Fall 2010

Scaled experimental study on excavation of lunar regolith with rakes/rippers and flat blade

Masafumi Iai

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SCALED EXPERIMENTAL STUDY ON EXCAVATION OF LUNAR REGOLITH
WITH RAKES/RIPPERS AND FLAT BLADE

by

MASAFUMI IAI

A DISSERTATION
Presented to the Faculty of the Graduate School of the
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY
In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

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GEOLOGICAL ENGINEERING

2010

Approved by

Leslie Gertsch, Advisor
Norbert Maerz
David Rogers
Jeffrey Cawfield
Ronaldo Luna
ABSTRACT

As humanity’s activities expand to the Moon, Mars, and other extra-terrestrial bodies, it will be necessary to use local resources rather than bringing everything from the Earth. This concept is called In-Situ Resource Utilization (ISRU), which starts with excavation and earthmoving. The present study focuses on loosening and moving of the lunar regolith by a ripper (or rake) and a wide blade with consideration of gravel content. After characterizing the lunar regolith and two of its simulants (JSC-1A and FJS-1), the relationship between the excavation energy and different conditions, namely gravel content, relative density, and tine spacing on a rake, is investigated with scaled experiments. Geotechnical properties of JSC-1A were determined, in addition to the simulants’ stress-strain relationships over a wide range of relative density (13% to near 100%). Gravel content of the lunar regolith, often overlooked in previous studies, is estimated based on the data of 11 Apollo cores, which reveals the maximum local gravel content is about 30% by weight. Also the grain size distribution of the lunar regolith up to 1 m grains is created by combining the data from Apollo and Surveyor missions. In the experiments, gravel (2 mm – 10 mm) is added to JSC-1A. In addition, a math model of the ripping force is developed as a function of material density, which could be the basis of an instrumented-ripper technique for detailed mapping of construction.

Prior ripping decreases total excavation energy by up to 20% if the relative density is ≥ 60% and the gravel content is ≤ 10%. The optimal tine spacing for JSC-1A at a penetration depth of 30 mm is 30 mm. Even a gravel content of 5% increases the reaction force on excavation tools, which underlines the necessity of consideration of gravel content for lunar excavation planning.
ACKNOWLEDGMENTS

I would like to thank my advisor, Dr Leslie Gertsch, who gave me an opportunity to work in the field of space mining, and whose supervision and support allowed me to complete my PhD research. I am also thankful to my committee, Dr Norbert Maerz, Dr David Rogers, Dr Jeffrey Cawlfield, and Dr Ronaldo Luna, for their kind suggestions and advice. Especially, it was a good luck for me to have Dr Luna in my committee, who gave me the go-ahead to write my first journal paper from this study.

Dr Hiroshi Kanamori and Mr Shigeru Aoki at Shimizu Corporation supplied me with their simulant, FJS-1, and technical assistance. Dr Taizo Kobayashi provided me with various suggestions and useful information. I am pleased to acknowledge their invaluable support and encouragement.

I am grateful to Daniel Vidt for his help obtaining photomicrographs of the simulant grains. Undergraduate students Rustin Atkeisson, Rachel Skipper, Allyson Finch, Erica Collins, and Ryan Williams assisted with the laboratory setups and computer analyses. Their help has been crucial.

Outside my PhD research, but yet related to lunar excavation, I got amazing friends and unique experiences in the Lunar Miners, a student design team that competed in the NASA Regolith Excavation Challenge.

Most importantly, I thank my parents for their continuous support that has allowed me to pursue everything I am interested in.
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1. INTRODUCTION

1.1. INTRODUCTION

There has been continuous interest in permanent activity on the Moon since the Apollo missions ended. Researchers have been evaluating various technical aspects necessary for industrialization and commercialization of the Earth-Moon system, such as lunar mining methods (Gertsch 1983) and concrete production from lunar regolith (Ishikawa et al. 1992). Following tens of lunar missions by the US and Soviet in the 20th century, the new millennium has begun with more attention to the Moon by the broad international community: European SMART-1 launched in 2003, Japanese Kaguya in 2007, Chinese Chang'e 1 in 2007, Indian Chandrayaan-1 in 2008, and US Lunar Reconnaissance Orbiter in 2009. Some of their lunar resources findings are interesting, such as possible deposits of water ice (Feldman et al. 1998), and the existence of uranium (Yamashita et al. 2009).

In-Situ Resource Utilization (ISRU) refers to any activity exploiting the extraterrestrial raw materials, mainly mineral resources. Such activity is also called space mining. It may involve chemical processing of minerals. For example, material extraction from regolith such as oxygen, volatile, metal, silicon, etc. (Nakamura and Senior 2008; Nayagam and Sacksteder 2006) and production of construction materials such as sulfur concrete (Meyers and Toutanji 2007). On the other hand, there are various applications of the local soil as it is. Such applications include site preparation, road construction and pavement; radiation, thermal, and meteoroid shielding (Lindsey 2003; Schonberg et al. 2010); berm construction around landing site (Skonieczny et al. 2009); thermal energy storage (Balasubramaniam et al. 2010).

When exploring or living on the Moon, Mars, or other planetary, ISRU would allow obtaining necessary resources in its vicinity rather than bringing them all the way from the Earth. Also, the raw material extracted or the fuel produced from the in-situ materials can be exported, for instance, from the Moon to Earth or to low earth orbit (Jones 1989). This is when our economic sphere is extended to the Earth-Moon system. Therefore ISRU is a key technology that enables long term exploration, expansion of space activities, and settlement in space.
1.2. PURPOSE

Excavation and earthmoving is an essential initial step of ISRU activities. Given the limited power consumption and mass for an excavator, it is important to optimize the excavation condition. The optimal excavation condition should depend on the conditions of the ground, such as relative density and gravel content. Through experimentation with lunar regolith simulants, this study shows the optimal ripping condition and its dependency on soil conditions, and points out the need for considering coarse grains in regolith when dealing with excavation force and energy.

1.3. SCOPE OF STUDY

First the geotechnical characteristics of simulant is detailed based on direct shear tests, sieve and hydrometer tests, bulk density measurement, and microscopic observation. This characterization is followed by excavation experiment with a ripper and a wide blade. As a simulant, JSC-1A lunar soil simulant is mainly used with or without additional gravel content. For comparison, another lunar soil simulant FJS-1 is used as well as a construction grade sand. The effect of density, gravel content, and tine setting of a rake are studied. Based on the experiment results, the ripping force is modeled and the effect of tool types and soil types are discussed.
2. LITERATURE REVIEW

2.1. IN-SITU RESOURCE UTILIZATION

In-Situ Resource Utilization (ISRU) refers to any activity exploiting the extraterrestrial raw materials, mainly mineral resources. Such activity is also called space mining. It may involve chemical processing of minerals such as material extraction from regolith of volatile, metal, silicon, glass, etc.

Knudsen et al. (1992) developed a process to produce oxygen from actual lunar material for the first time. Allen et al. (1994) determined, by hydrogen reduction, that “maximum oxygen yields from high-titanium soil and iron-rich glass are 3.0 and 5.4 wt.%, respectively.” Kanamori (1994) investigated various aspects of lunar concrete, such as cost and influence of lunar environment on strength, assembly method for lunar concrete structures, and production systems. Meyers and Toutanji (2007) analyzed lunar habitat structure using waterless concrete made of sulfur and JSC-1. Sulfur is the eleventh most abundant element in lunar regolith, and can be obtained as a by-product material of oxygen and carbon extractions. Also they improved strength and ductility of the sulfur concrete by using glass fibers made from lunar regolith as reinforcements.

Physical Science Inc. has been developing a solar thermal power system for thermochemical material processing (Nakamura and Senior 2008). Sunlight is concentrated by an array of solar concentrator, and then transmitted via flexible optical fibers to the thermal reactor where the lunar regolith is heated. Their solar thermal power system was successfully applied to the hydrogen reduction of ilmenite as an example of the lunar materials processing using JSC-1. For this type of material processing, it is essential to achieve uniform heating of regolith. Nayagam and Sacksteder (2006) explored various flow regimes encountered during vibrofluidization. It was shown that granular convection produces uniform temperature within the heated vibrofluidized reactor.

Lindsey (2003) surveyed thermal, radiation, and meteoroid protection, and concluded that 1-2 meters of regolith would serve to provide adequate overall protection for a lunar crew within a lunar habitat. It is noteworthy that "the highest-energy galactic cosmic rays particle will have interacted before passing through ~1000 g/cm² of matter,
which is the thickness of the Earth’s atmosphere or of ~5 m of lunar regolith.” (p53, Lunar Sourcebook). However she concluded 1 to 2 meters of lunar regolith provides adequate shielding, citing NASA’s current acceptable limit for radiation exposure of 25 rem/month and Silberberg (1985). Lindsey (2003) stated conservative meteoroid protection for a habitat structure can be achieved with 0.459m of regolith. For protection of the crew in case of a total thermal control system failure, she noted 0.1m to 10m would serve for thermal protection.

Balasubramaniam et al. (2010) proposed use of lunar regolith as thermal energy storage called thermal wadis. Thermal wadi is a solid material made by melting or sintering the lunar regolith using concentrated solar energy, microwave heating, or electrical resistance heating. The thermal mass of a thermal wadi can keep its temperature relatively constant whereas the temperature on the lunar surface varies typically from 100K to 400K during the Moon’s 27 day diurnal cycle. Thermal wadis can be used to keep rovers or other equipment within their operational temperature range.

There are various experimental studies on excavation equipment and tools. The tools for higher excavation efficiency have been tested such as the vibratory blade (Szabo et al. 1998), a percussive and pneumatic approach (Zacny et al. 2009), and a ripper (Iai and Gertsch 2010). Also different excavator designs have been implemented: a bucket wheel excavator (Johnson and King 2009), and a bucket ladder excavator (Iai 2007).

2.2. LUNAR REGOLITH

In 2009 and 2010, evidences of hydroxyl molecules on the Moon were reported, which drastically changed people’s idea about the Moon. Clark et al. (2009) reported detection of adsorbed water and hydroxyl on the Moon, and estimated the amount of water to be 10 to 1000 ppm, based on data obtained by Cassini spacecraft, which was followed by the observation by Chandrayaan-1 (Pieters et al. 2009) and by LCROSS (Dino 2009). Boyce et al. (2010) found about 1,600 parts per million of H₂O by ion microprobe measurements of late-stage apatite from lunar basalt 14053. Tompkins and Stroupe (1999) discussed a potential mission to the lunar south pole looking for water ice.

2.2.1. Lunar Regolith – Formation, Environment, and Properties. The surface of the Moon is divided into two regions, namely, maria and highlands. From the observer
on the earth, the lunar maria look dark while the lunar highlands bright. The highlands (also called “terra”) are anorthosite rich, light colored, rough, heavily cratered, older, and higher in altitude, and mostly composed of plutonic rocks. The maria, on the other hand, are darker, smooth, less cratered, and lower, and consists of basaltic lavas. Chemically, the highlands are Ca and Al rich while the maria are rich in Fe and Ti. Mineralogically, the highlands are abundant in feldspar whereas the maria is richer in pyroxene. Mare basalts exist on about 16% of the lunar nearside but less than 1% of the farside. Because of such distinct differences in mineral composition between the highlands and the maria, it has been suggested that there was large-scale chemical segregation of the original material that formed the Moon. The highlands are formed by the lighter materials accumulated on top of the “magma ocean” leaving the heavier materials such as olivine and pyroxene in deep layers. Then those heavy materials are brought to the surface by volcanic eruption, forming the maria basalt. (Vaniman et al. 1991, Lunar Sourcebook, Chapter 2)

In contrast to the division of the lunar surface into two parts, Jolliff et al. (2000) suggested the division into three major geochemical terranes based on analysis of the newer data obtained by remote sensing missions in 1990’s, Clementine and Lunar Prospector (Taylor 2000).

The current consensus about the regolith thickness is that “the regolith is generally about 4–5 m thick in the mare areas but may average about 10–15 m in older highland regions.” (McKay et al. 1991, p. 286). At the current rate of impact on the Moon, the regolith thickness is not growing as fast as in early lunar history because generation of new regolith requires the impact crater to be large enough to penetrate the current regolith layer and to excavate the underlying bedrock.

2.2.2. Geotechnical Properties of Lunar Regolith. Carrier et al. (1991) suggested that the recommended typical specific gravity, $G_s$, of lunar soil grains is 3.1 (p. 481, Lunar Sourcebook), and that the best estimates of typical density range is 1.45g/cm$^3$ to 1.55g/cm$^3$ for a depth range of 0cm to 15cm, and 1.61g/cm$^3$ to 1.71g/cm$^3$ for a depth range of 0cm to 60cm (p 484, Lunar Sourcebook). Based on the data given in the Lunar Sourcebook (p. 482, Table 9.3), the standard deviation of $G_s$ is 0.25. Given those data, the porosity, $n$, is estimated by
\[ n = 1 - \frac{\rho}{G_s \rho_w} \]  

(1)

where \( \rho_w \) is the density of water, i.e. 1g/cm\(^3\). Substituting into this equation either upper limit of \( \rho \) and lower limit of \( G_s \), or lower limit of \( \rho \) and upper limit of \( G_s \), range of estimated \( n \) is found to be 0.45 to 0.56. These porosity values correspond to void ratio of 0.82 to 1.28.

**2.2.3. Density of the Ground on the Moon.** The relation between vertical stress in the ground and depth on the Moon is shown in Fig 2.1. The acceleration of gravity on the Moon is 1.62m/s\(^2\), approximately one sixth of the earth's gravity. The bulk density of 1.7g/cm\(^3\) was used based on the in-situ bulk density of drill core samples collected on the Apollo 15, 16, and 17 missions (Carrier et al. 1991). Figure 2.1 was produced to show the depth under the lunar surface that corresponds to the normal stress of the direct shear tests conducted in this project. This issue is discussed later in Section 4.2.1, Range of Normal Stresses.

![Fig 2.1 Vertical Stress Beneath the Ground on the Moon](image-url)
2.2.4. JSC-1A Lunar Regolith Simulant. The availability of the returned lunar soil is very limited. Jaffe (1973) had to design a miniature direct shear apparatus to shear about 1g specimen of the returned lunar regolith. Carrier et al. (1973) also conducted direct shear tests in vacuum using a returned sample of 200g in total and produced three data points.

Simulant material is needed for use in larger quantities in unit element and bench scale tests. JSC-1, one of the most widely used regolith simulants, was initially manufactured in the 1990’s. Willman et al. (1995), Perkins and Madson (1996), and Klosky et al. (2000) reported geotechnical properties of JSC-1. When the supply of JSC-1 ran out, Orbital Technologies Corporation (ORBITEC) manufactured JSC-1A, a reproduction of JSC-1 regolith simulant, for NASA. JSC-1A was mined from the same quarry as JSC-1, a commercial cinder quarry at Merriam Crater, a volcanic airfall ash deposit of basaltic composition near Flagstaff, Arizona (Rickman et al. 2007). JSC-1 and JSC-1A resemble low-titanium lunar mare basalts from the Apollo 14 site (Sibille et al. 2005). This simulant is commercially available from ORBITEC. Gustafson (2009) at ORBITEC stated that "after the remaining 3 tons of JSC-1A are sold, it may not be available again due to the intellectual property holdings of ET Simulants."

The NU-LHT (NASA/USGS Lunar Highland Type) regolith simulant may substitute JSC-1A family of simulants in the future. However, JSC-1A is widely used for research today (Alshibli and Hasan 2009; Zeng et al. 2009) in addition to educational purposes. For example, the California Space Education and Workforce Institute acquired 8 tons of JSC-1A lunar regolith simulant in a 4m x 4m test box with the intent of making this test bed available for educational purposes to the lunar exploration community (CSEWI 2009). With this test box, they have hosted the Regolith Excavation Challenge, one of the NASA centennial challenges, which is designed to promote the development of mechanical designs to excavate lunar regolith. Since 2007, many teams have operated their robotic excavators in this challenge (Iai 2007).
2.3. SOIL EXCAVATION MODELING

In an attempt to model soil-tool interaction, Willman and Boles (1995) concluded existing analytical models were statistically invalid in predicting their experiment results, whereas Blouin et al. (2001) called for a common ground for validation procedure. To evade such puzzling models, Nakashima et al. (2008) proposed a very simple engineering parameter, called a specific cutting resistance, to characterize excavation force. Yet, Metzger (2005) is trying to unravel fundamental physics behind granular phenomena. Of course, numerical simulation plays an important role. Discrete Element Method (DEM) is getting attention for its capability of modeling grain shapes (Matsushima et al. 2009) while Muthuswamy and Tordesillas (2006) made an effort to incorporate micromechanics into finite element method (FEM).

King et al. (2010a) compared predicted excavation forces by 7 analytical models against the measured reaction force of a rod pushed through Ottawa sand and JSC-1A. They found that the Luth and Wismer (1971) model and the Zeng model gave closest fit over the range of excavation depth from 0.5cm to 8cm, and that the Gill and Vanden Berg (1968) model and the Qinsen and Shuren (1994) model show equivalent curves but significantly over estimate the forces while Balovnev (1983) model, McKeys (1985) model, and Swick and Perumpral (1988) model diverge due to their linearity.

2.3.1. Soil and Rock Excavation Modeling. Cigla and Ozdemir (2000) have made computer models for performance prediction of mechanical excavators, such as tunnel boring machines, and continuous miners. They apply those models to optimization of cutter head design. Their models are based on laboratory tests on rocks such as uniaxial compression strength and tensile strength and full-scale cutting tests, and calibrated with field performance data. Ozdemier et al. (1992) showed that, depending on the rock type and cutter type, there is an optimum spacing to penetration ratio that can produce the most efficient cutting in terms of minimum specific energy requirements (Fig 2.2). This optimal value depends on rock type and cutter type. So it is necessary to investigate the optimal condition for each material of interest.

Reece (1964) suggested to model the force, \( F \), required to fail soil mass by

\[
F = cb^2N_c + \gamma b^3N_g + q b^2N_q + c_a b^2N_a
\]  

where \( b \) is a characteristic dimension, which may be a cutting depth. Hettiaratchi and Reece (1967; 1974) later provided charts of those \( N \) factors based on the data obtained by numerical calculation of the Sokolovski’s method.

Since McKyes’s model is one of most popular model used by researchers for comparison (e.g. Shmulevich et al. 2007; Tamoi et al. 2004; Willman and Boles 1995), this model is explained below.
In McKyes’ (1989) model the excavation force, \( P \), acting on a excavation blade is given by

\[
P = \left( \gamma d^2 N_\gamma + c d N_c + q d N_q + c_a d N_{c_a} \right) w
\]  

(3)

where

\[
N_\gamma = \frac{1}{2 d} \left( 1 + \frac{s}{d} \right) \frac{\sin(\beta + \phi)}{\sin(\alpha + \beta + \delta + \phi)}
\]  

(4)

\[
N_c = \frac{\cos(\phi) (1 + \frac{s}{d})}{\sin(\beta) \sin(\alpha + \beta + \delta + \phi)} \left( \frac{1}{\sin(\alpha + \beta + \delta + \phi)} \right)
\]  

(5)

\[
N_{c_a} = -\frac{\cos(\alpha + \beta + \phi)}{\sin(\alpha) \sin(\alpha + \beta + \delta + \phi)}
\]  

(6)

\[
N_q = \frac{r (1 + \frac{s}{d})}{d} \frac{\sin(\beta + \phi)}{\sin(\alpha + \beta + \delta + \phi)}
\]  

(7)

where

\[
r = \frac{1}{\tan(\alpha)} + \frac{1}{\tan(\beta)}
\]  

(8)

\[
s = \sqrt{\frac{1}{\tan^2(\beta)} + \frac{2}{\tan(\alpha) \tan(\beta)}}
\]  

(9)

The symbols in the above equations, such as \( \alpha \), and \( \beta \), are defined in Fig 2.3. The friction angle of the soil is \( \phi \). The value of \( \beta \) has to minimize \( N_\gamma \). Also note that if the value of \( s/d \) is forced to be zero, the force due to the side failure zone is neglected, and therefore the force, \( P \), becomes an estimate for the excavation force in two dimensional soil cutting. The horizontal and vertical components, \( H \) and \( V \), of the force, \( P \), are

\[
H = P \sin(\alpha + \delta) + c_a d w / \tan(\alpha)
\]  

(10)

\[
V = P \cos(\alpha + \delta) - c_a d w + W
\]  

(11)

The soil is described by unit weight, \( \gamma \), and the shear strength parameters, \( c \) and \( \phi \). The inputs to the model are tool depth, \( d \), tool width, \( w \), tool angle, \( \alpha \), friction between tool and soil, \( \delta \), adhesion between tool and soil, \( c_a \), soil unit weight, \( \gamma \), soil shear strength parameters, \( c \) and \( \phi \), and surcharge load, \( q \).
Zeng et al. (2007) developed another analytical model based on principles of soil mechanics. Unlike McKyes’ model, their model is based on dynamic model so it takes into account the acceleration of the moved soil mass; the effect of side failure zone is modeled as the side friction force, $F_{\text{side}}$, acting on the vertical plains on the failure wedge in front of the blade. Similarity to McKyes’ model, surcharge load is incorporated as the uniformly distributed pressure on the soil surface; the failure surface is modeled as an inclined plain. The passive earth pressure, $P$, acting on the blade is based on the Mononobe-Okabe theory, which is widely used to calculate dynamic earth pressure on a retaining wall during earth quake.

$$P = \left[ \frac{\gamma d^2}{2} \left( 1 + \frac{a_v}{g} \right) K_{PE} + 2cd\sqrt{K_{PE} + qdK_{PE}} \right] w$$  \hspace{1cm} (12)

where $a_v$ is vertical acceleration of the failure wedge, $g$ is the gravitational acceleration and $K_{PE}$ is defined as
\[ K_{PE} = \frac{\sin^2(\phi - \alpha + \zeta)}{\cos \zeta \sin^2\alpha \sin(\delta + \alpha - \zeta) \left[ 1 - \frac{\sin(\delta + \phi) \sin(\phi + \zeta)}{\cos(\delta - \alpha - \zeta) \sin \alpha} \right]^2} \] (13)

\[ \zeta = \tan^{-1} \frac{a_h}{g + a_v} \] (14)

The side friction force is modeled as if a shear failure occurs on the vertical plains that passes the side edges of the blade. They first calculate the horizontal normal stress on those vertical plains, which is then plugged into the Mohr-Coulomb failure model to obtain friction force at every point on the vertical plains. Finally that friction force is integrated over the side area of the wedge to give

\[ F_{side} = \left( c d + q d \tan \phi K_0 + \frac{q d^2}{3} \tan \phi K_0 \right) L_w \] (15)

where \( K_0 \) is earth pressure coefficient at rest, and \( L_w \) is the length of the failure wedge at the surface, which is calculated based on geometrical consideration as a function of the blade angle and the inclination of the failure surface as

\[ L_w = d \left[ \tan \left( \frac{\pi}{2} - \alpha \right) + \frac{1}{\tan \beta} \right] \] (16)

Luth and Wismer (1971) model is known for being able to fit with the Viking mission data (Johnson and King 2009). Its horizontal and vertical component of excavation force are modeled as

\[ F_X = \rho gb \frac{0.5 l^{1.5} x^{1.73}}{\left( \frac{z}{l \sin[z]} \right)^{0.77}} \left( \frac{z}{b} \right)^{1.1} + 1.26 \frac{V^2}{gl} + 3.91 \] (17)

\[ F_Y = \rho gb \frac{0.5 l^{1.5} (0.193 - (\alpha - 0.714))^2}{\left( \frac{z}{l \sin[z]} \right)^{0.777}} \times \left( 1.31 \left( \frac{z}{b} \right)^{0.966} + 1.43 \frac{V^2}{gl} + 5.60 \right) \]

where the symbols are defined in Fig 2.4.
Fig 2.4 Definitions of Symbols in Luth and Wismer Model

Besides the models stemmed from the passive earth pressure theory, there are other line of research on excavation force. Zelenin et al. (1985) proposed an empirical model of soil cutting force. Hemami et al. (1994) applied it to estimation of resistance during bucket loading. Takahashi et al. (1999) formulated soil cutting force based on mechanics of particle interaction in their model of the resistive force on the bucket of a load-haul-dump machine.

