is named from occurrence in Mancos Valley and around town of Mancos, between La Plata Mountains and Mesa Verde, Montezuma Co., Colorado. It is a fine grained sedimentary rock with clay as its original constituent. It has high quartz content and is considered as a strong rock.

3.2.2 Pierre Shale

The Pierre Shale is an upper Cretaceous marine formation, which is well known for its ammonite fossils. Pierre shale has more porosity and usually more clay content than Mancos shale. In particular, it has much higher smectite content. Because smectites swell, they are frequently considered the cause of bit balling during drilling. Its high porosity, total clay and smectite contents are suitable for the upper end of the desired range of characteristics representing field shales.

3.2.3 Catoosa Shale

The Catoosa shale is a Pennsylvanian age, marine shale. Catoosa shale has the advantages of being relatively easy to store and handle, relatively inexpensive, and capable of causing bit balling. The Catoosa shale was selected as the primary medium for the direct shear and single cutter tests by Smith (1998).
3.2.4 Twin Creeks Siltstone

The Twin Creek formation is “a siltstone to very fine sandstone, cemented by a carbonate material.” Quartz is the dominant terrigenous component along with significant potassium feldspar and plagioclase. Carbonates are present as both the cement and as grains.

Table 3.1 presents a data containing mineralogy of the shales and siltstone discussed above.

3.3 Single Cutter Tests

Zijsling (1987) conducted single cutter tests on Mancos shale and Pierre shale to understand the cutting process of PDC cutters in shales. His single cutter apparatus used a pressure vessel to contain the rock sample. The sample was held between two end plates, one of which was connected to the top plug of the vessel. The cylindrical face of the sample was sealed with a rubber sleeve and three chambers were created in the pressure vessel to independently apply overburden, confining and well bore pressures on the sample. Oil and water based fluids were applied from well bore pressure chamber, which were used as a pressure medium. The cutter shaft was connected to the top plug, and a load cell was mounted on the cutter shaft to record the drag force, normal force and side force acting on the cutter and the torque associated with the forces. The cutter shaft was rotated by an electric motor, and the translation of the shaft was provided by a hydraulic servo system, which was able to run either in load control or displacement control mode. The control system enabled the cutting tests to be carried out over a multitude of revolutions in the flat top face of a sample (right – hand side of centre line in Figure 3.1) or in a predrilled sample (left – hand side of the centre line in Figure 3.1).

Prior to each test, the operating conditions to be simulated and the number of revolutions to be transversed by the cutter during the tests were programmed. A quick stop feature was used to stop the cutting process after a desired level of cut had been achieved, which enabled visual inspection of the pressure vessel.
Table 3.1: Descriptive data for Outcrop Shales

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Age</th>
<th>XRD Mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Qz</td>
</tr>
<tr>
<td>Mancos</td>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>Pierre</td>
<td>Cretaceous</td>
<td>50</td>
</tr>
<tr>
<td>Catoosa</td>
<td>Pennsylvanian</td>
<td>35</td>
</tr>
<tr>
<td>TC Siltstone</td>
<td>Jurassic</td>
<td>50+</td>
</tr>
</tbody>
</table>

Legend
Qz: Quartz
Fs: Feldspar
Ca: Calcite
Do: Dolorite
Si: Siderite
Py: Pyrite
Ch: Chlorite
Ka: Kaolinite
Il: Illite
Sm: Smectite
ML: Mixed layers
MI: ML Illite
MS: ML Smectite
During each test, the pressures, cutting forces, cutter position were recorded by an analog tape recorder. After a series of test were done, the analog tape recorder was connected to the computer provided with an A – D converter and was played at a reduced speed, which allowed the computer to analyze and process the results. During testing, no pore pressure was applied to create controlled pressure was incorporated. Figure 3.1 shows the single cutter tester used by Zijssling (1987).

The tests were initiated on cylindrical samples of 133 mm diameter x 72 mm long. The tests were carried out using a square cutter of size 10 mm x 10 mm set at a back rake angle of 20° and for constant depths of cut of 0.15 mm and 0.3 mm. The samples were conditioned to depths of 2100, 3000 and 3500 meters before being used for testing. The tests were carried out for various well bore pressure levels. The tests were carried out in Mancos shale at a cutting speed of 0.5 m/s. The cutting forces $F_N$ and $F_D$ were recorded for different specified time intervals and for different well bore pressures.

![Figure 3.1: Single cutter tester (after, Zijssling 1987)](image-url)
Figures 3.2 and 3.3 show the plots of $F_N$ and $F_D$, respectively for different well bore pressures for a depths of cut of 0.15 mm and 0.3 mm for Mancos shale. Figures 3.4 and 3.5 show the tangential force ($F_D$) and normal force ($F_N$), respectively plotted against the well bore pressure for Pierre shale for 0.3 mm depth of cut. Note that much smaller loads were required to break Pierre shale.

Figure 3.2: Normal cutting load on Mancos shale (after, Zijlslng 1987)

Figure 3.3: Tangential cutting loads on Mancos shale (after, Zijlslng 1987)
This research included data for Catoosa shale at different well bore pressures (300, 1000, 3000, 6000, 9000 psi) for a cutting depth of 0.075 inch and for Twin Creeks siltstone at well bore pressure of 1000 and 9000 psi for a cutting depth of 0.011 inch. Data on Pierre shale was not used as the tests at different depths of cut were conducted at one well bore pressure i.e 9000 psi.
Smith (1998) conducted single cutter experiments on Catoosa shale, Pierre shale and Twin Creeks siltstone to understand the cause of slow drilling in deep shales. He also conducted direct shear tests of friction between Catoosa shale and PDC using oil, water or mud at the contact surface as the fluid. The single cutter test apparatus was similar to the one described by Zijsling (1987). He reported that “the single cutter tester consisted primarily of a pressure vessel to contain a rock sample under simulated wellbore conditions and a rotary drive mechanism to rotate and advance a single cutter into the rock. Tests were performed at two or more depths of cut to represent penetration rates equivalent to both efficient and inefficient drilling. The majority of tests were performed at 0.011 inch and 0.075 inch depths of cut and 273 rpm. The cutters for the single cutter tests were trimmed to width of 0.37 inch, or about 70 percent of their original diameter.”

Well bore pressure, depth of cut per revolution, total axial cutter travel, rotary speed, and load limits were controlled during the test, and the width of cutter \(w\) and total depth of cut \(D\) were set before the start of the test. The axial load \(F_N\) and tangential load \(F_T\) applied to reach the total depth of cut were measured. The specific energy was then calculated using the Equation proposed by Smith (1998). The same principle was applied to obtain the specific energy for different well bore pressures. The test cell was filled with pressurized fluid to simulate conditions in the wellbore. A schematic diagram showing the operational concept of the apparatus is shown in Figure 3.6. Figure 3.7 shows the cutter used for cutting process. Preparation for a test involved mounting a 3.5 inch diameter rock sample in a sample holder as shown in Figure 3.9. Figure 3.10 shows an example of the specific energy \(\varepsilon_s\) measured during a test with a well bore pressure of 9000 psi (Smith, 1998) and it shows that specific energy increases with time.
Figure 3.6: Schematic of Single Cutter Apparatus

Figure 3.7: Cutter for cutting rock samples (Smith, 1998)
Figure 3.11 shows a rock sample after completion of the test. These tests were performed to know the major cause of slow drilling problems in shales. Smith concluded that global bit balling was the major cause of slow drilling problem.

3.3.1 Steady State Range

The steady state range defines the range of forces used to cut the rock in the single cutter apparatus. For example, see Figure 3.8 which shows a constant increase in the normal force followed by a sudden increase in the force which signifies that the cutter has come in contact with the rock which defines the starting stage of steady state range. The drop in the normal cutting forces represents the end of steady state range. “r” in Figure 3.12 represent the depth cutter has to travel before reaching the steady state range.

![Graph showing specific energy variation over time](image)

Figure 3.8: Variation of specific energy over time for WB pressure 9000 psi (Smith, 1998)
Figure 3.9: Single cutter test apparatus (Smith, 1998)
Figure 3.10: Rock sample in sample holder (Smith, 1998)

Figure 3.11: Sample after the experiment (Smith, 1998)
3.4 Detournay and Tan Approach

Detournay and Tan experimented with cutting tests that measure the load required to cause failure of rocks under confining stress. They also proposed models for predicting the specific energy at failure for shear dilatants rocks as a function of the test conditions and more fundamental rock strength parameters. They reported the results of an experimental investigation done to assess the dependence of the specific energy ($\varepsilon$) on the back rake angle ($\theta$), bottom hole pressure ($p_m$) and initial pore pressure ($p_o$), through a series of cutting experiments conducted on three different shales (Mancos, Pierre I and Johnstone). Figure 3.15 shows a sketch of cutter under down hole conditions.

A 70 MPa capacity autonomous triaxial cell (ATC), with a self-balanced actuator, was used for the tests, which can measure the sample deformations, axial load, and cell and pore pressures. A schematic of the cell is shown in Figure 3.16.
Figure 3.13: Forces obtained from single cutter tests at a confining pressure of 9000 psi (Smith, 1998)

Figure 3.14: Example force data from a single cutter test showing the steady state range (after, Smith 1998)
A computer controlled system was used to control the cell and pore pressures, and to perform data acquisition. The cell and pore pressures were applied and controlled using high precision stepping motor pumps. An instrumented cutting device was used in conducting the experiments under a prescribed confining pressure. The device consisted of three main components: a pressure vessel and sample holder, a cutter holder, and a set of four instrumented “fingers” with two cutters mounted on each one of them. Figure 3.17 shows the elevation and plan view of the cutting device.

Figure 2.14 shows the results of a series of cutting experiments performed on Johnstone, Pierre I shale and Mancos shale at various confining pressures ($p_m = 10, 30$ and $50$ MPa) using a cutter with a backrake angle of $15^\circ$.