2.3.3. Validity of Analytical Models. Although there are many models to estimate forces on a blade or a bucket, several researchers have noted their insufficient quality of estimation. For example, singularities in their equations limit the range of parameters where the models are applicable (Wilkinson and DeGennaroa 2007). The insufficient capability of those models to predict excavation forces is reported by Salokhe and Pathak (1992), Rajaram and Gee-Clough (1988), Willman and Boles (1995), Singh (1995), and Tamoi et al. (2004) based on their experiments.

Kobayashi (2002) pointed out that the model by McKyes and Ali, and its antecedent model by Godwin and Spoor predict the side failure zone that does not agree with that is observed experimentally by X-ray CT. He proposed his model to resolve this flaw. Willman and Boles (1995) used four analytical models by Hettiaratchi and Reece (1967), by Godwin and Spoor (1977), by McKyes and Ali (1977), and by Perumpral et al. (1983) to compare the predicted forces and the experiment results on lunar soil simulant, concluding that, based on t-tests, none of the predicted forces were valid to estimate their experiment results on a lunar regolith simulant MLS-1. They argued that the higher
density of soil led to the larger difference between prediction and measurement. Also experimental results tend to have large deviation in force amplitude, which the existing models have no way to estimate. The large deviation indicates the assumption of homogeneity is violated. Johnson and King (2009) used Luth and Wismer (1971)’s model for comparison with their data of excavation force by a bucket wheel. They needed to select part of their data to better match the soil cutting condition of the bucket wheel and the math model. They found that the data point at the beginning of the selected part is better estimated than the average of the rest of the data. This finding led them to suggest that the model might need improvement to describe the force change that occurs as digging proceeds. In other words, the model is not good at model the soil heap formed in front of a tool as excavation proceed, or suitable to estimate average excavation force, thus excavation energy over some distance.

However, there are, of course, some reports of successful prediction by those analytical models. It must be noted that, as Blouin et al. (2001) stated, “due to a lack of a uniform validation procedure, the impacts of decisions made during modeling and experimental validation may lead to contradictory results.”

2.3.4. Modeling of Surcharge Load. Regarding treatment of surcharge load, the existing excavation models can be classified into two groups (Table 2.1). One class of models (e.g. Balovnev model, and Qinsen and Shuren (1994) model) include surcharge load as the mass of the pre-defined shape and size of soil heap, and thus do not explicitly model its effect. The other class of models (e.g. McKyes model) have a term to incorporate the surcharge pressure uniformly distributed on the surface although they do not provide a way to estimate surcharge pressure. Those models are based on the passive earth pressure theory, which is developed mainly for analysis of retaining wall where no soil heap is formed.

In case of excavation, however, the surcharge load due to the soil heap in front of a tool is an essential part of the phenomenon. It has significant effect on the measured excavation force. The size of the soil heap grows until it reaches steady state; the surcharge stress distribution on the original surface is not uniformly distributed; the surcharge load affects the shape and inclination of the failure surface (Salokhe and
<table>
<thead>
<tr>
<th>Model</th>
<th>Surcharge load modeled as</th>
<th>Type of Blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>McKyes (1985) 2D</td>
<td>Surface pressure, $q$. (added to weight; $2q/d \rightarrow \gamma$)</td>
<td>Flat blade</td>
</tr>
<tr>
<td>Osman (1964)</td>
<td>Surface pressure, $q$. (added to weight; $2q/d \rightarrow \gamma$)</td>
<td>Flat blade</td>
</tr>
<tr>
<td>Swick and Perumpral (1988)</td>
<td>Surface pressure, $q$. (added to weight; $2q/d \rightarrow \gamma$)</td>
<td>Flat blade</td>
</tr>
<tr>
<td>Zeng et al. (2007)</td>
<td>Surface pressure, $q$. (added to weight; $2q/d \rightarrow \gamma$ if static)</td>
<td>Flat blade</td>
</tr>
<tr>
<td>McKyes (1985) 3D</td>
<td>Surface pressure, $q$. (added to weight; $2q/d \rightarrow \gamma$ for forward failure and $-2q/d/(2+3w/s) \rightarrow \gamma$ for side failure)</td>
<td>Flat blade</td>
</tr>
<tr>
<td>Hettiaratchi and Reece (1974)</td>
<td>Surface pressure, $q$. (added to weight; $2q/d \rightarrow \gamma$ approx. for forward failure and $q/d \rightarrow \gamma$ for side failure)</td>
<td>Flat blade</td>
</tr>
<tr>
<td>Balovnev (1983)</td>
<td>Not explicitly modeled (Weight of predetermined heap shape)</td>
<td>Curved dozer blade</td>
</tr>
<tr>
<td>Qinsen and Shuren (1994)</td>
<td>Not explicitly modeled (Weight of predetermined heap shape)</td>
<td>Curved dozer blade</td>
</tr>
<tr>
<td>Gill and Vanden Berg (1968)</td>
<td>Not explicitly modeled</td>
<td>Flat blade</td>
</tr>
<tr>
<td>Luth and Wismer (1971)</td>
<td>Not explicitly modeled</td>
<td>Flat blade</td>
</tr>
</tbody>
</table>

*: It is exact if $\delta=\phi=0$ and $Sc=Sq=\infty$; otherwise it is an approximation (Hettiaratchi and Reece 1974).
Pathak 1992; Selig and Nelson 1964). Although the surcharge load changes the failure surface inclination, most models do not describe that effect except for ones in which the failure surface inclination is determined by minimizing the total excavation force, $P$ (Table 2.2). There is no reason to dismiss such effects because it takes large portion of the total force, and such effect increases as the travel distance, $L$, increases. As Johnson and King (2009) suggested there is need for modeling the $L$ dependent component of excavation force.

Shmulevich et al. 2007 modified McKyes’s two dimensional model to take the excavation distance, $L$, into account. They were able to achieve reasonable correlation between the horizontal component of experiment results and that of their analytical model. First, they assumed surcharge pressure to be a function of $L$ as

$$q = \frac{\gamma L \tan \beta \tan \alpha}{2(\tan \beta + \tan \alpha)}$$

(18)

where $\alpha$ is the blade angle, $\beta$ is the inclination of the failure surface, and $\gamma$ is the unit weight of soil. This $q$ is plugged into the McKyes equation of $P$ (Eq (3)). Second, they added another term, $F_m$, to the horizontal force, $H$.

$$H = P \sin(\theta + \delta) + c_n d w/\tan \alpha + F_m$$

(19)

where

$$F_m = \frac{\gamma L d w}{2} \tan \phi$$

(20)

These equations are based on their assumptions. Namely “1) Half of the heap is considered in the calculation of normal pressure. 2) The soil wedge moves together with the blade. Consequently, only half of the heap slides above the soil surface out of the wedge range.”

The same problem of assumption of surcharge load is dealt with differently by Kobayashi et al. (2006). They assumed the surcharge pressure

$$q = \frac{Q}{\lambda w}$$

(21)

where $w$ is the blade width, and $Q$ is the gross weight of the soil heap given by

$$Q = \gamma d L w$$

(22)

and $\lambda$ is the distance from the tip of the soil heap to the tool surface measured on the
Table 2.2 Parameters that Affect the Shape and Inclination of Failure Surface

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameters that affect the shape and inclination of failure surface</th>
<th>Type of Blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>McKyes (1985) 2D</td>
<td>$\alpha, \delta, \phi$ (Minimize $N\gamma$)</td>
<td>Flat blade</td>
</tr>
<tr>
<td></td>
<td>Flat</td>
<td></td>
</tr>
<tr>
<td>Osman (1964)</td>
<td>$\alpha, \delta, \phi$ (Minimize P)</td>
<td>Flat blade</td>
</tr>
<tr>
<td></td>
<td>Curved (Log spiral and straight line)</td>
<td></td>
</tr>
<tr>
<td>Zeng et al. (2007)</td>
<td>$\alpha, \delta, \phi, \zeta$</td>
<td>Flat blade</td>
</tr>
<tr>
<td></td>
<td>Flat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$(\zeta$ is the inclination of acceleration vector. $\zeta=0$ for static)</td>
<td></td>
</tr>
<tr>
<td>McKyes (1985) 3D</td>
<td>$\alpha, \delta, \phi, d/w$ (Minimize $N\gamma$)</td>
<td>Flat blade</td>
</tr>
<tr>
<td></td>
<td>Flat</td>
<td></td>
</tr>
<tr>
<td>Hettiaratchi and Reece (1974)</td>
<td>Sokolovski’s method. Rupture distance ratio as function of $\alpha, \delta, \phi$ (Hettiaratchi et al.1966)</td>
<td>Flat blade</td>
</tr>
<tr>
<td>Balovnev (1983)</td>
<td>$\phi$ (Failure surface inclination is defined by $\pi/4-\phi/2$)</td>
<td>Curved dozer blade</td>
</tr>
<tr>
<td>Grisso (McKyes 1985)</td>
<td>All (Minimize P)</td>
<td>Flat blade</td>
</tr>
<tr>
<td></td>
<td>(Surcharge pressure, $q$, is not modeled)</td>
<td></td>
</tr>
<tr>
<td>Sokolovski’s method</td>
<td>All</td>
<td>Flat blade</td>
</tr>
<tr>
<td>(Hettiaratchi and Reece 1974</td>
<td>Curved</td>
<td></td>
</tr>
<tr>
<td>(Kobayashi 2002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Godwin and Spoor (1977)</td>
<td>Rupture distance ratio (determined by experimental data)</td>
<td>Flat blade</td>
</tr>
<tr>
<td></td>
<td>Curved</td>
<td></td>
</tr>
</tbody>
</table>
original surface, which is modeled as

\[
\lambda = \sqrt{\frac{2dL \sin(\alpha - \phi)}{\sin \phi \sin \alpha}}
\]

where \(d\) is the cutting depth, \(\alpha\) is the blade angle, \(\phi\) is the friction angle of soil.

**2.3.5. Modeling Based on Fracture Mechanics.** Existing prediction models for soil cutting resistance are stemmed from classical soil mechanics theory based on the rigid–plastic Mohr–Coulomb model of shear failure. However, there are cases where brittle fracture of soil is observed. Aluko and Chandler (2004) modeled the brittle fracture in two-dimensional soil cutting by fracture mechanics.

Palmer and Rice (1973) applied the concept of fracture mechanics to describe criteria of initiation and propagation of failure surface or shear band in a step in a slope (Fig 2.5 (a)). Puzrin and Germanovich (2005) later extended this approach to analysis of discontinuity parallel to the slope surface (Fig 2.5 (b)); Saurer and Puzrin (2008) also investigated the circular shear band formed by rotated shear blades. The advantage of this approach is that the physical phenomenon of gradual propagation of shear band is modeled whereas other approaches assume the shear band appears instantly.

![Fig 2.5 Shear Band Propagation Schematics. (a) A Cut in the Slope; (b) Discontinuity Parallel to the Slope Surface.](image)

**2.3.6. Numerical Models.** Given the experimental results that the existing analytical models are not so capable of representing excavation force, people have tried to find different ways to cope with soil modeling. Abo-Elnor et al. (2004) simulated soil-
blade interaction of sandy soil by finite element analysis. Singh (1995) concluded the analytical model was deficient and proposed an empirical model by learning with e.g. neural networks. Many researchers see DEM a promising modeling technique. Momozu (2003) showed that DEM elements needs to model tensile forces, or adhesion, between particles when modeling soil that tends to form lumps.

One of the difficulties in use of DEM is finding a proper DEM parameters, such as spring constants and damping ratio, to simulate real soil. Asaf et al. (2007) proposed a methodology to determine DEM parameters directly from the in-situ field-test results on the soil of interest rather than using the soil parameters obtained by conventional lab tests. Some people consider using spheres to represent soil grains is sufficient to simulate soil behavior whereas others do not (e.g. Sukumaran and Ashmawy 2003). Matsushima et al. 2009 used X-ray CT to reproduce the 3D shape of each particles of the FJS-1 lunar regolith simulant to simulate the behavior of the simulant.

Besides the DEM, Singh 1995 used a neural network to estimate soil behavior based on the measurement obtained in prior learning phase. Nakashima et al. 2008 used a simple empirical parameter, called specific cutting resistance (Hata 1979), to represent the excavation force and established a way to predict the specific cutting resistance at lower gravity using DEM.

2.4. SIMULANT EXCAVATION EXPERIMENTS

There have been several experimental studies of excavation of lunar soil simulant. The excavation speed in all of those experiments are slow to eliminate the effect of inertia: 10mm/s (Tamoi et al. 2004), 30.5mm/s (Willman and Boles 1995). The experiment conditions in those studies, such as type of material, its density, soil container size, excavation depth, are listed in Table 2.3.
<table>
<thead>
<tr>
<th>Container Size</th>
<th>Tool Motion</th>
<th>Tool Type</th>
<th>Material</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55m × 0.80m × &gt;0.065m (0.029m³, 50kg)</td>
<td>1D motion</td>
<td>Flat wide blade (80mm wide, α=90°, 57.5mm deep) (120mm wide, α=51°, 20mm deep)</td>
<td>JSC-1, 1.80g/cm³ Gravity: 1g and 1/6g</td>
<td>Boles et al. (1997)</td>
</tr>
<tr>
<td>0.65m × 0.38m × 0.12m (0.030m³, 50kg)</td>
<td>1D motion 30.5mm/s</td>
<td>Flat wide blade (130mm wide, α=60°, 40 mm, 70 mm, and 95 mm deep)</td>
<td>MLS-1, 1.92g/cm³</td>
<td>Willman (1995)</td>
</tr>
<tr>
<td>1.030m × 0.530m × 0.175m (0.096m³, 160kg)</td>
<td>1D motion 10mm/s</td>
<td>Flat wide blade (90°, 75°, 60°), (40mm, 50mm, 60mm deep) (60mm, 120mm, 180mm wide)</td>
<td>FJS-1, Toyoura sand Dr=45%,85%,</td>
<td>Tamoi et al. (2004)</td>
</tr>
<tr>
<td>110mm × 570mm × 400mm</td>
<td>2D motion</td>
<td>bucket (73mm wide with teeth 8mm long with a 7mm clearance)</td>
<td>Mixture of basaltic aggregates simulating lunar soil. 1.92g/cm³</td>
<td>Bernold (1991)</td>
</tr>
</tbody>
</table>
2.5. DIRECT SHEAR TEST

Taylor (1948) and more recently Schofield (2005) continue to remind us how interlocking and dilatancy play a role in the shear strength of soils and they both refer to the direct shear box as a tool to investigate these phenomena. The motivation for this experimental program stems from a return to basics using a testing device that provides volumetric behavior at small and large strains in dry granular materials, such as in the Moon. Both peak and critical state strength parameters are obtained, which are well suited to determine the energy requirements for excavation tools. This section presents the results of a series of direct shear tests performed on the JSC-1A lunar soil stimulant and it compares them to recently published results by other researchers using the triaxial test.

Coulomb was one of the first to use a direct shear box in the late 1700s which began the development of soil mechanics (Schofield 2005). Now that the new era of lunar construction is being considered, it is worthwhile to examine the direct shear test results.
to understand lunar regolith stimulant behavior under different shear stress conditions. Field conditions of loading can apply different stress paths on a solid element and will be subjected to different boundary conditions. This dictates the applicability of different soil strength tests to the field conditions as shown in Fig 2.6 (Kulhawy and Mayne 1990). For example, the direct shear test can represent the shearing conditions at the bottom of the circular failure surface under an embankment, and in front of the tip of a loaded wall such as a dozer blade in excavation tools. Therefore, the direct shear test is applicable to excavation and mining studies of lunar regolith, especially at large strains or critical state conditions. In fact, several researchers used direct shear tests to determine strength parameters for space-related study (Bernold 1994; Perko et al. 2006; Johnson and King 2009).

Fig 2.6 Applicability of Laboratory Tests to Field Conditions (Kulhawy and Mayne 1990) TC: Triaxial Compression, DS: Direct Shear, TE: Triaxial Extension.

2.6. EFFECT OF GRAVEL CONTENT ON EXCAVATION

There have been several experimental studies about excavation of the lunar surface (e.g. Boles et al. 1997; Willman 1995; Tamoi et al. 2004; Bernold 1991; Szabo et al. 1998). However, most, if not all, of them used a homogeneous simulant without
considering the effect of the gravel content in lunar regolith. This is due to lack of information as grain size analysis on the Apollo samples were done after coarse fragments (>1 mm) are removed from the samples (e.g. Heiken et al. 1973). As a result, older lunar regolith simulants contain grains up to 1mm (JSC-1 or JSC-1A) or 2mm (FJS-1, MLS-1). On the other hand, newer simulants tend to include larger grains with maximum grain size of 5mm (OB-1) or 10cm (NU-LHT-3C. Stoeser et al. 2008).

Removal of coarse fragments in the analysis of Apollo samples makes sense because it is widely recognized that the strength of soil-gravel mixture is governed by the strength of its matrix material alone as long as gravels in a matrix do not touch each other. For example, Fragaszy et al. (1992) concluded “large, subrounded-to-rounded smooth soil grains floating in a matrix of finer matrix material do not significantly influence the peak strength and deformation characteristics of the prototype soil” where floating state in their study corresponds to <40% gravel content. Bareither et al. (2008) concluded that peak friction angle for clean sand backfill with less than 30% gravel (4.75 mm – 25 mm) can be measured with similar accuracy regardless of gravels removed from the specimen or not. Savely (1990) mentioned an empirical criterion that modelling for roughness due to large size materials should be done "if more than 10% of the gradiation has a size greater than 50 mm or if 5% is greater than 600 mm."

However, there is a conflicting report by Simoni and Houlsby (2006), who concluded that “the results clearly indicate that even at low gravel fractions (0.1–0.2), when the oversize particles are in a floating state within the sand matrix, the peak strength, constant volume strength and maximum dilatancy rate of the mixtures, are all higher than those for the sand at the same density.” They reported increased critical state friction angles for sand and gravel mixtures with gravel >30% in comparison to that of sand matrix. They used medium rounded to sub-angular silica sand, up to 2mm and medium rounded to subangular gravels up to 20mm.

Also, the importance of larger grains are mentioned by people who studied the lunar samples. Duke and Nagle (1975) found that “the grain size of core strata varies greatly, with the fraction greater than 1 mm ranging from 0 to 45% in different horizons”

---

1 There are, however, a few data sets of grain size distribution of Apollo samples up to 8 or 4mm (Fig 7.13, 7.18, and 7.20 of McKay et al. 1991). See Table 4.8.
within the two cores they studied. Heiken et al. (1976) stated, about Apollo 15 deep drill core, that "Lunar grain size data is most useful when subcentimeter data are used rather than submillimeter " (Heiken et al. 1976, p.97).

2.7. MODELS AND PRESENTATION OF SIZE DISTRIBUTION MODELS

2.7.1. Models. Grain size distribution of soil is often modeled by either power law, Rosin-Rammler curve, or lognormal curve (Table 2.4). Also there are various less known models such as Nukiyama–Tanasawa model (González-Tello et al. 2008), Gilvarry Distribution (Sil’vestrov 2004). Power law is often used to describe the grain size distribution of extraterrestrial soils or rocks (e.g. Smith 1967; Shoemaker and Morris 1969; Hartmann 1969; Cintala et al. 1982; Thomas et al. 2001; Saito et al. 2006) probably because the power law is the simplest choice when the cumulative number, \( N(>x) \), of grains larger than size \( x \), are plotted against size, \( x \), on a log-log plot.

However, the power law has a problem when it is used to model the grain size distribution. Mason (1969) pointed out two flaws in this application of power law, and suggested to use the lognormal size distribution. First flaw he pointed out is that the total area covered by the particles with the power-law size-distribution theoretically goes to infinity or indeterminate. This problem can be avoided by choosing a proper size interval in integration, which was done by Shoemaker and Morris (1969). Still, there is another problem. He argued that, even if the size interval is chosen properly, the size distribution (not cumulative one) deduced from the power law has its mode at the size extremes, which is highly improbable.

The lognormal size distribution is widely used by geologists to model sediments. Also lognormal model is applied to lunar soil by Carrier (2003).

\[
Y = \Phi \left( \frac{\ln x - \mu}{\sigma} \right)
\]

where \( Y \) is percentage of the cumulative mass of particles of particle size \( < x \), \( x \) is particle size, and \( \Phi(x) \) is a standard-normal cumulative-distribution-function defined as

\[
\Phi(x) = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{x}{\sqrt{2}} \right) \right]
\]
Table 2.4 Grain Size Distribution Models in Literature

<table>
<thead>
<tr>
<th>Source</th>
<th>Equation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoemaker and Morris (1969) in Surveyor Program Results, p83</td>
<td>$N = K x^\gamma$ [Eq (1) in p86]</td>
<td>$N$: the cumulative number of particles with diameter $\geq x$ per 100m$^2$. $x$: diameter of a particle in millimeters.</td>
</tr>
<tr>
<td>Hartmann, p201</td>
<td>$N = C m^{-b}$</td>
<td>$N$: the cumulative number of fragments of mass $&gt; m$, $m$: particle mass</td>
</tr>
<tr>
<td>Aswegen and Cunningham (1986), p469</td>
<td>$R = 100 \exp(-0.693 \left(\frac{x}{\bar{x}}\right)^n)$</td>
<td>$R$: mass of rock retained on screen size, $x$, % $x$: screen size $\bar{x}$: median fragment size, ie 50% passing size</td>
</tr>
</tbody>
</table>

Note: $b = \beta/3$ if assumed that $r$ is proportional to $m^{1/3}$. 
Table 2.4 Grain Size Distribution Models in Literature (continued)

<table>
<thead>
<tr>
<th>Miyamoto et al. (2007), p 5 in Supporting Online Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$: cumulative number of boulders $&gt; x$</td>
</tr>
<tr>
<td>$x$: size of gravel in m</td>
</tr>
<tr>
<td>$N(&gt;x) = 4.8 \times 10^4 x^{-2.8}$</td>
</tr>
<tr>
<td>$n(x) = 1.3 \times 10^5 x^{-3.8}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Smith (1967)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$: number per centimeter size range per square meter</td>
</tr>
<tr>
<td>$x$: boulder dimension in cm</td>
</tr>
<tr>
<td>$f(x) = P x^n = (25 cm^{-1} m^{-2}) x^{-n}$ where $n = 2.9$.</td>
</tr>
</tbody>
</table>

On the other hand, in mining industry (Aswegen and Cunningham 1986; Spathis 2004), it is common to use the Rosin-Rammler curve, which is also known as Weibull distribution, to describe the grain size distribution.

$$Y = 1 - \exp\left(-\frac{x}{x_c}\right)^n$$

(26)

where $Y$ is percentage of the cumulative mass of particles of particle size $< x$, and $x$ is particle size.

Many people stated that difference between Rosin-Rammler and lognormal are marginal (e.g. Tümanok 1998; Maerz and Zhou 2000; Kondolf and Adhikari 2000). In addition, log-hyperbolic or log-Laplace PDFs may be used to describe size distribution. However, as Ferguson and Paola (1997, p.1062) noted, “these three- and four-parameter distributions fit fluvial bed and bedload GSDs only slightly better than does the two-parameter log-normal model.” So two parameter models, such as Rosin-Rammler or lognormal model, are preferred.

2.7.2. Presentation of Grain Size Distribution Curve. There are several different types of presentation of size distribution data. Those types are classified according to four aspects: namely, frequency or cumulation; normalized data or raw data; number, volume, or mass; larger, smaller, heavier, or lighter. Data used by geotechnical engineers are cumulative, normalized mass of smaller particles. Geologists use
cumulative, normalized mass of larger particles. Data of extraterrestrial soils or rocks are often presented as cumulative, raw, number per area of larger particles (e.g. Smith 1967; Shoemaker and Morris 1969; Hartmann 1969; Thomas et al. 2001).

2.7.3. Converting the Number Density into the Volume Density. The grain size distribution can be described in terms of either the number density or the volume density. The number density is defined as the number of particles in unit area. The volume density is defined as the ratio of the sum of the volume of particles to the volume of the space that contains those particles.

The following procedure is based on Shoemaker and Morris (1969, p.86) in Surveyor Program Results.

For a given cumulative number of particles,

\[ N_i = \text{(number of particles of a size larger than } D_i) \]  

(27)

where \( D_i \) is grain size. Data is arranged so that \( D_i < D_{i+1} \) and \( N_i > N_{i+1} \).

The cumulative area, \( A_i \), of fragments of diameter larger than \( D_i \) is

\[ A_i = a \left( N_i - N_{i+1} \right) \]  

(28)

where \( a \) is a representative area of particles in a size range between \( D_i \) and \( D_{i+1} \), which is

\[ a = \pi \left( \frac{d_i}{2} \right)^2 \left( \frac{5}{6} \right) \]  

(29)

in which \( d_i = \sqrt[D_i]{D_{i+1}} \) is a geometric mean of \( D_i \) and \( D_{i+1} \), and a factor \((5/6)\) is correction for buried particles (Mason 1969).

The percentage of cumulative volume, \( V_i \), of particles with diameter larger than \( D_i \) is

\[ V_i = \frac{A_i}{A_0 (1-n)} \]  

(30)

where \( A_0 \) is the area over which the grains are counted, and \( n \) is porosity. This equation is based on the principle of Delesse, which states that volume density, \( V_v \), is equal to areal density, \( A_a \). “The areal density of profiles on sections is an unbiased estimator of the volume density of structures” (Weibel 1980, p58).

Besides using the Delesse’s principle to convert the area density into the volume density, the other method is to integrate the number density to obtain the volume density directly. This method is used by (Miyamoto et al. 2007; Ferguson and Paola 1997)
\[ V_i = n_i \pi \left( \frac{d}{2} \right)^3 \]  

(31)

where \( n_i = (N_i - N_{i+1}) \) is the number of particles in a size range between \( D_i \) and \( D_{i+1} \); \( d \) is grain size.

2.7.4. Extrapolation of Grain Size Distribution. Meloy and O’Keefe (1968) stated that “Size distribution curves are generally found to be capable of being extrapolated when they result from a single process of comminution.” Based on the pictures of the lunar surface taken by Surveyor landers, the grains of the size between 1mm and 1m are counted to produce grain size distribution. In Section 3 of Surveyor Program Results, Shoemaker and Morris (1969) tried to extrapolate the size distribution for the grains finer than 1mm. They used a pair of power law functions: one for the coarse range (>1mm) and the other for the fine range (<1mm).

Later, based on comparison with the Apollo data, Carrier (1973, p.261) concluded that "The techniques developed to extrapolate the Surveyor particle counts below a grain size of 1mm are quantitatively inaccurate and qualitatively misleading." Although McKay et al. 1991 (p 306, Chapter 7, Lunar Sourcebook) stated that "Carrier (1973) determined that accurate estimation of grain-size distribution from the television images was not possible," this notion of estimation from television images being not possible is too much generalization. The weak point of Shoemaker and Morris (1969)’s technique is that extrapolation of grain size distribution was made using power law. Power law is known to represent unrealistic size distribution as Mason (1969) noted. Even when appropriate size distribution model was size distribution models.

2.7.5. Difference Between the Surface Counts and the Volume Counts. There must be unavoidable difference between grain size distribution estimated from the pictures of the surface (surface counts) and that estimated from weighing a volume of soil (volume counts). Hartmann 1969 suggested “an additive correction to surface counts of about 0.2 to 0.3 (Hartmann 1969, p.204)” to obtain volume counts. After comparing the data from the Surveyor I observation with industrial experience, Meloy and O’Keefe (1968) found it difficult to justify the power law applied to Surveyor I data. They suggested that “the surface distribution is not representative of the distribution through a volume.” They discussed that “The centers of blocks with radii between 1 and 1.5 meters,
for example, would be concentrated over a range from 1 to 1.5 meters above the surface, i.e. in a range of 500mm. On the other hand, the centers of those blocks with sizes from 1.0 to 1.5 mm would be concentrated in a range of 0.5mm.” and concluded that “the surface distribution of fragments probably is richer in visible chunks than the volume as a whole.” Also there is another concern that the smaller particles might be missed due to resolution of picture more often than the larger particles.

Also definition of grain size is another issue. It is usually considered that sieving classifies grains by the length of their intermediate axis. However it is known that the mesh size does not equal to the intermediate axis length of grains. Oakey et al. (2005), in their Eq (1), relates the equivalent sieve mesh to the intermediate and short axis length. On the other hand, the longest axis may be taken as the grain size (e.g. Saito et al. 2006; Fig 1 of Cintala et al. 1982). Leopold (1970) suggest that the shorter axis appearing on the surface can be used as the intermediate axis. Unfortunately, for the grain size distribution data from Surveyor images, no clear definition of grain size is provided.

Adams (1979) stated that “In photographs of river bed gravels a proportion of the pebbles are partly concealed by other pebbles or sand, or are in shadow, so that the actual pebble axes are not observed. Even for completely exposed pebbles [where the long, A, axis is revealed], the apparent short, b, axis may be less than the intermediate, B, axis because of tilting of the pebble to reveal a diameter between the intermediate, B, and the short, C, axes. A size intermediate between the actual B and C axes is also measured by sieving because pebbles may pass diagonally through the square mesh holes of the sieves. Thus, on the average, measured axes will be smaller than actual axes for both methods, and an empirical correction for the bias involved in converting photograph to sieve sizes is needed.”
3. EXPERIMENTAL SETUP AND PROCEDURES

This section describes material acquisition and preparation, geotechnical characterization of JSC-1A lunar regolith simulant, as well as the experiment setup and procedures for the excavation experiment.

3.1. MATERIAL ACQUISITION AND PREPARATION

125kg of JSC-1A lunar regolith simulant was obtained from Orbital Technology Corporation (Orbitec), Madison, Wisconsin. JSC-1A was prepared from mineral mined from a commercial cinder quarry at Merriam Crater, a volcanic airfall ash deposit of basaltic composition near Flagstaff, Arizona (Rickman et al. 2007). JSC-1A resembles low-Ti lunar mare basalts from the Apollo 14 site (Sibille et al. 2005).

80kg of FJS-1 was supplied by Shimizu Corporation, Tokyo, Japan. The FJS-1 was developed in 1995, and is composed mainly of crushed basaltic lava obtained from Mt. Fuji area, and well simulates bulk mechanical properties and approximates chemical composition of Apollo samples in lunar mare region (Kanamori et al. 1998). Its grain size distribution is shown in Fig 3.1.

![Fig 3.1 Grain Size Distribution of Lunar Regolith Simulants, FJS-1 and MKS-1](Provided by Shimizu Corporation)
Construction grade sand, also called terrestrial sand, was obtained from a stockpile at Rock Mechanics Center. Railroad ballast material, Iron Mountain Trap rock, from Iron Mountain, MO was used as additive gravel. The density of grains is 2.65 g/cm³ (Table 1.1, Sevi 2008) was used. This railroad ballast is subangular gravels crushed by a jaw crusher to have a size range such that retained on 2.36mm sieve and passes 9.423mm sieve. This material alone has porosity of 47% when no compaction is applied. For studying the effect of gravel content, the railroad ballast material was mixed into the JSC-1A. The gravel content in the experiments was set to 0%, 5%, 10% and 30% by mass.

3.2. GEOTECHNICAL CHARACTERIZATION OF JSC-1A

3.2.1. Bulk Density. Bulk density of soil is determined as the mass of soil divided by the volume of soil. The density of soil varies depending on compaction or how its particles are packed. The bulk density takes its minimum value at its loosest state whereas it takes maximum value at its densest state. However it is not possible to measure the true minimum and maximum values. So the density values determined according to ASTM D4254 and D4253 are termed the minimum and maximum index densities, respectively.

3.2.2. Relative Density. Relative density is commonly used to characterize and compare the engineering behavior of granular material. Therefore, it is necessary to prepare the soil specimens at the same relative density as the in-situ value on the lunar surface. The relative density, $D_r$, is defined in terms of minimum and maximum dry densities as:

$$D_r = \frac{\rho_d - \rho}{\rho_d - \rho_d,\text{min}} = \frac{1}{\rho_d,\text{min}} - \frac{1}{\rho_d,\text{max}} x 100 \quad (32)$$

Where $\rho$ is dry density of a soil specimen, $\rho_d,\text{min}$ is minimum dry density, and $\rho_d,\text{max}$ is maximum dry density.

3.2.3. Grain Size Distribution Characterization. The particle size distribution of two specimens of JSC-1A was obtained by sieve and hydrometer analysis tests based
on ASTM D 422. Calculation for hydrometer analysis was done using a spreadsheet by Bardet (1997).

3.2.4. Direct Shear Tests. Direct shear tests were conducted on the JSC-1A lunar regolith simulant following the ASTM D 3080-04 procedure. The hydraulic servo-controlled direct shear test device was manufactured by GCTS (model# SDS-100), as shown in Fig 3.2. A cylindrical shear box with an inner diameter of 101.6 mm (4") was used. The rate of shearing displacement was set to 1 mm/min via the horizontal actuator. The vertical normal stress was applied by the servo-controlled hydraulic actuator and held constant at 8 kPa, 16 kPa, 33 kPa, and 66 kPa. As the horizontal displacement progressed, the vertical and horizontal stresses were measured by a load cell attached between an actuator and the shear box. The upper half of the box is allowed to slide vertically, which eliminate an error due to friction between the box and the soil (Shibuya et al. 1997). The precision of the loading actuators and load cell for this hydraulic machine is about 1.2 kPa. Additionally, for the purpose of experimental repeatability, another direct shear device from GeoTest Instrument Corp. (model# S2215A) was used. The GeoTest device employs manually controlled pneumatic actuators. The same procedures and settings were used with this tester.

The direct shear specimens were prepared dry at different relative density conditions (loose, medium dense, dense, and very dense). For the loose specimen, the simulant was placed as loosely as possible in the shear box by pouring the soil slowly using a funnel, just as it is prepared for the minimum index density test. Then, a porous stone disc was placed on top of the simulant. For the medium and dense specimens, simulant was placed in the same way, then a load was applied on the porous stone disc and, if needed, vibration was applied until the target volume was reached. For the very dense specimen, simulant was compacted by tamping layer by layer with a wood rod of about 25 mm diameter. Immediately before the start of the test, the specimen density, $\rho$, was determined by:

$$\rho = \frac{m}{\pi d^4 h}$$  \hspace{1cm} (33)

where $m$ is the mass of the specimen, $d$ is the diameter of the shear box, and $h$ is the height of the sample.
3.3. EXCAVATION EXPERIMENT

To evaluate the potential effect of ripping on the excavatability of compacted lunar regolith, a series of scaled blading tests was conducted on two materials: terrestrial sand and JSC-1A simulant.

3.3.1. Sample Preparation. Two different test boxes were used: setup 1 and 2 (Table 3.1). This section describes how they were set up for the tests.

3.3.1.1 First test box. Setup 1 was used to test with FJS-1 lunar regolith simulant. Setup 1 consists of a wooden test box of 564mm × 602mm and about 97mm deep, and a load cell measuring the horizontal force. Vibratory compactor used in setup 1 has a 400mm × 570mm base plate resulting in the static pressure of 1.59kPa applied to the soil. Since this large vibrator blows up loose simulant a lot, pre-compaction was performed before using the large vibrator. For pre-compaction, a piece of cardboard was placed to cover entire surface, on which the smaller vibrator was moved over the cardboard to settle loose sand. Then the larger vibrator was directly placed on the surface to compact simulant. Table 3.2 outline the compaction procedure followed.

3.3.1.2 Second test box. Setup 2 is an improvement of setup 1, and was used with JSC-1A lunar regolith simulant. Setup 2 is designed to allow longer excavation distance. The lunar regolith simulant was compacted to one of three different density levels in the 350 mm by 900 mm by 120 mm box (Fig 3.3) with the vibratory plate compactor shown in Fig 3.4 (Manufacturer: Bulk Equipment Systems Technology Inc. Model Number: BE-1320-2B, rated at 230 V, 1.6 A, 3385 rpm). Vibratory compactor is attached on a 330mm
Table 3.1 Characteristics of Excavation Experiment Setup

<table>
<thead>
<tr>
<th></th>
<th>Setup 1</th>
<th>Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>FJS-1</td>
<td>JSC-1A</td>
</tr>
<tr>
<td>Measured Bulk Density</td>
<td>1.90 g/cm³, 1.88 g/cm³</td>
<td>2.03 g/cm³, 1.83 g/cm³</td>
</tr>
<tr>
<td>Box</td>
<td>Wood</td>
<td>Aluminum</td>
</tr>
<tr>
<td></td>
<td>565mm × 602mm at maximum</td>
<td>350mm × 900mm</td>
</tr>
<tr>
<td></td>
<td>Sand depth: ~97mm</td>
<td>Sand depth: ~120mm</td>
</tr>
<tr>
<td>Sensor</td>
<td>500lb load cell (w/ large offset)</td>
<td>500lb load cell</td>
</tr>
<tr>
<td></td>
<td>Long arm that deflects</td>
<td>Direct</td>
</tr>
<tr>
<td></td>
<td>Max: ~6kgf</td>
<td>Max: 226kg</td>
</tr>
<tr>
<td>Compaction</td>
<td>Plate size:</td>
<td>Plate:</td>
</tr>
<tr>
<td></td>
<td>400mm × 570mm × 5/8”</td>
<td>330mm × 485mm ×</td>
</tr>
<tr>
<td></td>
<td>thick wood</td>
<td>1/4” thick stainless steel</td>
</tr>
<tr>
<td></td>
<td>Pressure: 1.59kPa</td>
<td>Pressure: 1.94kPa</td>
</tr>
<tr>
<td></td>
<td>Procedure 1</td>
<td>Procedure 2</td>
</tr>
<tr>
<td>Density Measurement</td>
<td>Open tube alone</td>
<td>Open tube and bottom cup</td>
</tr>
<tr>
<td>Initial Excavation</td>
<td>Tool is pushed in.</td>
<td>Material is dug by hand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>for a wide blade.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tool is pushed in for tines.</td>
</tr>
<tr>
<td>Wide blade</td>
<td>1/16” thick, 100mm wide steel</td>
<td>1/4” thick, 100mm wide aluminum</td>
</tr>
</tbody>
</table>

Table 3.2 Procedure for Compaction of Simulant on Setup 1

1. Surface is made smooth and flat with a blade manually. But center area is raised to compensate subsiding by compaction.
2. A cardboard lid is placed on the surface before the vibrator is placed.
3. Small vibrator is moved over the cardboard lid.
4. Large vibrator is placed and run for 15 seconds.
× 485mm stainless steel plate with static pressure of 1.94kPa, and is moved back and forth during compaction as needed.

To prepare loose or medium dense soil, the entire test sample is loosened. The test box is first mated with another box of identical size and shape, with a 1/2” opening steel mesh between them (Fig 3.5). Those two boxes are fastened together before rolling over twice (Fig 3.6) to let the soil pass through the steel mesh, which loosens the soil compacted by a previous experiment run.

The compactor consists of the vibrator, a steel plate, and two handles. The bottom area of the compactor is 480 mm × 330 mm. The weights of the vibrator and the steel plate are 20.26 kg and 11.12 kg, which total 31.38 kg. The static pressure is 1.94 kPa. A handle weighs 0.61 kg.

The construction grade sand was compacted to the density level chosen for the test. Previous work (Gertsch et al. 2006) has shown that vibration is more effective than static pressure in creating the relative densities of dry regolith that have been observed on the Moon; it is similar to the impact-generated vibrations believed to densify the lunar regolith in situ.

Applying the portable compactor at different speeds, bias weights, and lengths of time enabled the simulant in the test box to be compacted to several different relative densities. Table 3.3 outline the compaction procedures followed for excavation test setup 2.

3.3.1.3 Preparation of samples with gravel added. If the sample with gravel added is repeatedly disturbed and compacted, the gravel content tends to increase in the disturbed part. For testing with the mixture of fines and gravel, it is necessary to make sure the sample is homogeneous. To achieve that, the entire sample in the test box was occasionally stirred to avoid accumulation of gravels.
Table 3.3 Procedure for Compaction of Simulant on Setup 2

1. Surface is made smooth and flat with a blade manually. But center area is raised to compensate for subsiding by compaction.
2. Loose material is tamped with a wood block manually.
3. A lid is placed on the surface.
4. The vibrator is placed on the lid.
5. The vibrator is turned on and moved back and forth 5 times.
6. Top portion is skimmed off by the actuated wide scraper.
Fig 3.5 Pair of Boxes for Preparation of Looser Soil

Fig 3.6 Loosening Procedure For Re-Initializing the Test Sample
3.3.2. Experiment Procedure. The test box was mounted beneath an instrumented tool carriage that moves at a constant nominal speed of about 8mm/s along the long axis of the box (Fig 3.7). The tool depth is set prior to each test. The force sensor on the tool carriage measures the horizontal force experienced by the tool during its traverse through the material. The scaled excavation tools used in this experiment (Fig 3.8) were designed to independently simulate ripping and blading. Ripping means loosening by a ripper in Fig 3.8 (A). The term, blading, is defined as earthmoving by a wide blade shown in Fig 3.8 (B).

Dozing, or blading, was modeled with a 100mm wide flat blade, and ripping was modeled with a rake of similar width that could be adjusted to mount a variable number of tines. It had eight positions at 15mm intervals for attaching 1.3mm × 75mm tines. Thus the test program was designed to evaluate the effects of tine spacing and depth, along with regolith density and gravel content.
Two types of tests were conducted. The first type was the control, in which the blade (Fig 3.8 B) was simply pulled across the regolith surface at a constant depth of 30 mm. The second type of test first pulled the rake (simulating a ripper, Fig 3.8 A) through the regolith at the same constant depth, then bladed the sample in the same configuration as used in the control test. Different numbers and positions of tines were tested in different series of tests. All tests discussed here kept the tool depth constant at 30mm with a few exceptions where data for 30mm deep excavation is accompanied with that for 45mm deep excavation. The specific test procedures are outlined below for the two test setups.