For $p_m \leq 30$ MPa, the coefficient $m$ is estimated to be $2.8$ for Pierre I shale, about $5$ for Mancos shale and around $8.9$ for Johnstone. For some experiments performed under conditions of large confining pressure ($50$ MPa), specific energy decreases with increase in confining pressure ($p_m$). This decrease in specific energy could be due to suppression of dilatancy at large confining pressure ($p_m$). They also reported that the single cutter experiments performed by
Zijssling (1987) on Mancos shale were in accord with their conclusions of internal friction angle (f) being equal to the interface friction angle (ψ).

![Autonomous triaxial cell diagram](image)

Figure 3.16: Schematic drawing of the autonomous triaxial cell

3.5 Friction Angle

Smith (1998) also conducted direct shear test on Catoosa shale to obtain the internal friction angle of Catoosa shale and interface friction angle between the Catoosa shale and PDC cutter.

Friction angle is the angle defining the friction between two surfaces. As described in the literature review, friction plays a vital role during the drilling operation of PDC cutters. The two Friction angles relevant to this study with sharp cutters are internal friction angle and interface...
friction angle on the cutter face. Direct shear tests are used to find the internal friction angle of soils. It is one of the earliest and simplest methods for testing the strength of soils (Das 1994, Holtz 1981).

Figure 3.17: Plan and elevation views of the cutting device
It can also be used to obtain the internal friction angle of rocks. Direct shear tests can be used to measure rock characteristics at large displacements that occur during failure, measure failure stress at low levels of confinement and to measure friction against other surfaces. Smith et al. (2002) applied the direct shear concept on cylindrical samples of Catoosa shale. The purpose of these tests was to explore the potential variations in strength and frictional characteristics of shales as a function of variables that would be encountered in field drilling situations. A detailed schematic of the apparatus is given in Figure 3.18.

Tests were performed on undersaturated Catoosa shale samples to determine shear stress at initial fracture, peak shear stress during failure, and residual shear stress for a range of normal stresses, typically at 200, 1000, and 9000 psi. These tests provide a basis for determining the internal friction angle for Catoosa shale.

![Figure 3.18: Direct shear apparatus](image-url)
These tests were conducted to both fail the intact rock and to measure friction against the opposing surface after initial failure or fracture. The tests were performed using different fluid environments such as air, water and mineral oil and WB mud. These environments were used to check the effect of the fluids on the behavior of the Catoosa shale. Triaxial tests were also conducted on the shale to get the peak shear stress and normal stress at failure.

A plot of shear stress versus normal stress at failure for different fluid environments is given in Figure 3.20. It also shows the equivalent results using triaxial tests. The internal angle of friction was obtained from this plot. There was no major difference in the internal frictional angle for different fluid environments. The average internal friction angle of the Catoosa shale obtained from the direct shear and triaxial test results was 14°.

Interface friction angle is the angle to horizontal at which a force acts on the cutter. Smith et al. (2002) conducted direct shear tests to study the affect of frictional forces on the PDC cutter face. They measured the shear stresses and normal stresses between rock and the contact surface of the PDC cutter. The same direct shear mechanism was applied as was used to measure the internal friction angle of Catoosa shale.
Figure 3.20: Comparison of direct shear and triaxial tests on Catoosa shale (after, Smith 1998)

Figure 3.21: Catoosa shale sample after a direct shear friction test on a PDC cutter (Smith, 1998)

Frictional effects were measured between the face of a broken rock sample and the surface of a PDC cutter, see Figure 2.21. The contact surfaces tested were the face of the broken rock and either the face of a standard PDC cutter, the face of a polished PDC cutter, or the surface of a
carbide matrix material used in drill bit bodies. The rock specimen was placed in the upper holder of the apparatus and PDC bits were placed in the bottom holder. Both the holders were placed in the shearing apparatus and a normal load was applied. After the application of the normal load, the rock was sheared against the PDC cutters and the shear loads were measured. From the measured shear loads and applied normal loads, dynamic friction coefficients were calculated. The test was also conducted with both standard and polished cutter to assess the difference in frictional coefficients. This test was conducted for different types of fluid environment, air, water, mineral oil, water based mud. A plot between the dynamic coefficient of friction and normal stress using a standard PDC cutter and Catoosa shale is given in Figure 3.25.

![Figure 3.22: Lower blocks with matrix, polished and standard PDC cutters (Smith 1998)](image)

The dynamic friction coefficients vary from 0.130 to 0.681. The interface friction angle values are interpreted from the dynamic friction coefficients values and they vary from 19 degrees to 23 degrees. The differences due to the fluid environment are not consistent enough to be significant for this study. The average value of interface friction angle between the standard PDC cutter and the Catoosa shale is 21 degrees.
Figure 3.23: Comparison of friction coefficient for different fluids
CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the variation of specific energy with bore hole pressure, quantitative assessment of internal friction angle and interface friction angle and quantitative assessment of rate of change (m) of specific energy with bore hole pressure are reported and discussed.

4.2 Variation of Specific Energy with Bore Hole Pressure

Measured values of specific energy were calculated using Equation 2.20 for use in the analyses in this chapter. The procedure for calculation of specific energy is as follows:

- The values of normal and tangential forces for Mancos and Pierre shale were obtained from Figures 3.2 through 3.5 reported by Zijsling (1987) and for Catoosa shale and Twin Creeks siltstone the values were obtained from the data reported by Smith (1998).
- The value of depth of cut, width of cutter and diameter of path for Mancos and Pierre shale were 0.3 mm, 10 mm and 90 mm respectively, and for Catoosa shale and Twin Creeks siltstone the values were 0.075”, 10 mm, 2.75” and 0.011”, 10 mm, 2.75” respectively.
- The specific energies obtained from Zijsling’s data were normalized for a back rake angle of 15° using Equation 4.1:

\[
 e_{15} = \left( \frac{e_0 + m_{15}p_m}{e_0 + m_{20}p_m} \right) e_{20}
\]

(4.1)

where \( e_{15} \) is the specific energy corresponding to back rake angle of 15°. \( m_{15} \) and \( m_{20} \) are the rate of change of specific energy corresponding to back rake angles of 15° and 20°.
- The calculated values of specific energies for Mancos and Pierre shale were plotted versus Zijsling’s (1987) bore hole pressures and for Catoosa shale and Twin Creeks
siltstone, the values were plotted against Smith (1998) used bore hole pressures. Tables 4.1 through 4.4 show the calculation of specific energies for Mancos shale, Pierre shale, Catoosa shale and Twin Creeks siltstone respectively.

- The values of specific energies for Mancos shale and Pierre shale reported by Detournay and Tan (2002) are also included in Tables 4.1 and 4.2 respectively. Figures 4.1 through 4.4 show the variation of specific energy with bore hole pressure for all the rock samples. The graphs for Mancos shale, Pierre shale and Catoosa shale show a non linear variation of specific energy with bore hole pressure which contradicts with Detournay and Tan (2002) assumption that the variation of specific energy is linear with bore hole pressure. It is impossible to conclusively interpret the variation of specific energy with bore hole pressure for Twin Creeks siltstone because only two data points are available in literature.

| Table 4.1: Variation of specific energy with bore hole pressure for Mancos shale |
|---------------------------------|---------------------------------|---------------------------------|
| BHP P_m (psi)                  | Zijssling $\varepsilon_s$ (psi)| Normalized Zijssling $\varepsilon_s$ (psi) |
| 0                              | 16948.77                        | 16948.83801                     |
| 2900                           | 67795.08                        | 58803.83                        |
| 5800                           | 92011.43                        | 77778.26                        |
| 8700                           | 104137.6                        | 87082.83                        |
| 11600                          | 116270.3                        | 96652.58                        |
| BHP P_m (psi)                  | 0                              | 1450                            |
|                                | 1450                            | 4350                            |
|                                | 4350                            | 5800                            |
|                                | 5800                            | 7250                            |
|                                | Detournay ($\varepsilon$) (psi) | 5800                            |
|                                | 29000                           | 36250                           |
|                                | 43500                           | 41325                           |
|                                | 36250                           | 43500                           |

| Table 4.2: Variation of specific energy with bore hole pressure for Pierre shale |
|---------------------------------|---------------------------------|---------------------------------|
| BHP P_m (psi)                  | Zijssling $\varepsilon_s$ (psi)| Normalized Zijssling $\varepsilon_s$ (psi) |
| 0                              | 5327.28                         | 5327.28                         |
| 1450                           | 10422.99                        | 9040.62                         |
| 2900                           | 13572.4                         | 11472.85                        |
| 4350                           | 9687.65                         | 8101.06                         |
| 5800                           | 10413.76                        | 8656.67                         |
| BHP P_m (psi)                  | 0                              | 1450                            |
|                                | 1450                            | 4350                            |
|                                | 4350                            | 4350                            |
|                                | 4350                            | 4350                            |
|                                | 7250                            | 7250                            |
|                                | Detournay ($\varepsilon$) (psi) | 1450                            |
|                                | 1450                            | 13050                           |
|                                | 13485                           | 13775                           |
|                                | 14500                           | 18850                           |

51
Table 4.3: Variation of specific energy with bore hole pressure for Catoosa shale

<table>
<thead>
<tr>
<th>BHP $P_n$ (psi)</th>
<th>Smith $\varepsilon_s$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>6642.1</td>
</tr>
<tr>
<td>1000</td>
<td>11703.22</td>
</tr>
<tr>
<td>3000</td>
<td>17238.95</td>
</tr>
<tr>
<td>6000</td>
<td>23323.67</td>
</tr>
<tr>
<td>9000</td>
<td>31209.7</td>
</tr>
</tbody>
</table>

Figure 4.1: Plot of specific energy against bore hole pressure for Mancos shale

Figure 4.2: Plot of specific energy against bore hole pressure for Pierre shale
Figure 4.3: Plot of specific energy against bore hole pressure for Catoosa shale