- Procedure for Excavation Run on Steup 1:
  1. Bring the carriage to the starting position.
  2. Attach a rod to the carriage to check levelness of the surface. Set its length so that the rod scratch the surface ~1mm.
  3. Move the carriage back and forth. If the scratch shows the surface is uneven, redo compaction.
  4. Attach the excavation tool to the carriage.
  5. Lower the tool and push it down to the digging depth.
  7. Flip the actuator switch.
  8. Stop the actuator when the builtin sand reaches the end of box
Procedure for Excavation Run on Setup 2:

1. Remove the gantry and the carriage from the test box.
2. Compact soil.
3. Set the gantry and the carriage back.
4. Bring the carriage to the starting position.
5. Skim off the top uneven surface with a wide scraper if necessary. Adjust height so the lowest surface is slightly (~1mm) skimmed.
6. Move the carriage to the other end and then back to the starting position.
7. Attach the excavation tool to the carriage. Lower the tool so it touches the surface.
8. Put a plate just in front of the tool, and push it down to the digging depth.
9. Dig soil behind the tool to the digging depth.
10. Lower the tool to the digging depth.
11. Start logging after making sure the tool does not touch anything.
12. Remove the plate.
13. Flip the actuator switch.
14. Stop the actuator when the buildup sand reaches the end of box.

3.3.3. Data Acquisition. The schematic of the data acquisition system for the experiment is shown in Fig 3.9. The reaction forces measured by load cells were logged by a computer at a rate of 100Hz. In addition, the voltage applied to the actuator was logged as well.

The load cells were connected to amplifiers, which output the voltage proportional to the load. The output of the amplifier was then wired to a DAQ terminal box, which was connected to a DAQ card (manufacturer: National Instruments) so that the LabView software on the computer can record the voltage data.

3.3.4. Density Measurement during Experiments. Density of simulant compacted in the test box was measured by taking a core sample with a sampler tube (Fig 3.10). During filling of the test box, cups affixed on top of stiff rods are buried at the bottom of the test box. The sampler tube is pushed into the soil directly above one of the buried cups. Once the contact between the sampler tube and the cup is confirmed by an electrical conductivity checker, the soil stopper, which is connected to the sampler tube,
(*) Load Cell X and Y measures the horizontal and vertical components of excavation force.

(†) Switches control the direction of motor rotation.

is held against the surface of the soil sample so the soil is prevented from loosening during handling. Then the cup and the tube are taken out of the soil by pushing the stiff rod up.

Fig 3.9 Data Acquisition System for Experiment

Fig 3.10 Soil Sampler for Density Measurement (A) Procedure (B) The Sampler Tube
The core sample is then weighed to calculate its density:

\[ \rho = \frac{M}{AL} \]  \hspace{1cm} (34)

where \( \rho \) is density, \( M \) is mass of sample, \( A \) is cross-sectional area of sample, and \( L \) is length of sample.

The error of density caused by errors in the measured parameters is

\[ \Delta \rho = \frac{\Delta M}{AL} - \frac{M}{A^2L} \Delta A - \frac{M}{AL^2} \Delta L \]  \hspace{1cm} (35)

\[ \Delta \rho = \rho \left( \left| \frac{\Delta M}{M} \right| + \left| \frac{\Delta A}{A} \right| + \left| \frac{\Delta L}{L} \right| \right) \]  \hspace{1cm} (36)

Error in the cross-sectional area, \( \Delta A \), is assumed to be zero since the diameter of the tube was measured with a caliper with relatively high accuracy. Error in other parameters are \( \Delta M = 1 \text{g} \), \( \Delta L = 1/32 \text{ inches} \).

For the sections of cores, parameters have similar values, such as \( M = 120 \text{g} \), \( L = 3 \text{cm} \). Those values give an error in density measurement of 0.07g/cm\(^3\).

For overall density measurement of cores, parameters are approximately \( M = 400 \text{g} \), \( L = 9 \text{cm} \). Those values give an error in density measurement of 0.02g/cm\(^3\).

In addition to the inaccuracy due to \( \Delta M \) and \( \Delta L \), another cause of error was spilling of simulant that was trapped in the gap between the tube and the rod. Probably this spill only affects the density of top section and the average density of all the sections. The resulting error is 0.06g/cm\(^3\) at maximum for the top sections.

Combining the error factors above, it is expected that the measured values of density have an average error of about 0.1g/cm\(^3\).

### 3.4. SIMILITUDE

It should be noted that these experiments were done in Earth's gravity to simulate excavation in lunar gravity, and that they were done with reduced-size equipment. These differences in scale needed to be taken into account. The main quantities involved in the phenomenon of excavation are gravitational acceleration, density, cohesion, mass, length,
and force. Lunar gravity is 1/6 of Earth's gravity. Since the JSC-1A regolith simulant is constructed to replicate the real lunar regolith at full size, the density and cohesion of the material in our experimental setup scale are equivalent to those of the lunar regolith. Therefore the scale factors for density and cohesion are set to one.

It is known that grain size poses a limitation in scaling of soil-structure interaction. Garnier et al. (2007) compiled a catalogue of scaling laws citing published data based on centrifuge tests. For example, the characteristic size of a shallow circular footing has to be larger than 35 times the mean grain diameter; the characteristic size of anchor plates has to be larger than 48 times the mean grain diameter.

The scaling factors that must be used to interpret the findings of this study are derived from dimensional analysis, as presented below. This procedure is based on Szucs (1980, p106). Dimensional analysis is only one of the ways to formulate similitude. If there is a mathematical model known to describe the phenomenon, scaling factors are derived from that model. When no functional model is available, dimensional analysis allows scaling factors to be determined without such a model.

First, the dimensions of the quantities of interest are listed. There are seven quantities, which are built up from three basic quantities. The Buckingham $\pi$ theorem indicates that the relationship between those seven quantities can be equivalently re-expressed by four ($=7-3$) dimensionless numbers.

\[
\begin{align*}
\text{Gravitational acceleration:} & \quad [g] = LT^{-2} \quad (37) \\
\text{Density:} & \quad [\rho] = ML^{-3} \quad (38) \\
\text{Cohesion:} & \quad [c] = ML^{-1}T^{-2} \quad (39) \\
\text{Mass:} & \quad [m] = M \quad (40) \\
\text{Length:} & \quad [l] = L \quad (41) \\
\text{Force:} & \quad [f] = MLT^{-2} \quad (42) \\
\text{Velocity:} & \quad [v] = LT^{-1} \quad (43)
\end{align*}
\]

The above equations are summarized in Table 3.4, which shows the relationships between a quantity and the basic quantities of mass, length, and time.
Table 3.4 Dimensions of Quantities

<table>
<thead>
<tr>
<th></th>
<th>(M)</th>
<th>(L)</th>
<th>(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity: $g$</td>
<td>0</td>
<td>1</td>
<td>−2</td>
</tr>
<tr>
<td>Density: $\rho$</td>
<td>1</td>
<td>−3</td>
<td>0</td>
</tr>
<tr>
<td>Cohesion: $c$</td>
<td>1</td>
<td>−1</td>
<td>−2</td>
</tr>
<tr>
<td>Mass: $m$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Length: $l$</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Force: $f$</td>
<td>1</td>
<td>1</td>
<td>−2</td>
</tr>
<tr>
<td>Velocity: $v$</td>
<td>0</td>
<td>1</td>
<td>−1</td>
</tr>
</tbody>
</table>

Taking logarithm of the above equations leads to the following.

\[
\log[g] = \log[L] - 2\log[T] \quad (44) \\
\log[\rho] = \log[M] - 3\log[L] \quad (45) \\
\log[c] = \log[M] - \log[L] - 2\log[T] \quad (46)
\]

Those three simultaneous equations are solved for $\log[L]$, $\log[T]$, and $\log[M]$.

\[
\log[g] + \log[\rho] = \log[M] - 2\log[L] - 2\log[T] \quad (47) \\
\log[c] - (\log[g] + \log[\rho]) = \log[L] \quad (48) \\
\log[g] - (\log[c] - (\log[g] + \log[\rho])) = -2\log[T] \quad (49) \\
2\log[g] - \log[c] + \log[\rho] = -2\log[T] \quad (50)
\]

\[
\log[\rho] + 3(\log[c] - (\log[g] + \log[\rho])) = \log[M] \quad (51) \\
3\log[c] - 3\log[g] - 2\log[\rho] = \log[M] \quad (52)
\]

Now that each of $\log[L]$, $\log[T]$, and $\log[M]$ was expressed in terms of $\log[g]$, $\log[c]$, $\log[\rho]$. It is possible to express the dimension of the rest of the quantities of interest (namely $m$, $l$, $f$, and $v$) in terms of $\log[g]$, $\log[c]$, $\log[\rho]$.

\[
\log[m] = \log[M] - 3\log[c] - 2\log[\rho] \quad (53) \\
\log[l] = \log[L] - \log[c] - (\log[g] + \log[\rho]) \quad (54) \\
\log[f] = \log[M] + \log[L] - 2\log[T] \quad (55)
\]
\[
\begin{align*}
&= (3\log[c] - 3\log[g] - 2 \log[\rho]) + (\log[c] - (\log[g] + \log[\rho])) \\
&+ (2\log[g] - \log[c] + \log[\rho]) \\
&= - 2\log[g] - 2 \log[\rho] + 3\log[c] \\
\log[v] &= (\log[c] - (\log[g] + \log[\rho])) - (2\log[g] - \log[c] + \log[\rho])/(-2) \\
&= \log[c] - \log[g] - \log[\rho] + \log[g] - \log[c]/2 + \log[\rho]/2 \\
&= (1/2)\log[c] - (1/2)\log[\rho] \\
\end{align*}
\]

Simplifying those, one gets
\[
\begin{align*}
3\log[c] - 3\log[g] - 2 \log[\rho] - \log[m] &= 0 \\
\log[c] - \log[g] - \log[\rho] - \log[l] &= 0 \\
- 2\log[g] - 2 \log[\rho] + 3\log[c] - \log[f] &= 0 \\
\log[c] - \log[\rho] - 2\log[v] &= 0
\end{align*}
\]

Those equations can then be converting back to the form without logarithm.
\[
\begin{align*}
\frac{c^3}{g^3 \rho^2 m} &= \pi_1 \\
\frac{c}{g \rho l} &= \pi_2 \\
\frac{c^3}{g^2 \rho^2 F} &= \pi_3 \\
\frac{c}{\rho v^2} &= \pi_4
\end{align*}
\]

If those dimensionless parameters, \( \pi_i \), are unchanged between two different instances of phenomena, those phenomena are considered to be similar to each other.

If the dimensionless number, \( \pi_1 \), is kept unchanged, then
\[
\frac{c^3}{g^3 \rho^2 m} = \frac{c'^3}{g'^3 \rho'^2 m'}
\]

which can be rearranged to obtain
\[
\left( \frac{c}{c'} \right)^3 \left( \frac{g'}{g} \right)^3 \left( \frac{\rho'}{\rho} \right) \left( \frac{m'}{m} \right) = 1
\]
Since the same material is used on the Moon and on the Earth, its density and cohesion must be common to the real and scaled phenomena. Therefore $\rho = \rho'$ and $c = c'$, which simplifies the above equation.

$$\left( \frac{g'}{g} \right)^3 \left( \frac{m'}{m} \right) = 1$$  \hspace{1cm} (67)

If $g'/g = n$, $m'/m = 1/n^3$.

Using the same approach and again setting $\rho = \rho'$ and $c = c'$, $\pi_2$ through $\pi_4$ lead to the following relationships:

$$\pi_2: \frac{c}{g' \rho' F} = \frac{c'}{g \rho F} \Rightarrow \frac{c}{g' \rho' F} \left( \frac{\rho'}{\rho} \right) \left( \frac{g'}{g} \right)^2 = 1 \Rightarrow \frac{g'}{g} = 1 \Rightarrow \text{if } g'/g = n, \frac{l'}{l} = 1/n.$$  \hspace{1cm} (68)

$$\pi_3: \frac{c'}{g' \rho^2} = \frac{c'}{g \rho^2} \Rightarrow \frac{c'}{g' \rho^2} = 1 \Rightarrow \frac{g'}{g} = 1 \Rightarrow \text{if } g'/g = n, \frac{F'}{F} = 1/n^2.$$  \hspace{1cm} (69)

$$\pi_4: \frac{c}{\rho v^2} = \frac{c'}{\rho' v'^2} \Rightarrow \frac{c}{\rho v^2} \left( \frac{\rho'}{\rho} \right) \left( \frac{v'}{v} \right)^2 = 1 \Rightarrow \frac{v'}{v} = 1 \Rightarrow v' = v.$$  \hspace{1cm} (70)

The above results are summarized in Table 3.5, and confirm the analysis summarized in Table 5.4 of Wood (2004).

Setting the scaling factor of gravity, stress, and density to $1/6$, $1$, and $1$, respectively, the above dimensional analysis results in the scale factor for length on the Moon being 6 times larger than on the experiment setup, the force scale factor being 36 times larger, the velocity scale factor being 1, and the mass and energy scale factors being 216 times larger. In other words, the blade and the ripper tested in these experiments are assumed to replicate the behavior of a tool 600mm wide, operating at the same speed on the Moon.

3.5. STUDY OF LARGE GRAINS IN LUNAR REGOLITH

In order to investigate the effect of large grains in the lunar regolith, which have been overlooked in past researches, data from Surveyor, Luna, and Apollo missions are used.
Ratio of coarse portion of the regolith, which varies along depth, is estimated from the results of analysis of Apollo cores. Data for 11 cores published in Lunar News (1978, 1979, 1980, 1981, 1982, 1986, 1987, 1988, 1992, 1993, 1994, and 1995) are used in this study. The core had been dissected in 5mm depth increments along three 1-cm-thick longitudinal layers (sections) starting at the top of the selected section and continuing through the length of the core. Soil from each increment of sections was separated into coarse and fine fractions using a 1-mm sieve (Schwarz 1994). Based on the mass of each fraction in each interval, the mass ratio of coarse fraction to the total mass of the increment was plotted against depth from the surface.

Surface grain count for a size range from 1mm to 1000mm is based on published analysis of the images of lunar surface taken by Surveyor landers and Luna 9 lander. This data is converted to a grain size distribution data based on mass by the procedure explained in Section 2.7. Then this grain size distribution is combined together with average grain size distribution data of fines, which Carrier (2003) deduced from about 350 samples collected during Apollo missions and Luna 24 mission. When combining two size distributions for different size range, it is necessary to estimate mass ratio of coarse grains (>1mm) to total, which is conducted based on data of Apollo samples.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>(Quantity under ng)/(Quantity under 1g)</th>
<th>If n = 1/6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>a'/a</td>
<td>n</td>
<td>1/6</td>
</tr>
<tr>
<td>Stress</td>
<td>σ'/σ</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Density</td>
<td>ρ'/ρ</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Length</td>
<td>L'/L</td>
<td>1/n</td>
<td>6</td>
</tr>
<tr>
<td>Mass</td>
<td>m'/m</td>
<td>1/n³</td>
<td>216</td>
</tr>
<tr>
<td>Force</td>
<td>F'/F</td>
<td>1/n²</td>
<td>36</td>
</tr>
<tr>
<td>Velocity</td>
<td>v'/v</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
4. RESULTS AND DISCUSSION

4.1. CHARACTERIZATION OF SOILS USED IN EXPERIMENTS

Before going on to the results of the excavation tests, Section 4.1 discusses the characteristics of the tested material.

4.1.1. Size Distribution Characteristics of JSC-1A. The measured grain size distribution is shown by a blue line in Fig 4.1 and Table 4.1 with parameters in Table 4.2. This grain size distribution has slightly shallower curve than those obtained by other researchers as shown in Fig 4.1. Nevertheless, this grain size distribution is within the 1-
Table 4.1 Results of Sieve Analysis and Hydrometer Tests

<table>
<thead>
<tr>
<th>Grain size (mm)</th>
<th>% finer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>100.0%</td>
</tr>
<tr>
<td>0.85</td>
<td>95.4%</td>
</tr>
<tr>
<td>0.425</td>
<td>83.9%</td>
</tr>
<tr>
<td>0.25</td>
<td>73.2%</td>
</tr>
<tr>
<td>0.15</td>
<td>60.4%</td>
</tr>
<tr>
<td>0.075</td>
<td>40.8%</td>
</tr>
<tr>
<td>0.0287</td>
<td>20.3%</td>
</tr>
<tr>
<td>0.0195</td>
<td>13.5%</td>
</tr>
<tr>
<td>0.0118</td>
<td>9.0%</td>
</tr>
<tr>
<td>0.0085</td>
<td>7.5%</td>
</tr>
<tr>
<td>0.0060</td>
<td>6.7%</td>
</tr>
<tr>
<td>0.0030</td>
<td>6.0%</td>
</tr>
<tr>
<td>0.0012</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

Table 4.2 Parameters of the Grain Size Distribution Curve of JSC-1A

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{60}$</td>
<td>0.148mm</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>0.110mm</td>
</tr>
<tr>
<td>$D_{30}$</td>
<td>0.050mm</td>
</tr>
<tr>
<td>$D_{10}$</td>
<td>0.013mm</td>
</tr>
<tr>
<td>$C_u$</td>
<td>11.0</td>
</tr>
<tr>
<td>$C_c$</td>
<td>1.3</td>
</tr>
</tbody>
</table>

standard deviation range of Apollo samples (Carrier 2003). The size distribution of the simulant used for this project reaches 100% at grain size of 2mm while the curve by
USGS reaches 100% at 1mm. Although JSC-1A is designed and fabricated to have 1mm grains or smaller, particles are retained on the 1mm sieve. Comparing to the ±1 standard deviation range of the lunar samples from Apollo 11 through 17 and Luna 24 (Carrier 2003), JSC-1A is almost within the typical range of lunar soil but is slightly more sorted. The simulant classifies as silty sand, SM, according to the USCS (Unified Soil Classification System; ASTM D2487-06). The silt-size content of the simulant by weight is as high as 40% and the clay-size content by weight is 6%. The parameters that typically describe the shape of the particle size distribution curve, $C_u$ and $C_c$, are presented in Table 4.2 with the corresponding $D_{10}$, $D_{30}$, $D_{50}$, and $D_{60}$ values. Those values indicate that the simulant can be described as well-graded, according to the criterion for separating well-graded sand from poorly-graded sand, i.e. $C_u \geq 6$ and $1 \leq C_c \leq 3$. Bernold (1991) and Carrier (2003) also suggested this description. Since USCS is designed to classify terrestrial soils, classification of soils with significant amounts of fines focuses more on the effect of water or plasticity. Fine-grained soils have more particles and more surface area per unit weight than coarser particles, and thus largely affect the behavior of soil with water. Therefore, according to USCS, the well-graded/poorly-graded distinction is not considered for sands with more than 12% fines, and JSC-1A falls in this category. Since there is no liquid water on the moon, there is no need to consider the effect of water on the fine-grained portion of the lunar regolith or its simulants.

**4.1.2. Particle Shape of JSC-1A.** The average specific gravity of the JSC-1A particles was determined to be $G_s = 2.90 \text{g/cm}^3$ according to ASTM D 854. The shapes of some representative particles are shown in Fig 4.2. Particles are classified as spherical to subprismoidal with sub angular to angular shape by visual comparison to the commonly used Powers (1982) chart. Figure 4.2 were captured with a Keyence VK-9700 3D Color Laser Confocal Microscope (18,000×), which provides the third dimension of the particle and its real color, unlike the SEM. Figure 4.2 (A) shows the 3D shape of a grain whereas (B) and (C) show the 2D view of grains.

**4.1.3. Minimum and Maximum Index Density of JSC-1A.** Table 4.3 shows $\rho_{\text{min}}$ and $\rho_{\text{max}}$ of JSC-1A determined according to Method A of ASTM D 4254-00 and ASTM D 4253-00. The measured $\rho_{\text{min}}$ is 4% lower than the other published data. Since the minimum density measurement is very sensitive to vibration during preparation, large
variation between operators is expected. Carrier et al. (1991) reported in their Table 9.6 the typical average values of relative density for lunar regolith as a function of depth, ranging from 65% to 92% for 60cm deep and shallower.

Fig 4.2 Microscopic Images of JSC-1A Particles (Picture provided by R. Pfaff at Keyence with help of D. Vidt)

<table>
<thead>
<tr>
<th></th>
<th>$\rho_{\text{min}}$, g/cm$^3$</th>
<th>$\rho_{\text{max}}$, g/cm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>1.53±0.01</td>
<td>2.03±0.02</td>
</tr>
<tr>
<td>Zeng et al. (2009)</td>
<td>1.566 (1.545-1.578)</td>
<td>2.028 (2.019 - 2.036)</td>
</tr>
<tr>
<td>Alshibli &amp; Hasan (2009)</td>
<td>1.556</td>
<td>2.016</td>
</tr>
</tbody>
</table>
4.1.4. Grain Size Distribution of Construction Grade Sand. The grain size distribution of the construction grade sand used in this study is shown in Fig 4.3. The associated parameters are listed in Table 4.4. This Construction grade sand is classified as SP, poorly graded sand, according to USCS (ASTM D 2487-06). Particle shapes are rounded to sub rounded.

![Grain Size Distribution Curve of Construction Grade Sand](image_url)

**Table 4.4 Size Distribution Parameters of Construction Grade Sand**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_c$</td>
<td>1.0</td>
</tr>
<tr>
<td>$C_u$</td>
<td>2.3</td>
</tr>
<tr>
<td>$D_{60}$</td>
<td>0.438 mm</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>0.384 mm</td>
</tr>
<tr>
<td>$D_{30}$</td>
<td>0.296 mm</td>
</tr>
<tr>
<td>$D_{10}$</td>
<td>0.193 mm</td>
</tr>
</tbody>
</table>
4.2. DIRECT SHEAR TESTS OF JSC-1A

Direct shear tests were conducted on specimens prepared at different relative densities. Figure 4.4, Fig 4.5, Fig 4.6, and Fig 4.7 show the shear stress, normal displacement, and dilatancy angle vs. shear displacement for each of the four relative densities used. For each density, four tests were conducted at different level of normal stress, specifically 8kPa, 16kPa, 33kPa, and 66kPa.

Shear stress curves for the very dense specimens >2.01g/cm³ (Dr>97%) exhibited a characteristic shape. Those curves show a steep rise and drop before and after the peak stress, followed by almost constant critical state stress. The dense specimen ~1.85g/cm³ (Dr=70%) is dense enough to show a more gradual peak at the higher normal stresses and the critical state stress shows a gradual decline. The medium and loose specimens do not show clear peak stresses.

The peak shear stress and critical state shear stress were plotted against normal stress, generating Mohr diagrams (Fig 4.8) from which the internal friction angle, $\phi_{ds}$, was determined (Table 4.5). Note that the repeatability of the tests is confirmed by the near-equivalence of the data obtained by the hydraulic apparatus with that obtained by the pneumatic apparatus (Fig 4.9 and Fig 4.10). Where particle interlocking plays a more significant role, in other words, in denser specimens, the Mohr diagrams become more curved (Fig 4.8). A power-law curved model,

$$\tau = a\sigma^b$$

was suggested by Carrier et al. (1991), who gave preliminary values of $a = 1.83$ and $b = 0.73$ for lunar soil when the stresses are expressed in kilopascals. Parameters, $a$ and $b$, are associated with the conventional parameters, $c$ and $\phi$, by the equations,

$$\tan\phi = ab\sigma^{b-1}$$  \hspace{1cm} (72)

$$c = a(1-b)\sigma^b$$  \hspace{1cm} (73)

Note that $c$ and $\phi$ are dependent on the normal stress, $\sigma$. A straight line fit is shown for comparison to the power-law curve and to the fitting parameters $c$ and $\phi$ commonly used in geotechnical engineering. So, the trend line described by parameters, $c$ and $\phi_{ds}$, should be regarded as a first-order approximation of the failure envelope, and are valid for the stress range of the tests. The parameter, $c$, for the highest density (>2.01g/cm³ or $D_r > 97\%$) is large compared to the $c$ values for lower densities, which is
Shear Stress, $\tau$, kPa

- $\sigma_{\text{mean}} = 68$ kPa
- $\sigma_{\text{mean}} = 33$ kPa
- $\sigma_{\text{mean}} = 15$ kPa
- $\sigma_{\text{mean}} = 8$ kPa

Nominal Shear Strain, %

Nominal Shear Strain, %

Normal Displacement, mm

Dilatancy Angle, $\psi$, degrees

Shear Displacement, mm

Fig 4.4 Test Results (Very Dense, $D_r > 97\%$)
Fig 4.5 Test Results (Dense, $D_r = 68\%-72\%$)
Fig 4.6 Test Results (Medium Dense, D_r = 43%-51%)
Fig 4.7 Test Results (Loose, $D_t = 13\%-18\%$)
Normal Stress, $\sigma$, kPa

Shear Stress, $\tau$, kPa

Peak
$\tau = 11.13 \sigma^{0.70}$

$(c, \phi)_{\text{Peak}} = (37.5 \text{kPa}, 68.1^\circ)$

Crit.
$\tau = 1.60 \sigma^{0.88}$

$(c, \phi)_{\text{Crit.}} = (2.3 \text{kPa}, 44.2^\circ)$

Peak
$\tau = 2.54 \sigma^{0.86}$

$(c, \phi)_{\text{Peak}} = (5.6 \text{kPa}, 52.8^\circ)$

Crit.
$\tau = 1.59 \sigma^{0.84}$

$(c, \phi)_{\text{Crit.}} = (5.7 \text{kPa}, 34.9^\circ)$

Peak
$\tau = 1.26 \sigma^{0.96}$

$(c, \phi)_{\text{Peak}} = (0.8 \text{kPa}, 46.2^\circ)$

Crit.
$\tau = 0.99 \sigma^{0.97}$

$(c, \phi)_{\text{Crit.}} = (0.9 \text{kPa}, 41.0^\circ)$

Peak
$\tau = 1.00 \sigma^{0.90}$

$(c, \phi)_{\text{Peak}} = (0.8 \text{kPa}, 34.1^\circ)$

Crit.
$\tau = 0.90 \sigma^{0.92}$

$(c, \phi)_{\text{Crit.}} = (0.6 \text{kPa}, 33.4^\circ)$

(a) Very Dense $D_t > 97$

(b) Dense $D_t = 68\%-72$

(c) Medium Dense $D_t = 43\%-51$

(d) Loose $D_t = 13\%-18$

Fig 4.8 Mohr Diagrams of JSC-1A for Four Different Specimen Densities Based on Direct Shear Test Results
Table 4.5 Internal Friction Angle, $\phi_{ds}$, of JSC-1A

<table>
<thead>
<tr>
<th></th>
<th>Density, g/cm³</th>
<th>Relative Density, %</th>
<th>Peak, deg.</th>
<th>Critical State, deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose</td>
<td>1.58 - 1.60</td>
<td>13 – 18</td>
<td>34.1°</td>
<td>33.4</td>
</tr>
<tr>
<td>Medium</td>
<td>1.71 - 1.75</td>
<td>43 – 51</td>
<td>46.2°</td>
<td>41.0</td>
</tr>
<tr>
<td>Dense</td>
<td>1.84 - 1.86</td>
<td>68 – 72</td>
<td>52.8°</td>
<td>34.9</td>
</tr>
<tr>
<td>Very Dense</td>
<td>&gt; 2.01</td>
<td>&gt; 97</td>
<td>68.1°</td>
<td>44.2</td>
</tr>
</tbody>
</table>

Fig 4.9 Mohr Diagram: Peak Shear Stress Values Obtained by Pneumatic Apparatus and by Hydraulic Apparatus. Specimen density is 1.67-1.74 g/cm³ for Pneumatic, 1.73-1.75 g/cm³ for Hydraulic (1), and 1.66-1.69 g/cm³ for Hydraulic (2)
reasonable for overconsolidated materials (in this case overcompacted). The internal friction angle for the densest specimens is surprisingly high, nearly 70 degrees, whereas it is approximately 30 degrees for the loosest specimens.

Normal displacement curves show no or little contraction for any of the specimens except for the loosest specimen. It is obvious that compacted JSC-1A is highly dilatant. Dilatancy angle, $\Psi$, was calculated using the following equation under the assumption of plane strain conditions (Bolton 1986; Wood 1990).

$$\frac{dy}{dx} = - \tan \Psi \quad (74)$$

where, $dx$ and $dy$ are the horizontal and vertical displacement increments (negative for dilation) in the direct shear test (Fig 4.11). Figure 4.4 (c) thru Fig 4.7(c) show the trend of the dilatancy present only at pre-critical state stress conditions. It is observed that the dilation angle gets smaller as the normal stress increases, but this trend is not always noticeable. This is only clear in Fig 4.5 for a relative density of about 70%.
4.2.1. **Range of Normal Stresses.** The normal stresses used in the shearing tests (8 kPa to 66 kPa) correspond to depths of 3 m to 24 m below the lunar surface (Fig 2.1). It has to be admitted that most foreseen near-term lunar activities are at shallow depths of not more than 5 m. Also the current consensus is that “the regolith is generally about 4-5 m thick in the mare areas but may average about 10-15 m in older highland regions.” (McKay et al. 1991, p. 286). However, the choice of the range of normal stresses (8 to 66kPa) is comparable to the confining stresses used in previous research on JSC-1A. This comparison is needed to establish a correlation between direct shear data and triaxial data on JSC-1A.

For example, in the published triaxial data on JSC-1A, Arslan and Batiste (2007) used normal stress of 15kPa to 60kPa; Alshibli and Hasan (2009) used 10kPa to 200kPa; Zeng et al. (2009) used 100kPa to 200kPa. Even with samples of the returned lunar soil, Carrier et al. (1973) used 31kPa to 69kPa for normal stress in their direct shear tests; and Scott (1987) used 26kPa to 55kPa in their triaxial tests. Jaffe (1973) is exceptional in that he used normal stress of 0.032kPa to 31kPa (corresponding to 0.01m to 11m deep on the Moon) on his miniature shear apparatus with a 1.3g sample.

4.2.2. **Friction Angle vs Relative Density.** Figure 4.12 shows the friction angles plotted against relative density with two trend lines; one for the peak friction angle, the other for the critical state friction angle. As expected, the peak friction angle increases with relative density and the critical state friction angle does not increase as much. This result agrees with the fact that the friction angle at large deformation where critical state is achieved is theoretically independent of initial density or void ratio. Additionally, the results show that the peak friction angle becomes equal to the critical state friction angle at about $D_r = 20\%$. 

---

**Fig 4.11 Schematic of Dilatancy Angle, $\Psi$, and Displacement Increments, $dx$ and $dy$.**
4.2.3. Discussion. The critical state friction angle is estimated based on the data presented above. Also the results of the direct shear tests of JSC-1A are related to the published data of the triaxial tests of the same material.

4.2.3.1 Critical state friction angle. The critical state friction angle is characteristic value of a soil independent of initial compaction. Figure 4.13 shows friction angle at peak, $\phi_{\text{peak}}$, plotted against corresponding dilatancy angle, $\Psi_{\text{peak}}$. $\phi_{\text{peak}}$ was calculated by Eq (72) based on curved failure envelope model. $\Psi_{\text{peak}}$ was defined by Eq (74).

$$\left(\phi_{\text{ds}}\right)_{\text{peak}} = 1.23\Psi_{\text{peak}} + 36.2^\circ$$ (75)

where $(\phi_{\text{ds}})_{\text{peak}}$ means the peak internal friction angle obtained by direct shear tests.

Shear strength of the soil can be decomposed into the strength due to the internal friction at critical state and the strength due to the interlocking of the particles. So the
value of $\phi_{\text{peak}}$ at $\Psi_{\text{peak}} = 0$ is an estimate of the critical state friction angle of a soil. This method is more reliable than taking the friction angle at large strain as the critical state value (Simoni and Houlsby 2006). Therefore the critical state friction angle of JSC-1A is found to be $\phi_{cs} = 36.2^\circ$. This value falls within the range (36° - 41°) of the critical state friction angles published by others using different tests (Arslan and Batiste 2007; Alshibli and Hasan 2009).

![Fig 4.13 Relationship of Friction Angle ($\phi_{\text{peak}}$) to Dilatancy Angle ($\Psi_{\text{peak}}$)](image)

4.2.3.2 Correlation to triaxial test results. It is a consensus that the triaxial test is a more sophisticated soil strength test than the direct shear test. However, the direct shear test has been and will be the favored option for mining engineers, aerospace engineers, and commercial geotechnical labs “because the testing procedures are simple, and it is capable of approximately simulating the deformation conditions of plane strain as occurs in many field” (Liu 2006). In fact, several researchers conducted only direct shear tests to determine strength parameters in space applications (Carrier et al. 1973;
Bernold 1994; Perko et al. 2004; Perko et al. 2006; Johnson and King 2009), and for terrestrial study (e.g. Fang et al. 2002).

Therefore it is meaningful to correlate the direct shear test results to the published triaxial data on JSC-1A (Arslan and Batiste 2007; Alshibli and Hasan 2009; and Zeng et al. 2009) in a similar manner like the correlation equations for different types of tests and soils (e.g. Kulhawy and Mayne 1990; Wanatowski and Chu 2007) where the difference between \( \phi \) from direct shear tests and \( \phi \) from triaxial compression tests are described as a function of relative density, \( D_r \). For JSC-1A, the following expression is proposed to relate the internal angle of friction of the triaxial compression tests to that of the direct shear test (Iai and Luna 2010).

\[
\phi_{\text{tc}} = (\phi_{ds})_{\text{peak}} - 25D_r + 11
\]  

(76)

4.3. LARGE GRAINS IN LUNAR REGOLITH

There have been several experimental studies about excavation of the lunar surface (e.g. Boles et al. 1997; Willman 1995; Tamoi et al. 2004; Bernold 1991; Szabo et al. 1998). However, all of them apparently used a homogeneous simulant without considering the effect of the gravel content in lunar regolith. This is due to lack of information as most, if not all, of grain size analyses on the Apollo samples were done after coarse fragments (>1 mm) were removed from the samples (e.g. Heiken et al. 1973). As a result, older lunar regolith simulants contain grains only up to 1mm (JSC-1 or JSC-1A) or 2mm (FJS-1, MLS-1) in size. On the other hand, newer simulants tend to include larger grains with maximum grain size of 5mm (OB-1) or 10cm (NU-LHT-3C) (Stoeser et al. 2008).

4.3.1. Ratio of Coarse to Fine Particles by Weight. Eleven of the dissected core samples from Apollo missions (Lunar News 1978-1995) were analyzed. Based on the mass of coarse and fine fractions in each interval, the mass ratio of coarse fraction to the total mass of the increment was plotted against depth from the surface (Fig 4.14). If there was an oversized particle larger than 5mm, the mass of that particle is included in the mass of one of the intervals in which that particle lies. Therefore, oversized particles exit often appear as surges in the plots. So the isolated peaks on the plots should be
interpreted as an individual oversized particle rather than an actual surge in the ratio of coarse fragments.

There are data of interval sample mass published in *Lunar News* (1978-1995) for Apollo cores, 12027, 14211/10, 14220, 15008/07, 15009, 15011/10, 60014/13, 64002/01, 68002/01, 76001, and 79002/01. They are collected in different missions (Table 4.6). The inner diameter of core tubes for 12XXX and 14XXX are 2cm whereas the inner diameter is 4cm for the rest. Some of the core tubes consist of two or more sections. Soil sample contained in each section is given a sample number. For example, one of the cores from Apollo 14 mission has two sample numbers, namely 14211 for upper tube section, and 14210 for lower section. This pair of sample numbers is written as 14211/10 in this dissertation.

According to the plots (Fig 4.14), it is safe to say that the coarse fraction is at least 5% by mass for the most part of those cores. There are some sections where the coarse fraction consistently exceeds 30%, for example, depth ranges from 0mm to 200mm and 400mm to 450mm of 79002/01, and 400mm to 500mm of 60014/13. Also, 400mm to 600mm depth of 68002/01 contains more than 20% coarse material. Detailed information of the sites where those cores are collected are listed in Appendix B.

It is reasonable to conclude that the gravel content can go up to 30% locally. Therefore, it was decided that the gravel (> 1 mm) content to be used in the experiment would be 0%, 5%, 10%, and 30%.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>12XXX</td>
<td>Apollo 12</td>
</tr>
<tr>
<td>14XXX</td>
<td>Apollo 14</td>
</tr>
<tr>
<td>15XXX</td>
<td>Apollo 15</td>
</tr>
<tr>
<td>6XXXX</td>
<td>Apollo 16</td>
</tr>
<tr>
<td>7XXXX</td>
<td>Apollo 17</td>
</tr>
</tbody>
</table>
Fig 4.14 Local Gravel Content of Lunar Regolith as Function of Depth for 11 Apollo Core Samples
Fig 4.14 Local Gravel Content of Lunar Regolith as Function of Depth for 11 Apollo Core Samples (continued)
4.3.2. Mass Ratio of Larger Grains to Total. For the grains of 1mm or finer, Carrier (2003)’s data is employed. For the larger grains, size distribution data from Surveyor observation is used. To combine two separate size distribution curves, it is necessary to find the percentage of the grains < 1mm in lunar regolith in situ. This percentage is estimated based on the size fraction data of the scooped Apollo surface samples (Table 4.7).

Since the opening of scoop is 152mm × 93mm for larger scoop, and 66mm × 30mm for small scoop (Allton 1989), this data does not include information about large grains. However, it is assumed that the grains larger than those opening have negligible effect on estimating how much portion of lunar regolith grains is less than 1mm. In Table 4.7, the ratio of the larger grains to the total mass is calculated in the right most column. Their arithmetic mean is 0.19. Also the weighted median is calculated to be 0.13, which is believed to be less affected by the very high values, such as 0.86 for 15400. So the estimates of fine (<1mm) fraction, f, is $f = 1 - 0.19 = 0.81$ or $f = 1 - 0.13 = 0.87$.

4.3.3. Grain Size Distribution for 1000mm and Finer. The size distribution data for the lunar regolith have been treated separately for 1mm and finer, and for larger particles. Carrier (2003) compiled the grain size distribution data from nearly 350 samples taken in the vicinity of seven landing sites on the Moon: Apollo 11, 12, 14, 15, 16, and 17, and Luna 24, and plotted them altogether in geotechnical presentation (Fig 4.15) and in geological presentation (Fig 4.16), giving average distribution, and ±1σ upper and lower bound distributions.

For the grains larger than 1mm, several sources of information are available (Table 4.8). Among those, Surveyor data is most useful since it gives size distribution from about 1mm to 1000mm, which is relevant to excavation operations.

Based on available data, the grain size distribution for the grains of 1000mm or finer was constructed and plotted on semilog plot (Fig 4.17), lognormal plot (Fig 4.18), and Weibull plot (Fig 4.19). The size distribution for grains 1mm or finer is based on Carrier (2003), which is scaled by fine (<1mm) fraction, $f = 0.67$, 0.87, or 0.95. The value $f=0.87$ is based on the data of Apollo surface samples as discussed in the previous section. The values $f = 0.67$ and 0.95 were chosen so the curves for finer grains (<1mm) and for coarser grains (>1mm) connect to each other as much as possible. The data for
Table 4.7 Coarse Fragments in Apollo Scooped Surface Samples

<table>
<thead>
<tr>
<th>Size Fraction*</th>
<th>&gt;10mm</th>
<th>4-10mm</th>
<th>2-4mm</th>
<th>1-2mm</th>
<th>&lt;1mm</th>
<th>Total mass</th>
<th>(&gt;1mm)/(total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil # (Weights in grams)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10002</td>
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<td>837.1</td>
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<td>12.9</td>
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<td>687.2</td>
<td>735.3</td>
<td>0.07</td>
</tr>
<tr>
<td>73240</td>
<td>1.6</td>
<td>22.3</td>
<td>14.4</td>
<td>14.9</td>
<td>192.7</td>
<td>245.9</td>
<td>0.22</td>
</tr>
<tr>
<td>74220</td>
<td>0</td>
<td>0.98</td>
<td>0.17</td>
<td>0.68</td>
<td>7.77</td>
<td>9.6</td>
<td>0.19</td>
</tr>
<tr>
<td>78220</td>
<td>0</td>
<td>1.5</td>
<td>2.7</td>
<td>5.2</td>
<td>227.1</td>
<td>236.5</td>
<td>0.04</td>
</tr>
<tr>
<td>78500</td>
<td>109.3</td>
<td>19.2</td>
<td>16.1</td>
<td>21.4</td>
<td>718.7</td>
<td>884.7</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Weighted mean 0.19
Weighted stdev 0.20
Weighted median 0.13

*: Data from Table 9.1 in Lunar Sourcebook, which is originally from Morris et al. 1983.
Fig 4.15 Geotechnical Particle Size Distribution: Middle Curve Showing the Average Distribution; Left-Hand and Right-Hand Curves Showing ±1 Standard Deviation (After Carrier 2003)

Fig 4.16 Geological Particle Size Distribution: Middle Curve Showing Average Distribution; Left-Hand and Right-Hand Curves Showing ±1 Standard Deviation (After Carrier 2003)
coarser grains, which is from Surveyor and Luna 9, are plotted according to the procedure presented in Section 2 with a porosity, \(n\), of 0.5 as representative of estimated in-situ values (Table 4.9).

As can be seen in Fig 4.17, Fig 4.18, or Fig 4.19, the regolith grain size distribution of Surveyor VII landing site in the highland region is coarser than others, which agrees with the general consensus that the highland regolith is coarser than the mare regolith.

Table 4.8 Available Data Sources for Data of Larger Grains

<table>
<thead>
<tr>
<th>Data source</th>
<th>Size Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Size Distribution Curve</td>
<td></td>
</tr>
<tr>
<td>Luna 9 (Smith 1967)</td>
<td>10 mm to 230 mm.</td>
</tr>
<tr>
<td>Apollo (Lunar Sourcebook, Fig 7.9)</td>
<td>up to 16 mm</td>
</tr>
<tr>
<td>Apollo (Lunar Sourcebook, Fig 7.13, 7.18)</td>
<td>up to 8 mm</td>
</tr>
<tr>
<td>Apollo (Lunar Sourcebook, Fig 7.20)</td>
<td>up to 4 mm</td>
</tr>
<tr>
<td>Apollo (McKay et al. 1974, Fig 3, 6)</td>
<td>up to 8 mm</td>
</tr>
<tr>
<td>Apollo (McKay et al. 1988, Fig 2)</td>
<td>up to 16 mm</td>
</tr>
<tr>
<td>Surveyor I (Shoemaker and Morris 1969, Fig 3-68)</td>
<td>1 mm to 1000 mm</td>
</tr>
<tr>
<td>Surveyor III (Shoemaker and Morris 1969, Fig 3-68)</td>
<td>1 mm to 256 mm</td>
</tr>
<tr>
<td>Surveyor V (Shoemaker and Morris 1969, Fig 3-68)</td>
<td>1 mm to 64 mm</td>
</tr>
<tr>
<td>Surveyor VI (Shoemaker and Morris 1969, Fig 3-68)</td>
<td>2 mm to 64 mm</td>
</tr>
<tr>
<td>Surveyor VII (Shoemaker and Morris 1969, Fig 3-68)</td>
<td>1 mm to 512 mm</td>
</tr>
<tr>
<td>Lunar Orbiter III (Cintala et al. 1982)</td>
<td>1 m to 30 m</td>
</tr>
</tbody>
</table>

Other forms of data

<table>
<thead>
<tr>
<th>Apollo Cores* (Core diagrams from e.g. Lunar News)</th>
<th>about 1 mm to 10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo Rocks†</td>
<td>about 10 mm to 50 mm</td>
</tr>
</tbody>
</table>

*: Size distribution may be deduced by counting recorded grains.
Fig 4.17 Grain Size Distribution Curve of Lunar Regolith on Semilog Plot. (* Modified after Carrier (2003))

Fig 4.18 Grain Size Distribution Curve of Lunar Regolith on Lognormal Plot. (* Modified after Carrier (2003))
**Table 4.9 Estimated Porosity of Lunar Surface**

<table>
<thead>
<tr>
<th>Density Range(*)</th>
<th>Density of Grains(†)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$, g/cm³</td>
<td>$\rho_s$, g/cm³</td>
<td>$n$</td>
</tr>
<tr>
<td>0cm-15cm deep</td>
<td>1.45 - 1.55</td>
<td>3.1</td>
</tr>
<tr>
<td>0cm-30cm deep</td>
<td>1.53 - 1.63</td>
<td>3.1</td>
</tr>
<tr>
<td>30cm-60cm deep</td>
<td>1.69 - 1.79</td>
<td>3.1</td>
</tr>
<tr>
<td>0cm-60cm deep</td>
<td>1.60 - 1.71</td>
<td>3.1</td>
</tr>
</tbody>
</table>

*) $\rho_s$ is density of soil solid. Recommended typical specific gravity of lunar soil is 3.1 as given in Table 9.3 on p.482, Lunar Sourcebook.