Table 4.4: Variation of specific energy with bore hole pressure for Twin Creeks siltstone

<table>
<thead>
<tr>
<th>BHP</th>
<th>Smith $\varepsilon_s$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_m (psi)</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>38546.62</td>
</tr>
<tr>
<td>9000</td>
<td>81179.34</td>
</tr>
</tbody>
</table>

Figure 4.4: Plot of specific energy against bore hole pressure for Twin Creeks siltstone
4.3 Calculation of m from Specific Energy

The rate of change (m) of specific energy was calculated from Equation 2.28. For this calculation following steps were used:

- The values of specific energies ($\varepsilon$) have been calculated in the previous Section 4.3.
- The value of specific energy at atmospheric condition ($\varepsilon_0$) was calculated using Equation 4.2.

$$\varepsilon_0 = a + bq$$  \hspace{1cm} (4.2)

where, $a = -1.38$ MPa (-200.1 psi) and $b = 0.85$ are constants and $q$ is the unconfined compressive strength, as explained by Richard et al. (1998).

The values of unconfined compressive strength $q$ for Mancos and Pierre shale were 65 MPa (9425 psi), 15 MPa (2175 psi) respectively, as reported by Detournay and Tan (2002). Specific energies at atmospheric condition ($\varepsilon_0$) for Catoosa shale and Twin Creeks siltstone were obtained at zero bore hole pressure by extrapolation using the specific energy versus bore hole pressure graphs of both Catoosa shale and Pierre shale, reported in Figures 4.3 and 4.4.

- The values of bore hole pressure ($p_m$) for Mancos and Pierre shale were 10 MPa (1450 psi), 20 MPa (2900 psi), 30 MPa (4350 psi), 40 MPa (5800 psi) and 50 MPa (7250 psi), as used by Zijssling (1987) in his testing. For Catoosa shale, the values of bore hole pressure were 300 psi, 1000 psi, 3000 psi, 6000 psi and 9000 psi and for Twin Creeks siltstone the bore hole pressures used were 1000 psi and 9000 psi.
- Tables 4.5 through 4.8 show the calculated values of m for the all the rock types. The Figures 4.5 through 4.8 show the variation of m with bore hole pressure for Mancos shale, Pierre shale, Catoosa shale and Twin Creeks siltstone respectively.
The variation of m studied with the aid of Tables 4.5 through 4.8 for the all of the rock types show a decreasing trend of m for increasing bore hole pressures which contradicts the Detournay and Tan (2002) assumption that m is constant against the increasing bore hole pressures. Only Detournay and Tan’s data for Pierre shale show a roughly linear trend implying m is constant, see Figure 4.2.

<table>
<thead>
<tr>
<th>Table 4.5: Calculation of m for Mancos shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zijssling $\varepsilon_s$ (psi)</td>
</tr>
<tr>
<td>67795.08</td>
</tr>
<tr>
<td>92011.43</td>
</tr>
<tr>
<td>104137.6</td>
</tr>
<tr>
<td>116270.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.6: Calculation of m for Pierre shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zijssling $\varepsilon_s$ (psi)</td>
</tr>
<tr>
<td>10422.99</td>
</tr>
<tr>
<td>13572.4</td>
</tr>
<tr>
<td>9687.65</td>
</tr>
<tr>
<td>10413.76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.7: Calculation of m for Catoosa shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith $\varepsilon_s$ (psi)</td>
</tr>
<tr>
<td>6642.1</td>
</tr>
<tr>
<td>11703.22</td>
</tr>
<tr>
<td>17238.95</td>
</tr>
<tr>
<td>23323.67</td>
</tr>
<tr>
<td>31209.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.8: Calculation of m for Twin Creeks siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith $\varepsilon_s$ (psi)</td>
</tr>
<tr>
<td>38547</td>
</tr>
<tr>
<td>81179</td>
</tr>
</tbody>
</table>
Figure 4.5: Plot of m against bore hole pressure for Mancos shale

Figure 4.6: Plot of m against bore hole pressure for Pierre shale
Figure 4.7: Plot of m against bore hole pressure for Catoosa shale

Figure 4.8: Plot of m against bore hole pressure for Twin Creeks siltstone
4.4 Calculation of Interface Friction Angle from Force Ratio

The calculated values of interface friction angle from single point cutter tests using Equation 2.29 for Catoosa shale were cross checked with the interface friction angles measured with direct shear (DS) tests conducted on the Catoosa shale against a standard PDC cutter by Smith (1998) to check the validity of the interface friction angles obtained from Equation 2.29. Figure 4.9 shows decreasing trends for both calculated and measured interface friction angles. However, the interface friction angles obtained from direct shear tests were significantly lower than those implied from the single point cutter tests except at 9000 psi.