*) $\rho$ is bulk density of soil, from "best estimates" of density range given in Table 9.4 or a table on p.492, Lunar Sourcebook.

On the other hand, for the rest of Surveyor data in the mare region, the regolith has less coarse grains. Although Surveyor I curve is notably coarse, Mason (1969) noted this data contain an outlier, i.e. exceptionally coarse sample, which he excluded from his analysis.
Data from Surveyor III, V, and VI are similar to each other and connect smoothly to the finer size distributions with $f = 0.87$ to $0.95$, which corresponds to 13% and 5% gravel content. Surveyor III curve connects to the finer distribution with $f = 0.87$, which is estimated from Apollo surface samples. The Surveyor VI curve and the finer distribution with $f = 0.95$ are most closely arranged in a straight line on the Weibull plot (Fig 4.19), which means this entire distribution can be modeled by the Rosin-Rammler distribution. The size distributions with data of Surveyor III, V, and VI on the mare region are curved slightly downward on the lognormal plot, which resembles the Bishop ash flow comparing to other types of volcanic deposits (Sheridan 1971, Fig 3. Reproduced in Fisher and Schmincke 1984, Fig 5-31). Also it is interesting to note that those mare size distribution curves are more close to straight line on Weibull plot (Fig 4.19) than on lognormal plot (Fig 4.18). This is opposite to Murai (1961)’s findings that the grain size distribution curves of pyroclastic flow deposits tend to be gentle downward concave lines on Weibull plot and nearly straight lines on lognormal plot (Also available in Fisher and Schmincke 1984, Fig 5-31). Murai also reported that dry-mud flow deposits and auto-brecciated lava flows follow Rosin-Rammler curve, which is a straight line on Weibull plot. He suggests the incompatibility with Rosin-Rammler curve means the effectiveness of a sorting agency in the emplacement of deposits because it is accepted that artificial crushing results in Rosin-Rammler distribution (e.g. Kittleman 1964). Thus, higher compatibility with Rosin-Rammler plot agrees with the suggested mechanism of lunar regolith formation that is crushing by repeated meteoroid impacts.

4.4. SPECIFIC ENERGY

Operation of excavation tools in dense or medium-dense compacted simulant very evidently followed stick-slip behavior, which is common in rock and stiff soils. Figure 4.20 compares typical force traces measured during raking of simulant compacted to three different densities. This was much less noticeable in the loose simulant or the construction grade sand.

In order to compare the fluctuating force traces, integration is useful to smooth the data (e.g. Asaf et al. 2007). The force traces, $F(x)$, were integrated over the excavated distance to calculate the total energy consumed for excavation to that point. Cumulative
energy values were calculated after 200mm and 400mm of travel to determine whether the data was free of initiation effects. Then the energy values were divided by the nominal excavated or disturbed volume (a product of the tool width, $w$, depth, $d$, and excavated distance, $L$), to give the specific energy, $SE$:

$$SE = \frac{\int_0^L F(x)dx}{wdL}$$  \hspace{1cm} (77)

Note that the specific energy is, by definition, proportional to the average excavation force. Both data sets showed the same trends, so only the 200mm-waypoint data are discussed here. Each specific energy value shown the following figures is the average of three runs for each test condition.

8-Tine Ripping of JSC-1A at 3 Compaction Levels

![Typical Force Traces during Raking (Ripping)](image)

Fig 4.20 Typical Force Traces during Raking (Ripping)

4.5. EXCAVATION ENERGY FOR DIFFERENT CONDITIONS

For comparison of the effect of density of the simulant, JSC-1A was compacted to three different densities, namely $1.88 \text{g/cm}^3 (D_r=76\%)$, $1.81 \text{g/cm}^3 (D_r=61\%)$ and
1.71g/cm³ (Dr=43%), where Dr denotes relative density. These are referred to as dense, medium dense, and loose, respectively (shown by the vertical dashed lines in Fig 4.21). For comparison purposes, construction grade sand was also tested, compacted to 1.79g/cm³ (Dr=78%). The minimum and maximum densities of construction grade sand were determined to be 1.60g/cm³ and 1.85g/cm³, respectively.

Direct shear tests conducted between 8kPa and 65kPa normal stress permitted calculation of the peak and residual friction angles of the simulant at several relative density values. Figure 4.21 shows the resulting relationships. The residual friction angle remains nearly constant, but the peak friction angle is more sensitive to density, as expected. The increased spread between peak and residual friction angles with higher relative density is likely to be associated with greater ripping effectiveness as well as higher forces experienced by the ripper.

![Fig 4.21 Friction Angle of JSC-1A vs. Relative Density](image)

**4.5.1. Dense Construction Grade Sand.** Two simple findings are evident from the experiment results on densely compacted construction grade sand (Fig 4.22 and Fig 4.23). The more tines on the rake, the more energy is consumed during ripping. However, the energy consumed by blading, shown by the dark portion of each bar in Fig 4.22, is independent of the number of tines used to pre-loosen the material, as indicated by the
dashed trend lines on the figure. Thus ripping adds energy consumption while blading energy is not decreased. So, it can be said that ripping construction grade sand has little or even negative effect on the total excavation energy. This is consistent with empirical observations.

Fig 4.22 Excavation of Densely Compacted Construction Grade Sand. Dashed Lines are Approximations
### 4.5.2. JSC-1A

The effect of ripping dense JSC-1A is very different (Fig 4.24). Except when the eight-tined rake was used, the total excavation energy (the sum of the raking and blading energies) in JSC-1A is less than when the blade was used without prior ripping.
The blading energy in dense JSC-1A varies depending on the number of rake tines while it is independent of this parameter in the construction grade sand. The raking energy, as expected, is proportional to the number of tines; this agrees with the construction grade sand results. The four-tine rake gives the lowest total excavation energy in dense JSC-1A. This tool had a tine spacing of 30mm (1.2 inch). This suggests that using one or two tines does not loosen the soil enough whereas using eight tines increases the drag force without a concomitant loosening effect in the regolith.

The same tendency can be seen in the case of medium dense JSC-1A (Fig 4.25). The total excavation energy after four-tine ripping ($9.3 \text{kJ/m}^3$) is 6% less than the total excavation energy without ripping. This reduction is less than seen in the dense JSC-1A, where 20% reduction was observed. It appears that the benefit of ripping medium density simulant is not as great as in dense simulant. Another difference is that the total excavation energy with prior eight-tine ripping is less than the total excavation energy without prior ripping. This was not the case for the dense simulant. Even so, the four-tine rake is still the optimal choice for minimizing total excavation energy.

Fig 4.25 Excavation of Medium Dense JSC-1A. Dashed Curves Are Approximations
The loosely compacted JSC-1A simulant showed a different result than the more densely compacted simulant samples (Fig 4.26). The result was rather similar to that of compacted construction grade sand. The blading energy is not changed significantly by the presence or absence of ripping. Thus, ripping only increases the total excavation energy without providing any improvement of excavation efficiency.

Ripping was found to increase excavation efficiency for dense and medium density simulant, whose relative densities were 76% and 61%, respectively. But ripping degraded the efficiency of excavation in loose simulant (47% relative density). Therefore it appears that ripping improves excavation efficiency in lunar regolith that is denser than 60% relative density. This likely includes all lunar regolith below a depth of a few centimeters.

4.5.3. Consideration on Tine Spacing. Figure 4.27 shows the result of raking with different spacings between only two tines. The topmost data is for the largest spacing, and the bottom bar is for a single tine, which is equivalent to zero spacing. The raking energy is constant for larger tine spacings but begins to decrease once the spacing falls below 30mm. It is reasonable to assume that two tines far apart are independent of
each other, resulting in twice the energy consumption of single-tine raking. As the
spacing decreases below a critical value, the failure zones surrounding each tine begin to
overlap. The transition between these two phenomena seems to occur around a critical
spacing, $s_{\text{crit}}$, of 30mm for the JSC-1A simulant under these experimental conditions.

![Diagram showing effect of spacing on raking (ripping) using two tines]

Fig 4.27 Effect of Spacing on Raking (Ripping) using Two Tines

Another point to note in Fig 4.27 is the relation between blading energy and
ripper tine spacing. The blading energy for ripper tine with spacings of 105mm and
75mm, which are nearly as wide as the blade (100mm wide) appears to be less than that
for narrower spacings. This is probably because the paths of the outermost tines nearly
coincided with the edges of the blade. Loosening by tines may have prevented the stress
due to the blade from transmitting sideways as much as in less well-matched pairings,
resulting in smaller side failure zone, and thus smaller blading energy. But this
mechanism requires further study to confirm. Still it will be important to consider the
effect of ripper tine positions with respect to side failure zone development of the
following blade.

To verify this result, we measured the actual width of the failure zones on the
regolith surface after raking. First, 13 raked surfaces were photographed after completion
of the raking. On each picture, which covers a section about 100mm long along the raking path, the width of the failure zone was sampled at its intersection with five lines drawn at equal intervals (Fig 4.28). The five failure zone width samples were averaged. The width of failure zone is most frequently between 12 and 16mm (Fig 4.29). This means that the failure zones of neighboring tines overlap when they are spaced less than 24 to 32 mm apart.

Based on the findings mentioned above, we can deduce that the optimal spacing that gives the minimum total excavation energy is equal to the spacing that allows neighboring failure zones to just touch each other. The width of the failure zone in the regolith thus determines the optimal spacing of the ripper tines.

![Fig 4.28 Surface Failure Pattern from a Single Tine (Traversed Left to Right. Width of Failure Surface Measured at 20mm Interval)](image-url)
4.6. EXCAVATION FORCE MODELING

After excluding the force data near the ends of the box, where the end effect biases the measured force, the average force experienced by the rake was calculated and plotted against corresponding relative density (Fig 4.30). The resistive force experienced by the ripping tool increases more rapidly at higher relative density (which corresponds to higher friction angles).

This result confirms McKyes’ (1985) approach to earthmoving force prediction, which approximates the excavation force by summing the weight of soil, the cohesion of soil, and the surcharge load as discussed in Section 2. Their effects are represented by several factors that are functions of soil parameters and cutting conditions. Those factors increase more rapidly as friction angle increases, which agrees with the trend seen in Fig 4.30.

When analyzing the reaction force on ripping or raking tools that use different numbers of tines, it is necessary to consider the effect of interference of the failure zones in front of each tine. It would be invalid if the effect of a tine is simply multiplied by the number of tines. A function that includes the effects of the spacing and the number of tines was needed.
Figure 4.30 shows the variation of average ripping force of a two-tine rake with tine spacing (Iai and Gertsch 2009), at three different gravel contents. The value for the zero spacing is the ripping/raking energy due to a single tine. If the tine spacing is large enough compared to the width of the failure zone caused by a single tine, the tines do not interfere with each other. This causes the ripping energy to be independent of tine spacing if that threshold spacing is exceeded. In this particular case of a two-tine ripper, the raking energy is twice the energy experienced by a single tine. If the tine spacing is narrower than the failure zone width, the failure zones in front of each tine overlap. Figure 4.31 shows that the average ripping force for a tine spacing larger than 30mm is almost constant, which agrees with the critical spacing, $s_{\text{crit}}$, of 30mm that was determined previously (Section 4.5).

The dependence of the ripping force, $F_r$, on tine spacing shown in Fig 4.31 is modeled by the following equation.

$$F_r = \left[ 2 - \exp \left( \frac{-s}{s_{\text{crit}}/2} \right) \right] F_1$$  \hspace{1cm} (78)

where $s$ is the spacing between the tines; $F_1$ is an intercept determined by fitting the above equation to the experiment data. $F_1$ is determined to be 5.5N for gravel content of
Fig 4.31 Effect of Tine Spacing on the Average Ripping Force for Different Gravel Content

0% and 10%, or 9.5N for gravel content of 30%. Note that the tests with 5% gravel were skipped. The physical meaning of $F_1$ is the force acting on one tine without effects from adjacent tines.

To formulate ripping force model, an assumption is made that the average force, $F_r$, of ripping/raking with a two-tine tool can be written as the product of the force on one tine, $F_1$, and a factor, $K$, representing the effect of configuration of a rake.

$$F_r = K(n,s)F_1$$

where $F_1$ is a function of relative density, $D_r$, and gravel content, $G$, and $K$ is a function of spacing, $s$, and the number, $n$, of tines. The term in the square brackets in Eq (78) represents the effect of spacing only in the case of a two-tine rake. Thus,

$$K(2,s) = 2 - \exp\left(-\frac{s}{s_{crit}/2}\right)$$

The $K$ factor is controlled by the sizes of the failure zones between inner tines (inner zone) and outside the end tines (outer zone). To describe the effect of more than
two tines mounted on a tool, the contribution of the inner zone must be multiplied while that of the outer zone must not. The factor, $K$, was developed to be:

$$K(n,s) = 1 + [K(2,s) - 1](n - 1)$$  \hspace{1cm} (81)

Using this factor in least-squared-error curve fitting of the force-density data in Fig 4.30, the average raking force for that particular situation is represented by:

$$F_r(n,s,D_r) = K(n,s) \cdot F_1 \cdot (0.011)\exp(6D_r)$$

$$= \left[1 + \left[1 - \exp\left(-\frac{s}{s_{crit}/2}\right)\right](n - 1)\right] F_1 \cdot (0.011)\exp(6D_r)$$  \hspace{1cm} (82)

where $D_r$ is relative density (as a decimal number from 0 to 1, not in percent); $F_1$ is obtained by interpolation of the data set mentioned earlier (5.5N for gravel content of 0% and 10%, or 9.5N for gravel content of 30%). Note that this equation can then be used to estimate the relative density of the substrate once the resistive force on the ripper is measured.

### 4.7. EFFECT OF GRAVEL CONTENT

#### 4.7.1. Blading without Prior Ripping

The experiment results show the average blading energy without prior ripping has obvious correlation with the gravel content as shown in Table 4.10. The gravel content was set to be up to 30% since the local gravel content is estimated to be up to 30% as mentioned in Section 4.3.

<table>
<thead>
<tr>
<th>Gravel Content</th>
<th>Specific Energy for Blading</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>16 kJ/m³</td>
<td>Fig 4.24</td>
</tr>
<tr>
<td>5%</td>
<td>21 kJ/m³</td>
<td>-</td>
</tr>
<tr>
<td>10%</td>
<td>25 kJ/m³</td>
<td>Fig 4.35</td>
</tr>
<tr>
<td>30%</td>
<td>30 kJ/m³</td>
<td>Fig 4.36</td>
</tr>
</tbody>
</table>
Obviously a small percentage of gravel has an effect on the reaction force acting on a wide blade even though it has been suggested that a small amount of gravel can be ignored in measuring shear strength of the sand-gravel mixture (Savely 1990; Fragaszy et al. 1992; Bareither et al. 2008).

4.7.2. Ripping. The ripping force with a two tine rake did not increase when the gravel content increased to 10% as indicated in Fig 4.32 where $F_1$ is plotted against gravel content. The force, $F_1$, on a tine was obtained for different gravel contents by fitting the curve of Eq (2) to the data shown in Fig 4.31. On the other hand, when the gravel content increases from 10% to 30%, $F_1$ nearly doubled (Fig 4.32). This suggests that, for <10% gravel content, either tines did not have much interaction with gravels, or the gravels pushed by a tine easily moved away. This is in contrast to the case of a wide blade described earlier. On the other hand, the deviation of ripping force on the same two-tine rake continuously increases from 0% to 30% gravel content as shown in Fig 4.33. Raw ripping force is presented in Fig 4.34.

![Fig 4.32 Average Force on a Single Tine, $F_1$, as Function of Gravel Content]
Increase in deviation without change in average means an increase in the maximum value. Thus although some people suggest that a small amount of large particles has little effect on shear strength of soil (Savely 1990; Fragaszy et al. 1992; Bareither et al. 2008), it is important to take into account even low gravel content in regolith when it comes to designing excavation equipment, which needs to overcome the maximum reaction force rather than only the average force.

The optimal spacing that minimizes the total excavation energy varies ambiguously with gravel content. It was about 30 mm for the compacted JSC-1A with no gravel (Fig 4.24), about 105 mm for JSC-1A with 10% gravel (Fig 4.35) where the total energy reduced by 20%. But for 30% gravel content, there was no clear minimum of total excavation energy (Fig 4.36). Although the total excavation energy for the eight-tine rake with narrowest spacing of 15 mm exhibits the minimum energy on the plot (Fig 4.36), its blading energy does not accurately represent the complete energy to move the loosened material away. The narrow spacing prevented gravel from passing through between tines, which caused the gravel-JSC-1A mixture to be pushed out of the way by the rake, just like being pushed away by a wide blade. This results in little material left in place to be moved by the following pass by a wide blade, leading to anomalously small blading energy (Fig 4.37). It must be noted that this anomaly occurred because the experiment was done with tools scaled down according to similitude. In geotechnical experiments based on similitude, including the present study, particles of soil are not scaled. Particle size should not be comparable to a characteristic size of a structure used in a scaled experiment as noted in Section 3.4. Therefore, it has to be recognized that the results with gravels up to ~10 mm and a rake with 15 mm spacing won’t be similar to the phenomena that would occur under the lunar gravity.

Overall, it can be said that raking with any spacing does not improve the excavation efficiency on lunar regolith with 30% gravel content.
Fig 4.33 Deviation of Raking Force as a Function of Gravel Content

Fig 4.34 Typical Force Traces on Simulant with Different Gravel Content during Raking (Ripping) by an Eight Tine Rake
Fig 4.35 JSC-1A with 10% Gravel

Fig 4.36 JSC-1A with 30% Gravel
After 8 TineRaking After Blading

≤10% gravel

30% gravel

Fig 4.37 Effect of Eight Tine Raking on JSC-1A with 10% gravel vs. with 30% gravel

4.8. INCLINATION OF FORWARD FAILURE SURFACE

The inclination, $\beta$, of the forward failure surface was observed during excavation with different conditions. This inclination, $\beta$, is the inclination of a simplified straight line passing from the bottom edge of the cutting tool to the surface expression of the forward failure surface (Fig 4.38). Thus $\beta$ can be taken as an average inclination of the forward failure surface, which in fact is curved.

![Diagram](https://via.placeholder.com/150)

Fig 4.38 Schematic of Failure Surface and Definition of $\beta$

Figure 4.39 shows one of video frames when a surface expression of failure appears. Once the soil heap grows large enough to cover the failure surface, the measurement of $\beta$ stops. This is why some plots of $\beta$ shown in Fig 4.40 end at shorter traverse distance than others. For deeper excavation, i.e. (e) and (f) of Fig 4.40, the failure surfaces are covered before distance of 200mm is reached whereas, for shallower cases, travel is farther before the failure surface is covered.
It is important to note that, for any cases in Fig 4.40, the inclination, $\beta$, decreases as the excavation proceeds. Then it reaches a plateau for an excavation depth of $d = 30\text{mm}$. The plateau is not seen for $d = 45\text{mm}$ because the failure surface is hidden earlier. Obviously, $\beta$ depends on the size of soil heap in front of the blade, which determines the surcharge load, although most analytical models do not formulate this dependency as noted in Section 2. The value of $\beta$ at plateau is between $12^\circ$ and $15^\circ$ for an excavation depth of $d = 30\text{mm}$. This angle happens to coincide with the $\beta$ value of $13^\circ$ from McKyes model for $\phi=40^\circ$, which is close to the residual friction angle of JSC-1A (Fig 4.12), $d/w = 0.3$ and $\alpha = 90^\circ$ where $d$ is excavation depth, $w$ is blade width, and $\alpha$ is blade angle. However, note that this is merely a coincidence since $\beta$ in McKyes model is determined independent of any surcharge load.

4.9. DEGRADATION OF SIMULANT

Since the simulant has been repeatedly compacted, raked, and bladed, the question of simulant degradation was raised. It was felt that the grain size distribution could be skewed toward the finer sizes if handling were damaging the pre-existing grains. If this were true, then the percentage of fines would increase with time and the larger particles would become less angular and more rounded. To evaluate this, photomicrographs of unused and heavily used simulant were compared. The heavily used sample had been subjected to 75 episodes of compaction to high relative density.
(a) 30mm deep; densely prepared and 4-tine raked.

(b) 30mm deep; densely prepared and 2-tine raked

(c) 30mm deep; loosely prepared and 4-tine raked

(d) 30mm deep; loosely prepared and 2-tine raked

(e) 45mm deep; loosely prepared and 4-tine raked

(f) 45mm deep; densely prepared and 2-tine raked

Fig 4.40 Failure Surface Inclination during Blading at Different Depth on the Material Compacted Differently and Loosened by Different Rakes
By visual comparison with Power’s (1982) chart, change in the roundness of the grains was not observed (Fig 4.41).

The change in the percentage by mass of the fine portion, that passes #200 (75µm) US Standard sieve, of the stimulant was measured for the same samples (Fig 4.42). This showed that the fines content had actually decreased. This likely is due to loss of airborne fines stirred up by motion and handling.