![Graph showing comparison of interface friction angles calculated from force ratio to the interface friction angles calculated from direct shear tests for Catoosa shale and Polished cutters.](image)

Figure 4.9: Comparison of interface friction angles calculated from force ratio to the interface friction angles calculated from direct shear tests for Catoosa shale and Polished cutters

This may be due to the friction angle calculated from forces on the cutter being influenced by the chamfer on the edge of the cutter. The friction angles measured in the direct shear tests are also potentially affected by two assumptions

1) The normal stress was calculated assuming that the entire end area of the sample was evenly loaded, which was not true for the broken samples. This might be a reason why the direct shear friction angles are lower than those calculated by SPC tests.
ii) The friction is influenced primarily by the initial normal stress applied to the rock sample rather than just the normal stress at the time of the measurement.

Values of interface friction angles were also calculated from Zijsling’s data for Mancos and Pierre shale.

- The normal and tangential forces reported in Figures 3.2 through 3.5 were used to calculate the interface angles for Mancos and Pierre shale at a back rake angle of 20°, as reported by Zijsling (1987).

- For Catoosa shale, the normal and tangential forces reported by Smith (1998) were used to calculate the interface friction angle for a back rake angle of 10° and for Twin Creeks siltstone, the back rake angle used was 55°.

The calculated interface friction angles from single point cutter data for all the rock samples are shown in Tables 4.9 to 4.13. Figures 4.10 through 4.14 show the variation of interface friction angles with bore hole pressure. Measured values obtained from Equation 2.29 and obtained from direct shear test for show a same angle for a bore hole pressure of 1000 psi, where as it differs for 9000 psi Twin Creeks siltstone. The plots, Figures 4.10 to 4.13, for Mancos shale and Twin Creeks siltstone indicate a roughly constant or slightly increasing trend of interface friction angle with increasing bore hole pressure. The plot of Pierre shale, Figure 4.11, indicates an increase and than a decrease versus increasing bore hole pressure. Catoosa shale, Figure 5.12, shows a strong decrease versus increasing pressure. Some decrease was expected based on the direct shear measurements. These comparsions do not provide a conclusive basis for validating the calculation of interface friction angle from single point cutter tests. Nevertherless, the corrected Equation 2.29 seems to provide a reasonable estimate of interface friction angle.
Table 4.9: Calculation of interface friction angle from force ratio for Mancos shale

<table>
<thead>
<tr>
<th>BHP P&lt;sub&gt;m&lt;/sub&gt; (MPa)</th>
<th>BHP P&lt;sub&gt;m&lt;/sub&gt; (psi)</th>
<th>Zijsling F&lt;sub&gt;N&lt;/sub&gt; (kN)</th>
<th>Zijsling F&lt;sub&gt;D&lt;/sub&gt; (kN)</th>
<th>F&lt;sub&gt;N&lt;/sub&gt;/F&lt;sub&gt;D&lt;/sub&gt;</th>
<th>Ψ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>0.15</td>
<td>0.67</td>
<td>13.69</td>
</tr>
<tr>
<td>20</td>
<td>2900</td>
<td>0.55</td>
<td>0.6</td>
<td>0.92</td>
<td>22.50</td>
</tr>
<tr>
<td>40</td>
<td>5800</td>
<td>0.65</td>
<td>0.85</td>
<td>0.76</td>
<td>17.40</td>
</tr>
<tr>
<td>60</td>
<td>8700</td>
<td>0.85</td>
<td>1.05</td>
<td>0.81</td>
<td>18.99</td>
</tr>
<tr>
<td>80</td>
<td>11600</td>
<td>1.2</td>
<td>1.3</td>
<td>0.92</td>
<td>22.70</td>
</tr>
</tbody>
</table>

Table 4.10: Calculation of interface friction angle from force ratio for Pierre shale

<table>
<thead>
<tr>
<th>BHP P&lt;sub&gt;m&lt;/sub&gt; (MPa)</th>
<th>BHP P&lt;sub&gt;m&lt;/sub&gt; (psi)</th>
<th>Zijsling F&lt;sub&gt;N&lt;/sub&gt; (kN)</th>
<th>Zijsling F&lt;sub&gt;D&lt;/sub&gt; (kN)</th>
<th>F&lt;sub&gt;N&lt;/sub&gt;/F&lt;sub&gt;D&lt;/sub&gt;</th>
<th>Ψ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>0.11</td>
<td>0.91</td>
<td>22.27</td>
</tr>
<tr>
<td>10</td>
<td>1450</td>
<td>0.31</td>
<td>0.215</td>
<td>1.44</td>
<td>35.25</td>
</tr>
<tr>
<td>20</td>
<td>2900</td>
<td>0.385</td>
<td>0.28</td>
<td>1.38</td>
<td>33.97</td>
</tr>
<tr>
<td>30</td>
<td>4350</td>
<td>0.2</td>
<td>0.2</td>
<td>1.00</td>
<td>24.99</td>
</tr>
<tr>
<td>40</td>
<td>5800</td>
<td>0.21</td>
<td>0.215</td>
<td>0.98</td>
<td>24.32</td>
</tr>
</tbody>
</table>

Table 4.11: Calculation of interface friction angle from force ratio for Catoosa shale

<table>
<thead>
<tr>
<th>BHP P&lt;sub&gt;m&lt;/sub&gt; (psi)</th>
<th>Ψ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td>1000</td>
<td>36</td>
</tr>
<tr>
<td>3000</td>
<td>34</td>
</tr>
<tr>
<td>6000</td>
<td>11</td>
</tr>
<tr>
<td>9000</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4.12: Calculation of interface friction angle from force ratio for Twin Creeks siltstone

<table>
<thead>
<tr>
<th>BHP P&lt;sub&gt;m&lt;/sub&gt; (psi)</th>
<th>Ψ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>9000</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 4.10: Variation of interface friction angle with bore hole pressure for Mancos shale
Figure 4.11: Variation of interface friction angle with bore hole pressure for Pierre shale

Figure 4.12: Variation of interface friction angle with bore hole pressure for Catoosa shale

Figure 4.13: Variation of interface friction angle with bore hole pressure for Twin Creeks siltstone
4.5 Assessment of Internal and Interface Friction Angles

The interface friction angles reported in Section 4.4 were compared to the internal friction angles of specific rocks to check Detournay and Tan’s assumption that these angles are equal. The internal friction angle for Mancos shale was 23°, as reported by Detournay and Tan (2002). The interface friction angles for Mancos shale varied from 14° to 23°, as reported in Table 4.9. The internal friction angle for Pierre shale was 19°, as reported by Detournay and Tan (2002). The interface friction angles for Pierre shale varied from 22° to 35°, as reported in Table 4.10. Smith (1998) reported an internal friction angle of 14° for Catoosa shale by conducting direct shear tests on the Catoosa shale. The calculated interface friction angles varied from 40° to 9°, as reported in Table 4.11. The internal friction angle for Twin Creeks siltstone was reported as 36° and the interface friction angle varies from 48° to 56°, as reported in Table 4.12. It can be seen from the above discussion that the internal friction angles are sometimes similar, but are not equal consistently to the interface friction angle for all the rocks. The results obtained imply that the Detournay and Tan (2002) assumption that internal friction angle is equal to the interface friction angles should not be accepted without verification for a particular rock and cutter finish.

4.6 Quantitative Assessment of m from Internal Friction, Interface Friction Angle and Back Rake Angles

Values of m from the friction angles and back rake angle were calculated using Equation 2.26. Following approach was used to calculate m:

- Interface friction angles obtained in Section 4.5 were used to calculate m.
- Known values of internal friction angles as described in Section 4.5 and back rake angles used in the single cutter experiments were used. These values were substituted in Equation 2.26 to obtain values of m for Mancos shale, Pierre shale, Catoosa shale and Twin Creeks siltstone.
Tables 4.13 through 4.17 show the calculation of m for Mancos shale, Pierre shale, Catoosa shale and Twin Creeks siltstone respectively.

<table>
<thead>
<tr>
<th>Table 4.13: Calculation of m for Mancos shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi (^\circ) )</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>23</td>
</tr>
<tr>
<td>23</td>
</tr>
<tr>
<td>23</td>
</tr>
<tr>
<td>23</td>
</tr>
<tr>
<td>23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.14: Calculation of m for Pierre shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi (^\circ) )</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.15: Calculation of m for Catoosa shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi (^\circ) )</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>34</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.16: Calculation of m for Twin Creeks siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi (^\circ) )</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>36</td>
</tr>
<tr>
<td>36</td>
</tr>
</tbody>
</table>

The m values obtained in Section 4.3 based on Equation 2.28 were compared to predicted values obtained in this Section using Equation 2.26 for all the rock samples to check the equality of rate of change (m) obtained from the two different approaches. The Figures from 4.16 to 4.19 show plots of rate of change (m) from the different approaches against the bore hole pressures. It is clearly evident from the graphs that the rate of change coefficient (m) with different bore hole pressures is not same for both the approaches, which proves that m using Equation 2.26
calculated from the friction angles and back rake angle is not a good estimate of m in Equation 2.28 based on these data sets.

Figure 4.14: Comparison of m with bore hole pressure for Mancos shale

Figure 4.15: Comparison of m with bore hole pressure for Pierre shale
Figure 4.16: Comparison of $m$ with bore hole pressure for Catoosa shale

Figure 4.17: Comparison of $m$ with bore hole pressure for Twin Creeks siltstone
CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

There were four objectives to be addressed by this research. The first was the validity of the assumption that specific energy varies linearly with confining pressure. The second was the validity of the Detournay and Tan (2002) assumption that interface friction angle equals internal friction angle. The third issue was to make a quantitative assessment of the theoretical relationship between interface friction angle, cutter force angle, and cutter rake angle. The fourth issue was to make a quantitative assessment of the theoretical relationship proposed by Detournay and Tan (2002) for calculating the rate of change coefficient for specific energy versus effective confining pressure.