Energy levels required to reduce the sizes of regolith grains from $D_{80}=0.35$mm to $D_{80}=0.15$mm, $E_r$, are calculated based on the Bond work index as shown in Table 4.11. $D_{80}=0.35$mm represents to the grain size distribution of JSC-1A while $D_{80}=0.15$mm represents the $+1\sigma$ upper bound of the size distribution of lunar regolith below 1mm (Carrier 2003). Also the energy that the vibratory compactor input to the soil, $E_i$, was calculated.

$$E_i = P_a \lambda \eta nT$$  \hspace{1cm} (83)

where $P_a$ is apparent power input to the motor, $n$ is number of repetition, $T$ is time per compaction; the power factor, $\lambda$, of the motor and the comminution efficiency, $\eta$, are assumed to be 1. Under those assumptions, the input energy, $E_i$, is nearly equal to the required energy, $E_r$. However, the comminution efficiency is expected to be significantly less than 1. Thus the true input energy is much smaller than the required energy, which means there should not be significant comminution occurring during the experiments in this study.

![Grains of JSC-1A Before and After 75 Tests](Picture provided by R. Pfaff at Keyence with help of D. Vidt)
Fig 4.42 Degradation of JSC-1A
Table 4.11 Preliminary Calculation of Comminution Energy

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<td>Power input to grains</td>
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†: Vibratory compactor (Model Number: BE-1320-2B) 230V, 1.6A.

Note: $E_r$ is nearly equal to $E_i$ under assumption of $\lambda =1$ and $\eta =1$. Since $\lambda <1$ and $\eta <<1$, the real power input to grains is much less than the calculated $E_i$. 
5. CONCLUSIONS AND RECOMMENDED FUTURE WORK

5.1. CONCLUSIONS

5.1.1. From Direct Shear Tests.

- Relative density significantly affects the shear behavior of JSC-1A.

The direct shear testing program conducted on JSC-1A lunar regolith simulant with wide range of relative density provided insights into the dilatancy and volumetric behavior during shearing. The shear stress response showed a characteristic shape at high density conditions. The calculated dilatancy angle verified the highly dilative nature of the simulant, which is probably one of the reasons behind the very high friction angle for denser simulant. This finding is important when considering the excavation of lunar regolith, as it will require more energy to shear the granular material exhibiting such interlocking and a tendency to dilate.

- A conversion equation was proposed for JSC-1A between the direct shear friction angle and the triaxial friction angle.

\[ \phi_{lc} = (\phi_{ls})_{\text{peak}} - 25D_r + 11 \]  
(76)

This formula successfully correlates the direct shear data with the triaxial data over a wide range of relative density values. This relationship may allow other investigators to conduct a simpler direct shear test in dry conditions and relate them to the more comprehensive parameter from the triaxial tests.

- The dilatancy was related to the internal friction angle based on a direct measurement of dilatancy.

\[ (\phi_{\text{ds}})_{\text{peak}} = 1.23 \psi_{\text{peak}} + 36.2^\circ \]  
(75)

An extreme low confining stress in the Moon may result in the dilative conditions.
5.1.2. From the Excavation Experiments.

- Ripping prior to excavation with a flat blade increases excavation efficiency by decreasing the total energy of excavation where it has been compacted to \( \geq 60\% \) relative density and \( \leq 10\% \) gravel content.

  The total energy of excavation is the sum of ripping energy and blading energy. The percentage of energy reduction is 20\% for dense sample, and 6\% for medium dense sample.

- Ripping degraded the efficiency of excavation in loose simulant (47\% relative density). Therefore it appears that ripping improves excavation efficiency in lunar regolith that is denser than 60\% relative density. This likely includes all lunar regolith below a depth of a few centimeters.

  The excavation energy reduction comes from the strength difference between the original, compacted material and the ripped material. Ripping helps when the compacted material is significantly stronger than its loose state. To ensure the validity of repeated experiments on the same batch of simulant, degradation of grains was evaluated and found neglibile.

- The optimal spacing between tines for JSC-1A at a penetration depth of 30 mm was found to be 30 mm.

  The degree of effectiveness of ripping also depends on the number and position of the ripper’s tines. It was confirmed by the experiments that tine spacing is optimal when the failure zone due to each tine just contacts the failure zone next to it. The optimal spacing between tines for JSC-1A at a penetration depth of 30 mm was found to be 30 mm. This conclusion is supported both by the force measurement and by the observation of the failure zone on the surface of simulant.
• The optimal spacing that gives the minimum total excavation energy is equal to the spacing that allows neighboring failure zones to just touch each other. The width of the failure zone in the regolith thus determines the optimal spacing of the ripper tines.

• The energy of blading that follows two-tine ripping with spacings nearly as wide as the blade width was less than that for blading following two-tine ripping with spacing narrower than the blade width.

This is probably because the paths of the outermost tines nearly coincided with the edges of the blade for wider spacings. Loosening caused by tines may have prevented the side failure zone due to the blade from growing as much as in less well-matched pairings.

• An empirical equation relating ripping or raking force to relative regolith density, tine spacing, and the number of tines, was developed by taking account of the interference of failure zones caused by tines.

This equation can also be used to estimate the in situ relative density from the measured ripping force over a site. Thus, the utility of collecting ripping and blading force measurements goes beyond improving the efficiency of excavation for mining, site preparation, and construction. The data gathered thereby will comprise a map of the regolith resistance with abundant and better coverage of the terrain with a simpler tool than the data of soil samples collected at several locations (e.g. van Bergeijk et al. 2001). Density variations reflect regolith formation and modification mechanisms, and are thus a record of the history of the lunar (or terrestrial or martian) surface. In addition, soil stabilization will be necessary when constructing a lunar base. Characterization of soil density and other properties is important since spatial variation may undermine the usability of roads or other facilities constructed on or under the ground surface.
The experiment showed even the simulant with 5% gravel content exhibits the increased average and deviation of the reaction force on an excavation tool.

Although it is a wide spread perception that small amount of gravels does not affect shear strength measured in shearing tests, the experiment showed otherwise. This result underlines an importance of awareness of the effect of gravel content. Beyond experimenting only with homogeneous lunar regolith simulant, excavation equipment designers need to consider the effect of gravel content in lunar regolith. Additionally, it is a possibility that the gravels in the regolith can be separated and used as pavement material or other construction materials for higher bearing capacity. More attention is needed to the larger grains in the regolith and its heterogeneity when discussing excavation on the Moon or other extraterrestrial bodies.

5.2. RECOMMENDED FUTURE WORK

- Full scale field tests will be important to investigate actual performance of excavation operation. The size of excavation tools should be determined based on actual mission objectives. The LANCE blade designed for the NASA Lunar Electric Rover is an example (Schuler et al. 2010; King et al. 2010). The effect of gravels on large scale blade may be different from that obtained by small scale experiments. However using a full scale tool on the earth means the effect of gravity is not scaled. It will also be necessary to evaluate the weight of the vehicle that operates an excavation tool. Lower gravity environment such as the Moon and Mars are expected to be unfavorable for excavation because of reduced traction. However, the effect of gravity on excavation tool on a mobile platform has not been evaluated by experiment although Kobayashi (2010) reported mobility performance of a vehicle itself is degraded.

- Modeling with a numerical method such as DEM, FEM, or hybrid approaches will be helpful to study the behavior of the highly heterogeneous soil like lunar regolith including gravel-size and larger particles. Such heterogeneity of material is not possible for classical analytical models to adequately deal with. When designing excavation equipment and planning excavation activity, information on both the
maximum and the average excavation force is important. Also, to simulate realistic situations, the motion of an excavation tool should be modeled as well as the behavior of the soil.

- Develop a methodology for uniform and consistent soil preparation for excavation experiments in relatively large boxes such as used in this project. Schröter et al. (2005) and Li et al. (2009) showed that the bulk density of the granular material can be precisely controlled by changing flow pulse supplied to a fluidized bed in which the granular material is placed. Their granular material consisted of grains of the same size, thus their method would not be directly applicable to the material with grains of well-graded soils. However, a precise, repeatable preparation of soil sample is essential for any experiment, and thus a experiment setup with some automated soil preparation will minimize measurements deviation due to inconsistency of sample preparation.

- Develop a technique for the determination of distribution or uniformity of density in such a experimental box.

- Investigate the characteristics of the soil heap formed in front of an excavation tool. Experiment results show that the soil heap significantly affects the excavation force and the average inclination of failure surface, which agrees with Salokhe and Pathak (1992), Selig and Nelson (1964), and King et al. (2010b). However, little research has been done about it. It will be important first to
  - Quantitatively show that the contribution of the soil heap load to the excavation force is large.
  - Characterize and model the size and shape of the soil heap in steady state or as a function of travel distance. In many excavation studies including the present study, the steady state where the size of the soil heap does not change was not achieved completely. To achieve the complete steady state of heap formation, the excavation distance needs to be longer than 800mm used in this study if the same soil and tools are used. (Note travel distance of 700mm was adequate length in case of Rajaram and Gee-Clough 1988)
  - Study the change of soil strength properties as the soil is moved out of its original location, pushed up to form a heap, and falls down the heap. Knowing
the significance of soil heap on the soil cutting behavior, a future autonomous excavation robot may need to visually monitor the shape of soil heap and loosened volume on or under the surface during excavation.

- Develop standard reporting protocol for soil friction angle. The friction angles measured by different tests differ. Report must state type of test, the range of normal stress used for testing, the failure state (peak or critical state), and the compactness or relative density of soil because the friction angle depends on those factors. Therefore, when constructing any theory using soil friction angle, this protocol would clarify what type of friction angle the theory is based on. Many papers dealing with excavation do not clarify the above-mentioned conditions. Also for dense material, peak friction angle is largely different from critical state friction angle. When using the traditional Coulomb and Terzaghi theory for passive earth pressure, Fang et al. (2002) showed proper selection of friction angles, that is peak or critical state, is important to estimate experimental results of peak or ultimate passive wall thrust. As early as 1939, Terzaghi clearly noted, talking about the equation of shear resistance of soil, \( s = p \tan \phi \), “the angle of internal friction \( \phi \) can assume any value between the angle of repose and an angle greater than 40 degrees, depending on the degree of compactness of the sand.”

In summary, to proceed forward, experiments in more realistic setup and numerical simulation by DEM will be important. To establish firm theoretical understanding, more consistent automated experiments are desired and the theoretical analysis beyond passive earth pressure theory is necessary. Especially, modeling of soil heap and surcharge load, and their effect on formation of failure surface are interesting unanswered subjects in addition to consideration of change in soil properties, such as friction angle and density, during earthmoving.
APPENDIX A.

ZINGG DIAGRAM OF ROCK SAMPLES FROM APOLLO 16 AND 17
Zingg diagram of Rock Samples from Apollo 16 and 17. (Rock Size from 0.25 cm to 28 cm. Number of Samples: 417. Intermediate/Long Average = 0.75. Short/Intermediate = 0.75.)

The ratio of axis length of rock particles collected during Apollo 16 and 17 missions are presented in the figure. Data sources are Butler (1972); Ryder (1993); Neal and Taylor (1993a); Neal and Taylor (1993b); Meyer (1994).

The Zingg diagram is divided into four regions by a vertical dashed line at $c/b = 2/3$, and a horizontal dashed line at $b/a = 2/3$ where $a$, $b$, and $c$ is the length of long, intermediate, and short axes. Particles associated with the left top region is classified as “disc-shaped”; left bottom as “bladed”; right top as “spherical”; right bottom as “rod-like” (Bunte and Abt 2001, p. 86; Boggs 2006, p. 66).

As note in the caption of the figure, average values of the ratios of axes are $b/a = 0.75$ and $c/b = 0.75$. It is interesting to compare them with the axis length ratios of FJS-1 reported by Matsushima et al. (2009), which are $b/a = 0.723$, and $c/b = 0.694$. 

APPENDIX B.

APOLLO CORE SAMPLE DATA
Issues of *Lunar News* that was referred to when plotting the local gravel content of the lunar regolith (Fig 4.14)

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<td>Apollo 11/-</td>
<td>19.5</td>
<td>Collected 20 ft northwest of the Lunar Module (LM). The LM landed in a flat region in the southwest part of the Mare Tranquillitatis approximately 50 km from the closest highland material. (jsc_1101.tif)</td>
</tr>
<tr>
<td>10005</td>
<td>Single Drive Tube</td>
<td>Apollo 11/-</td>
<td>19.5</td>
<td>Collected 20 ft northwest of the Lunar Module (LM). The LM landed in a flat region in the southwest part of the Mare Tranquillitatis approximately 50 km from the closest highland material. (jsc_1101.tif)</td>
</tr>
<tr>
<td>12025</td>
<td>Double Drive Tube</td>
<td>Apollo 12/-</td>
<td>19.5</td>
<td>rim of a 10m diameter crater south of Halo Crater (jsc_1205.tif)</td>
</tr>
<tr>
<td></td>
<td>/28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12026</td>
<td>Single Drive Tube</td>
<td>Apollo 12/-</td>
<td>19.5</td>
<td>near the Landing Module; Sample 12026 was collected in drive tube 1 near the LM at the end of the first Extra Vehicular Activity (EVA) period on the northeast edge of Surveyor Crater. (jsc_1201.tif)</td>
</tr>
<tr>
<td>12027</td>
<td>Single Drive Tube</td>
<td>Apollo 12/-</td>
<td>19.5</td>
<td>in the bottom of a 20cm-deep trench at the edge of Sharp Crater; This core was taken in the bottom of a trench that intercepted the rim crest of Sharp Crater, which is 13 meters in diameter. (Using the relation, rim thickness =.04 radius (McGetchin et al. 1973), one can expect 26 cm of rim crest deposits at the sampling site.) The trench was approximately 20 cm deep and the core extended the section from the depth of 20 cm to approximately 53 cm. (CN_26_1_17_80.pdf)</td>
</tr>
</tbody>
</table>
**Apollo Coring Sites (continued)**

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Type</th>
<th>Mission/Station</th>
<th>Inside Diameter</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>14211/10</td>
<td>Double Drive Tube</td>
<td>Apollo 14/Station A</td>
<td>19.5</td>
<td>Core 14211/10 was collected at station A, on the smooth plains part of the Fra Mauro Formation, and at least 350 m west of the nearest ridge. The coring site was 180 m northeast of the LM, 1 km southwest from 370 m Cone Crater and off the continuous ejecta of Cone Crater. Other nearby craters include 80 m North Triplet, which is 120 m to the southeast, and three 20 m unnamed craters, with one, seen in AS14-64-9048 being relatively fresh. (CN_23_4_26_79.pdf)</td>
</tr>
<tr>
<td>14220</td>
<td>Single Drive Tube</td>
<td>Apollo 14/Station G</td>
<td>19.5</td>
<td>Core 14220 was taken at station G, 6 meters east from the trench. Which sampled a surficial dark brown layer, then a thin layer of small, glassy-like pebbles, and a third layer, 18 inches belot: the surface, of some very light material, Station G was located 100 meters East from 100-m North Triplet Crater, on the Fra Mauro Plains, and was 200 m Southwest from the Fra Mauro Ridge, 1 km Southwest from Cone Crater, and 500 m Southwest from the continuous ejecta blanket of Cone Crater. (CN_24_7_17_79.pdf)</td>
</tr>
<tr>
<td>14230</td>
<td>Single Drive Tube</td>
<td>Apollo 14/Station G</td>
<td>19.5</td>
<td>Collected at Triplet Crater, Station G. (jsc_1408.tif)</td>
</tr>
</tbody>
</table>
### Apollo Coring Sites (continued)

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Type</th>
<th>Mission/Station</th>
<th>Inside Diameter</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>15006 /.../01</td>
<td>Drill Core</td>
<td>Apollo 15/Station 8</td>
<td>20.4</td>
<td>Collected from the regolith developed on Palus Putredinis, and is hopefully a representative section of the regolith developed on the mare surface, although its location at Station 8, 50 m from the ALSEP central station, may have been on the edge of a ray. (jsc_1519.tif)</td>
</tr>
<tr>
<td>15008 /07</td>
<td>Double Drive Tube</td>
<td>Apollo 15/Station 2</td>
<td>42.9</td>
<td>rim of a 10m crater between Elbow and St George at the Front; Core 15008/7 was taken at Station 2, on the crest of a 10 meter, crater (photo NASA S-80-33144) that was approximately 1 1/2 m deep. Station 2 was located on the northeastern flank of St. George Crater, on a 15°-17° slope, approximately 600 m laterally and 80 m uphill from the base of the Apennine Front. St. George is a subdued 2 km crater, and astronauts noted very little coarse material or boulders near the coring site. (CN_30_1_19_81.pdf)</td>
</tr>
<tr>
<td>15009</td>
<td>Single Drive Tube</td>
<td>Apollo 15/Station 6</td>
<td>42.9</td>
<td>inside the rim of a 10m crater approx 100m east of Spur at the Front; 15009, a single drive-tube obtained at the Apennine front, station 6 of Apollo 15 (LN_49_Summer_87.pdf)</td>
</tr>
<tr>
<td>15011 /10</td>
<td>Double Drive Tube</td>
<td>Apollo 15/Station 9A</td>
<td>42.9</td>
<td>Collected from the edge of Hadley Rille, roughly 200m west of Scarp. (jsc_1501.tif)</td>
</tr>
<tr>
<td>Core ID</td>
<td>Type</td>
<td>Mission/Station</td>
<td>Inside Diameter</td>
<td>Location</td>
</tr>
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<td>-----------</td>
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<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>60007/…/01</td>
<td>Drill Core</td>
<td>Apollo 16/Station 10</td>
<td>20</td>
<td>approx 105m southwest of the LM landing area; 60014/013 core sample was taken in April 1972 at Station 10', about 75 m west-southwest of the LM (Lunar Module) at the Descartes landing site in the Central Highlands. Three cores were taken near the LM in a triangular pattern; 60010/9 and 60014/13, both double drive tubes; and 60007-1, a deep drill string. (LN_53_Jan_92.pdf)</td>
</tr>
<tr>
<td>60010/09</td>
<td>Double Drive Tube</td>
<td>Apollo 16/Station 10</td>
<td>40</td>
<td>60014/013 core sample was taken in April 1972 at Station 10', about 75 m west-southwest of the LM (Lunar Module) at the Descartes landing site in the Central Highlands. Three cores were taken near the LM in a triangular pattern; 60010/9 and 60014/13, both double drive tubes; and 60007-1, a deep drill string. (LN_53_Jan_92.pdf)</td>
</tr>
<tr>
<td>60014/13</td>
<td>Double Drive Tube</td>
<td>Apollo 16/Station 10</td>
<td>40</td>
<td>60014/013 core sample was taken in April 1972 at Station 10', about 75 m west-southwest of the LM (Lunar Module) at the Descartes landing site in the Central Highlands. Three cores were taken near the LM in a triangular pattern; 60010/9 and 60014/13, both double drive tubes; and 60007-1, a deep drill string. The material sampled by the 60014/13 core is believed to be South Ray Crater Ejecta. (LN_53_Jan_92.pdf)</td>
</tr>
</tbody>
</table>
### Apollo Coring Sites (continued)

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Type</th>
<th>Mission/Station</th>
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<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>64002/01</td>
<td>Double Drive Tube</td>
<td>Apollo 16/Station 4</td>
<td>40</td>
<td>Core 64001/2 was collected at Station 4, the highest station on Stone Mountain. The surface slope is about 16° on a 100 m scale (1). The local slope for 64001/2 was influenced by the core being taken, on the down slope side, 7-8 m from the rim of a subdued, shallow crater of 15 m diameter. The regolith was gray in color. In the crater, white soil was observed at 1 cm depth, and none was found in a trench in the bottom of the crater. A soil penetrometer test taken adjacent to the core indicated relatively dense soil to 27 cm depth underlain by softer soil (2). (CN_32_7_6_81.pdf)</td>
</tr>
<tr>
<td>68002/01</td>
<td>Double Drive Tube</td>
<td>Apollo 16/Station 8</td>
<td>40</td>
<td>Collected 1 and 2 m from the edge of a 10 to 15 m crater that appears to be about 2 m deep. (jsc_1607.tif)</td>
</tr>
<tr>
<td>69001</td>
<td>Single Drive Tube</td>
<td>Apollo 16/Station 9</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>
### Apollo Coring Sites (continued)

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Type</th>
<th>Mission/Station</th>
<th>Inside Diameter</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>70009/.. .03</td>
<td>Drill Core</td>
<td>Apollo 17/ Landing Module site</td>
<td>20</td>
<td>Approximately one crater diameter east from the 700M crater Camelot, and lies near the northwest margin of the central cluster ejecta. (jsc_1701.tif)</td>
</tr>
<tr>
<td>70012</td>
<td>Single Drive Tube</td>
<td>Apollo 17/ Landing Module site</td>
<td>40</td>
<td>This core was hand driven to a hard layer at 28 cm depth .5 m inside the plus-Y footpad of the LM. The site lies on regolith developed on basaltic subfloor, near the center of the valley, approximately 750 m equidistant between the large (300 to 400 m) craters Camelot and Sherlock. (jsc_1738.tif)</td>
</tr>
<tr>
<td>73002/01</td>
<td>Double Drive Tube</td>
<td>Apollo 17/ Station 3</td>
<td>40</td>
<td>The sampling site lies near the base of a major scarp that crosses the Taurus-Littrow valley. This site is approximately 50 m east of the 700 m Lara Crater and is surrounded by small, local craters. (jsc_1740.tif) light mantle</td>
</tr>
<tr>
<td>74002/01</td>
<td>Double Drive Tube</td>
<td>Apollo 17/ Station 4</td>
<td>40</td>
<td>74002/74001 was collected in the middle of a patchy deposit of orange glass, at a low area on the southwest rim of Shorty Crater, just east of a large boulder of fractured basalt. The double drive tube 74001, that rias collected at the trench site. (CN_13_2_23_77.pdf) the contact between the orange and black soil; unusually dense soil (74001 was 2.35g/cm3 and 74002 was 2.00g/cm3)</td>
</tr>
<tr>
<td>Core ID</td>
<td>Type</td>
<td>Mission/Station</td>
<td>Inside Diameter</td>
<td>Location</td>
</tr>
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</tr>
<tr>
<td>76001</td>
<td>Single Drive Tube</td>
<td>Apollo 17/Station 6</td>
<td>40</td>
<td>This single drive tube from station 6 is the only certain stratigraphic sample of massif regolith and is the only core that can be oriented with certainty. It was driven into firm soil on an 11° slope to the south. (jsc_1740.tif)</td>
</tr>
<tr>
<td>79002/01</td>
<td>Double Drive Tube</td>
<td>Apollo 17/Station 9</td>
<td>40</td>
<td>southeast and downslope from the rim of Van Serg Crater; The 79002/001 double drive tube was collected at Station 9, about 70 m south of Van Serg Crater, a 90 m crater just south of the North Massif and the Sculptured Hills in the Taurus Littrow Valley (Fig. 1). The upper section, 79002, was extruded in June and preliminary information is now available. (LN_47_Fall_86.pdf) coarse ejecta</td>
</tr>
<tr>
<td>Mission</td>
<td>Mare/Highland</td>
<td>Description of Landing Location (taken from the references)</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
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<td>------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Surveyor I</td>
<td>Mare</td>
<td>&quot;The landing site was at 2.45 S, 316.79 E (selenographic) on a flat area inside a 100 km crater north of Flamsteed Crater in southwest Oceanus Procellarum.&quot; Landed 02 June 1966, 06:17:36 UT</td>
<td>NSSDC ID: 1966-045A <a href="http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1966-045A">http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1966-045A</a></td>
<td></td>
</tr>
<tr>
<td>Surveyor V</td>
<td>Mare</td>
<td>&quot;Surveyor 5 touched down on the lunar surface on 11 September 1967 at 00:46:44 UT (8:46:44 p.m. EDT 10 September) at 1.41 N, 23.18 E (selenographic coordinates) on a 20 degree slope of a 9 x 12 meter rimless crater in southwest Mare Tranquillitatis.&quot;</td>
<td>NSSDC ID: 1967-084A <a href="http://nssdc.gsfc.nasa.gov/databse/MasterCatalog?sc=1967-084A">http://nssdc.gsfc.nasa.gov/databse/MasterCatalog?sc=1967-084A</a></td>
<td></td>
</tr>
<tr>
<td>Mission</td>
<td>Mare/Highland</td>
<td>Description of Landing Location (taken from the references)</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
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<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Surveyor VI</td>
<td>Mare</td>
<td>&quot;Surveyor 6 touched down on the lunar surface on 10 November 1967 at 01:01:06 UT (8:01:06 EST 9 November) in Sinus Medii, a flat, heavily cratered mare region, at 0.49 N, 358.60 E (selenographic), the center of the Moon's visible hemisphere.&quot;</td>
<td>NSSDC ID: 1967-112A <a href="http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1967-112A">http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1967-112A</a></td>
<td></td>
</tr>
<tr>
<td>Surveyor VII</td>
<td>Highland</td>
<td>&quot;Touchdown occurred at 01:05:36.3 UT on 10 January 1968 (8:05:36 p.m. EST 9 January) at 40.86 S, 348.53 E (selenographic) on an ejecta blanket about 29 miles north of the rim of Tycho crater in the lunar highlands.&quot;</td>
<td>NSSDC ID: 1968-001A <a href="http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1968-001A">http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1968-001A</a></td>
<td></td>
</tr>
</tbody>
</table>

Cited references are linked from Lunar Mission Summaries <http://www.lpi.usra.edu/lunar/missions/>
APPENDIX C.