Specific energies were calculated for Mancos shale and Pierre shale from the forces obtained from Figures 3.2 through 3.5. The calculated specific energies were plotted against the bore hole pressure to see the variation of specific energy with bore hole pressure. The specific energies calculated by Smith (1998) for Catoosa shale and Twin Creeks siltstone were also plotted against the bore hole pressures. The Figures show a non linear variation of specific energy with bore hole pressure which contradicts Detournay and Tan (2002) assumption of linear variation of specific energy with bore hole pressure. This is reinforced by the large variation and decreasing trend for the rate of change coefficient (m) shown in Figures 4.5 to 4.8.

The validity of the Detournay and Tan (2002) assumption that internal friction angle equal to the interface friction angle was checked by calculating the interface friction angle from the force ratio equation and comparing the calculated values of interface friction angle to the reported internal friction angles. From the obtained graphs it can be concluded that the variation of interface friction angles obtained is not equal to the internal friction angle which proves that Detournay and Tan (2002) is not valid. Interface and internal friction angles are sometimes
similar, but not consistently equal for the rock types. Detournay and Tan’s assumption of equal interface and internal friction angles should not be accepted without verification for particular rock and cutter finish. The comparison of interface friction angles calculated from direct shear tests and force ratio Equation 2.29 do not provide an appropriate basis for validating the calculation of interface friction angle from single point cutter tests. Nevertheless, the corrected Equation 2.29, seems to provide a reasonable estimate of interface friction angle.

The rate of change coefficient \( (m) \) is not constant for different bore hole pressures as indicated by Detournay and Tan (2002). The estimate rate of change coefficient \( (m) \) calculated using the Equation 2.26 for the calculated interface friction angles, and known internal and back rake angles does not agree with those based on the measured specific energies for the same test conditions in any of the four rock types analyzed. Consequently, the proposed Equation 2.26 for calculating \( m \) from the friction angles and back rake angle is not valid for any of the test results reported by Zijsling (1987) and Smith (1998).

The difference in the results may be possibly due to:

- Difference in the material properties between the rock samples used by Zijsling and those used by Detournay and Tan (2002).
- The interface friction angle obtained from the force ratio may apply only to the minimum force required to move the sheared rock rather than the average force required to break the rock.
- The concept of \( m \) being only a function of internal friction angle, interface friction angle and back rake angle may not be valid.

5.2 Recommendations

- Single point cutter tests should be performed on Catoosa and Twin Creeks siltstone with bevel on cutter and with a standard surface.
• Direct shear tests should be performed on Mancos shale and Pierre shale to obtain internal friction angles and interface friction angles for different bore hole pressures, and the dependency of the internal friction angle and interface friction angle on the bore hole pressure should be checked to allow more rigorous conclusions about the validity of Equation 2.29.

• rate of change coefficient of specific energy (m) should be obtained with more reliable values of internal friction angle, interface friction angle and be cross checked with Detournay and Tan’s proposed Equation 2.26 for both Mancos shale and Pierre shale for a more conclusive evaluation of their approach.

• More data points should be available for Twin Creeks siltstone to see the variation of specific energy with bore hole pressure, check whether interface friction angle is equal to the internal friction angle and to see whether rate of change coefficient (m) is constant.

• Based on the assumptions and models examined and discussed in the thesis, it is clear that there is need for more sophisticated models for predicting the relationship between rock strength parameters and forces measured during rock cutting experiments.
REFERENCES


Transactions. v 9, n 1, pp 123-128.

high-speed and high-wear conditions.” Journal of Petroleum Technology. v 33, n 12,
p 2316-2321.

on cutters temperature for polycrystalline diamond compact bits.” Journal of Energy
Resources Technology. v 115, p 124-132.

between PDC drill cutters and rocks.” International Journal of Rock mechanics

boreholes.” International Journal of Rock Mechanics Mining Sciences &

McCray, A. W and Cole, F. W. (1986). “Oil well drilling technology.” University of
Oklahoma press.


Merchant, E. M. (1945). “Mechanics of the metal cutting process. I. Plasticity conditions in


PDC’s cutter.” International Journal of Rock Mechanics & Mining Sciences. v 34, n
3-4, Paper No. 095.


APPENDIX NOTATIONS

d  Diameter of the Path

DOC  Depth of Cut

$F_N$  Normal Force on the Cutter

$F_T$  Tangential Force on the Cutter

$p_m$  Bore Hole Pressure

$m$  Rate of Change Coefficient of Specific Energy

$w$  Width of the Cutter

$\varepsilon$  Specific energy

$\varepsilon_0$  Specific Energy at Atmospheric Conditions

$\theta$  Back Rake Angle

$\varphi$  Internal Friction Angle

$\psi$  Interface Friction Angle
VITA

Mahendra Shewalla was born in 1983, in Hyderabad, India. He completed his Bachelor’s degree in Chaitanya Bharathi Institute of Technology, Osmania University, in June 2005. He came to United States of America in July 2005, to pursue a master’s degree in geotechnical engineering in Louisiana State University. It is expected that he will fulfill the requirements for the master’s degree in civil engineering in December 2007.