FORCE TRACES FOR ALL TESTS
Comparison between 25lb loadcell and 500lb loadcell

JSC-1a (loose): 30mm deep (no raking) (25lb loadcell)
Run IDs: 091017-1453, 091017-1603, 091017-1621
Conditions: 30 mm deep Flat 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 7J at 400mm

JSC-1a (loose): 30mm deep (no raking) (500lb loadcell)
Run IDs: 090926-1232, 090926-1249, 090926-1306
Conditions: 30 mm deep Flat 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 3.5J at 200mm, 9J at 400mm.
Fluctuation of excavation force measured with different loadcells looks different.
Compliance of a loadcell might have affected phenomenon.
Comparison between 25lb loadcell and 500lb loadcell (Rake 1/8 and Wide Blade)

**JSC-1a (dense): 30mm deep (Raking 1/8) (25lb loadcell)**

Run IDs: 091004-1359, 091004-1437, 091004-1504

Conditions: 30 mm deep Rake 1/8 0 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 2J at 200mm, 4J at 400mm

**JSC-1a (dense): 30mm deep (Raking 1/8) (500lb loadcell)**

Run IDs: 090522-1416, 090522-1502, 090522-1536

Conditions: 30 mm deep Rake 1/8 0 Compacted(100%) JSC-1A

Cumulative Excavation Energy: 2.3J at 200mm, 5J at 400mm
JSC-1a (dense, raked 1/8): 30mm deep (Wide Blade) (25lb loadcell)
Run IDs: 091004-1412, 091004-1445, 091004-1511
Conditions: 30 mm deep Flat 0 Raked 1/8 JSC-1A
Cumulative Excavation Energy: 6J at 200mm, 14J at 400mm

JSC-1a (dense, raked 1/8): 30mm deep (Wide Blade) (500lb loadcell)
Run IDs: 090522-1423, 090522-1514, 090522-1542
Conditions: 30 Flat 0 1/8 raked JSC-1A
Cumulative Excavation Energy: 6J at 200mm, 14J at 400mm
Comparison between 25lb loadcell and 500lb loadcell (Rake 4 and Wide Blade)

JSC-1a (dense): 30mm deep (Raking 4) (25lb loadcell)

Run IDs: 091009-1236, 091009-1305, 091009-1335

Conditions: 30 mm deep  Rake 4  0  Compacted(100%50Hz30s)  JSC-1A

Cumulative Excavation Energy: 0.8J at 200mm, 1.2J at 400mm

JSC-1a (dense): 30mm deep (Raking 4) (500lb loadcell)

Run IDs: 090521-1138, 090521-1327, 090521-1412

Conditions: 30 mm deep  Rake 4  0  Compacted(100%)  JSC-1A

Cumulative Excavation Energy: 1J at 200mm, 2J at 400mm
JSC-1a (dense, raked 4): 30mm deep (Wide Blade) (25lb loadcell)
Run IDs: 091009-1245, 091009-1312, 091009-1344
Conditions: 30 mm deep Flat 0 Raked 4 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 16J at 400mm

JSC-1a (dense, raked 4): 30mm deep (Wide Blade) (500lb loadcell)
Run IDs: 090521-1158, 090521-1345, 090521-1429
Conditions: 30 mm deep Flat 0 4 raked JSC-1A

Cumulative Excavation Energy: 8J at 200mm, 20J at 400mm
JSC-1a (medium): 30mm deep (no raking) (25lb loadcell)

Run IS: 090916-1535, 090916-1623, 090916-1647

Conditions: 30 mm deep  Flat  0  Compacted(20/40%15Hz45s)JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 15J at 400mm.
Comparison between Setup 1 and Setup 2 (30mm deep)

**JSC-1a (dense): 30mm deep (no raking) (500lb loadcell)**
Run IDs: 090925-1624, 090925-1648, 090925-1715
Conditions: 30 mm deep Flat 0 Compacted (100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 9J at 200mm, 20J at 400mm.

**JSC-1a (dense): 30mm deep (no raking)**
Run IDs: 081106-1105, 081106-1227, 081106-1317
Conditions: 30 mm deep Flat 0 Compacted JSC-1A

Cumulative Excavation Energy: 10J at 200mm, 25J at 400mm.
Comparison between loose and dense (30mm deep, 500lb loadcell)

JSC-1a (loose): 30mm deep (no raking) (500lb loadcell)

Run IDs: 090926-1232, 090926-1249, 090926-1306

Conditions: 30 mm deep Flat 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 3.4J at 200mm, 9J at 400mm

JSC-1a (dense): 30mm deep (no raking) (500lb loadcell)

Run IDs: 090925-1624, 090925-1648, 090925-1715

Conditions: 30 mm deep Flat 0 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 9J at 200mm, 21J at 400mm
Comparison between Setup 1 and Setup 2 (45mm deep)

Experiment setup and condition are kept same. Same load cell. Sand box is directly on blocks. Simulant in Setup 2 might have been a little bit looser. Results does not look very different.

**JSC-1a (dense): 45mm deep (no raking) (500lb loadcell)**

Run IDs: 090925-1742, 090926-1009, 090926-1133

Conditions: 45 Flat 0 Compacted(100%50Hz5) JSC-1A

Cumulative Excavation Energy: 20J at 200mm, 42J at 400mm

**JSC-1a (dense): 45mm deep (no raking)**

Run IDs: 081106-1557, 081106-1623, 081111-1100

Conditions: 45 Flat 0 Compacted JSC-1A

Cumulative Excavation Energy: 30J at 200mm, 60J at 400mm.
JSC-1A (medium): 30mm deep (no raking)
Run IDs: 090916-1535, 090916-1623, 090916-1647
Conditions: 30 mm deep Flat 0 Compacted(20/40%15Hz45s)JSC-1A
Cumulative Excavation Energy: 6J at 200mm, 15J at 400mm

JSC-1A (medium): 45mm deep (no raking)
Run IDs: 090918-1500, 090918-1527, 090918-1544
Conditions: 45 Flat 0 Compacted(20/40%15Hz45s)JSC-1A
Cumulative Excavation Energy: 13J at 200mm, 32J at 400mm
JSC-1A (medium), 30mm deep

**Raking 1/3/5/7:**

Run IDs: 090919-0943, 090919-1013, 090919-1042, 090919-1108

Conditions: 30 mm deep Rake 1/3/5/7/ 0 Compacted(20/40%15Hz45s) JSC-1A

Cumulative Excavation Energy: 1.6J at 200mm, 3J at 400mm

**Wide Blade:**

Run IDs: 090919-0954, 090919-1019, 090919-1046, 090919-1116

Conditions: 30 mm deep Flat 0 Raked 1/3/5/7/JSC-1A

Cumulative Excavation Energy: 4J at 200mm, 11J at 400mm
JSC-1A (medium), 30mm deep

Raking 1/2/3/4/5/6/7/8:
Run IDs: 090919-1140, 090919-1201, 090919-1223
Conditions: 30 mm deep  Rake1/2/3/4/5/6/7/8 0  Compacted(20/40%15Hz45s)  JSC-1A

Cumulative Excavation Energy: 2.4J at 200mm, 5J at 400mm

Wide Blade:
Run IDs: 090919-1146, 090919-1206, 090919-1227
Conditions: 30 mm deep  Flat 0  Raked 1/2/3/4/5/6/7/8 JSC-1A

Cumulative Excavation Energy: 3.4J at 200mm, 9J at 400mm
JSC-1A (medium), 30mm deep

**Raking 1/8:**
Run IDs: 090920-1007, 090920-1040, 090920-1105
Conditions: 30 mm deep  Rake1/8  0  Compacted(20/40%15Hz45s) JSC-1A

Cumulative Excavation Energy: 1.1J at 200mm, 2J at 400mm

**Wide Blade:**
Run IDs: 090920-1022, 090920-1043, 090920-1111
Conditions: 30 mm deep  Flat  0  Raked1/8  JSC-1A

Cumulative Excavation Energy: 5J at 200mm, 13J at 400mm
**JSC-1A (medium), 45mm deep**

**Raking 1/8:**

Run IDs: 090921-1241, 090921-1311, 090921-1352

Conditions: 45 Rake 1/8 0 Compacted(20/40%15Hz45s) JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 6J at 400mm

**Wide Blade:**

Run IDs: 090921-1252, 090921-1328, 090921-1358

Conditions: 45 Flat 0 Raked 1/8 JSC-1A

Cumulative Excavation Energy: 11J at 200mm, 26J at 400mm
JSC-1A (medium), 30mm deep

**Raking 4:**
Run IDs: 090921-1422, 090921-1452, 090921-1517
Conditions: 30 mm deep Rake4 0 Compacted(20/40%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.5J at 200mm, 1J at 400mm

**Wide Blade:**
Run IDs: 090921-1432, 090921-1458, 090921-1524
Conditions: 30 mm deep Flat 0 Raked4 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 15J at 400mm
JSC-1A (dense), 30mm deep, 500lb LC
Wide Blade:
Run IDs: 090925-1624, 090925-1648, 090925-1715
Conditions: 30 mm deep  Flat  0  Compacted(100%50Hz30s)  JSC-1A

Cumulative Excavation Energy: 9J at 200mm, 21J at 400mm

JSC-1A (dense), 45mm deep, 500lb LC
Wide Blade:
Run IDs: 090925-1742, 090926-1009, 090926-1133
Conditions: 45 Flat  0  Compacted(100%50Hz5)  JSC-1A

Cumulative Excavation Energy: 20J at 200mm, 42J at 400mm
JSC-1A (loose), 30mm deep, 500lb LC

Wide Blade:

Run IDs: 090926-1232, 090926-1249, 090926-1306

Conditions: 30 mm deep Flat 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 3.4J at 200mm, 9J at 400mm
JSC-1A (loose), 30mm deep

**Raking 3/6:**
Run IDs: 090927-1118, 090927-1142, 090927-1203
Conditions: 30 mm deep Rake3/6 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.23J at 200mm, 0.6J at 400mm

**Wide Blade:**
Run IDs: 090927-1127, 090927-1148, 090927-1210
Conditions: 30 mm deep Flat 0 Raked 3/6 JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 9J at 400mm
**JSC-1A (loose), 30mm deep**

**Raking 4/5:**

Run IDs: 090927-1230, 090927-1254, 090927-1314

Conditions: 30mm deep  Rake4/5  0  Compacted(20%15Hz45s)  JSC-1A

Cumulative Excavation Energy: 0.2J at 200mm, 0.5J at 400mm

**Wide Blade:**

Run IDs: 090927-1235, 090927-1259, 090927-1322

Conditions: 30mm deep  Flat  0  Raked 4/5  JSC-1A

Cumulative Excavation Energy: 3.6J at 200mm, 10J at 400mm
JSC-1A (loose), 30mm deep

Raking 3/5:
Run IDs: 091003-0945, 091003-1011, 091003-1035
Conditions: 30mm deep Rake 3/5 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.23J at 200mm, 0.6J at 400mm

Wide Blade:
Run IDs: 091003-0954, 091003-1018, 091003-1043
Conditions: 30mm deep Flat 0 Raked 3/5 JSC-1A

Cumulative Excavation Energy: 3.4J at 200mm, 9J at 400mm
JSC-1A (loose), 30mm deep

Raking 8:
Run IDs: 091003-1108, 091003-1135, 091003-1158
Conditions: 30mm deep Rake 8 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.07J at 200mm, 0.15J at 400mm

Wide Blade:
Run IDs: 091003-1118, 091003-1142, 091003-1205
Conditions: 30mm deep Flat 0 Raked 8 JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 8J at 400mm
**JSC-1A (dense), 30mm deep**

**Raking 1/8:**

Run IDs: 091004-1359, 091004-1437, 091004-1504

Conditions: 30mm deep Rake 1/8 0 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 2J at 200mm, 4J at 400mm

**Wide Blade:**

Run IDs: 091004-1412, 091004-1445, 091004-1511

Conditions: 30mm deep Flat 0 Raked 1/8 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 14J at 400mm
JSC-1A (dense), 30mm deep

**Raking 1/3/5/7:**
Run IDs: 091005-1309, 091005-1339, 091005-1412
Conditions: 30mm deep  Rake 1/3/5/7  0  Compacted(100%50Hz30s)  JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 6J at 400mm

**Wide Blade:**
Run IDs: 091005-1319, 091005-1346, 091005-1422
Conditions: 30mm deep  Flat  0  Raked 1/3/5/7  JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 14J at 400mm
**JSC-1A (dense), 30mm deep**

**Raking 4:**
Run IDs: 091009-1236, 091009-1305, 091009-1335
Conditions: 30mm deep Rake 4 0 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 0.8J at 200mm, 1.2J at 400mm

**Wide Blade:**
Run IDs: 091009-1245, 091009-1312, 091009-1344
Conditions: 30mm deep Flat 0 Raked 4 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 16J at 400mm
JSC-1A (loose), 30mm deep

Raking 2/7:
Run IDs: 090928-1236, 090928-1300, 090928-1322
Conditions: 30mm deep Rake2/7 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.2J at 200mm, 0.5J at 400mm

Wide Blade:
Run IDs: 090928-1243, 090928-1307, 090928-1332
Conditions: 30mm deep Flat 0 Raked 2/7 JSC-1A

Cumulative Excavation Energy: 3.5J at 200mm, 9J at 400mm
JSC-1A (loose), 30mm deep

Raking 2/6:
Run IDs: 090928-1441, 090928-1503, 090928-1535
Conditions: 30mm deep Rake2/6 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.23J at 200mm, 0.6J at 400mm

Wide Blade:
Run IDs: 090928-1447, 090928-1512, 090928-1542
Conditions: 30mm deep Flat 0 Raked 2/6 JSC-1A

Cumulative Excavation Energy: 3.4J at 200mm, 9J at 400mm
JSC-1A (loose), 30mm deep

**Raking 3/5:**

Run IDs: 091003-0945, 091003-1011, 091003-1035

Conditions: 30mm deep  Rake 3/5  0  Compacted(20%15Hz45s)  JSC-1A

Cumulative Excavation Energy: 0.23J at 200mm, 0.6J at 400mm

**Wide Blade:**

Run IDs: 091003-0954, 091003-1018, 091003-1043

Conditions: 30mm deep  Flat  0  Raked 3/5  JSC-1A

Cumulative Excavation Energy: 3.4J at 200mm, 9J at 400mm
**JSC-1A (loose), 30mm deep**

**Raking 8:**
Run IDs: 091003-1108, 091003-1135, 091003-1158
Conditions: 30mm deep Rake 8 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.07J at 200mm, 0.15J at 400mm

**Wide Blade:**
Run IDs: 091003-1118, 091003-1142, 091003-1205
Conditions: 30mm deep Flat 0 Rake 8 JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 8J at 400mm
JSC-1A (dense), 30mm deep

**Raking 1/8:**
Run IDs: 091004-1359, 091004-1437, 091004-1504
Conditions: 30mm deep Rake 1/8 0 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 2J at 200mm, 4J at 400mm

**Wide Blade:**
Run IDs: 091004-1412, 091004-1445, 091004-1511
Conditions: 30mm deep Flat 0 Raked 1/8 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 14J at 400mm
JSC-1A (dense), 30mm deep

**Raking 1/3/5/7:**
Run IDs: 091005-1309, 091005-1339, 091005-1412
Conditions: 30mm deep Rake 1/3/5/7 0 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 6J at 400mm

**Wide Blade:**
Run IDs: 091005-1319, 091005-1346, 091005-1422
Conditions: 30mm deep Flat 0 Raked 1/3/5/7 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 14J at 400mm
JSC-1A (dense), 30mm deep

Raking 4:
Run IDs: 091009-1236, 091009-1305, 091009-1335
Conditions: 30mm deep Rake 4 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 0.8J at 200mm, 1.2J at 400mm

Wide Blade:
Run IDs: 091009-1245, 091009-1312, 091009-1344
Conditions: 30mm deep Flat Raked 4 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 16J at 400mm
JSC-1A (loose), 30mm deep

Wide Blade:

Run IDs: 091017-1453, 091017-1603, 091017-1621

Conditions: 30mm deep  Flat  0  Compacted(20%15Hz45s)  JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 7J at 400mm
**JSC-1A (loose), 30mm deep**

**Raking 2/7:**
Run IDs: 090928-1236, 090928-1300, 090928-1322, 091017-1535
Conditions: 30mm deep Rake2/7 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.2J at 200mm, 0.5J at 400mm

**Wide Blade:**
Run IDs: 090928-1243, 090928-1307, 090928-1332, 091017-1544
Conditions: 30mm deep Flat 0 Raked 2/7 JSC-1A

Cumulative Excavation Energy: 3.5J at 200mm, 9J at 400mm
JSC-1A (loose), 30mm deep

**Raking 1/2/3/4/5/6/7/8:**
Run IDs: 091018-1326, 091018-1348, 091018-1412
Conditions: 30mm deep  Rake 1/2/3/4/5/6/7/8  0  Compacted(20%15Hz45s)  JSC-1A

Cumulative Excavation Energy: 1J at 200mm, 2J at 400mm

**Wide Blade:**
Run IDs: 091018-1333, 091018-1355, 091018-1422
Conditions: 30mm deep  Flat  0  Raked 1/2/3/4/5/6/7/8 JSC-1A

Cumulative Excavation Energy: 2.7J at 200mm, 7J at 400mm
JSC-1A (loose), 30mm deep

Raking 1/3/5/7:
Run IDs: 091018-1448, 091018-1513, 091018-1536
Conditions: 30mm deep Rake 1/3/5/7 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 0.5J at 200mm, 1J at 400mm

Wide Blade:
Run IDs: 091018-1456, 091018-1520, 091018-1543
Conditions: 30mm deep Flat 0 Raked 1/3/5/7 JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 8J at 400mm
**JSC-1A (loose), 30mm deep**

**Raking 1/8:**

Run IDs: 091023-1240, 091023-1307, 091023-1350

Conditions: 30mm deep   Rake 1/8   0   Compacted(20%15Hz45s)   JSC-1A

Cumulative Excavation Energy: 0.13J at 200mm, 0.4J at 400mm

**Wide Blade:**

Run IDs: 091023-1251, 091023-1315, 091023-1357

Conditions: 30mm deep   Flat   0   Raked 1/8   JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 8J at 400mm
**JSC-1A (loose), 45mm deep**

**Raking 1/3/5/7:**
Run IDs: 091024-1303, 091024-1331, 091024-1405
Conditions: 45 Rake 1/3/5/7 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 1J at 200mm, 2.4J at 400mm

**Wide Blade:**
Run IDs: 091024-1311, 091024-1349, 091024-1425
Conditions: 45 Flat 0 Raked 1/3/5/7 JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 16J at 400mm
JSC-1A (dense), 60mm deep

**Raking 1/8:**
Run IDs: 091130-1337, 091130-1413, 091130-1504
Conditions: 60 Rake 1/8 0 Compacted(100%50Hz75s10bf) JSC-1A

Cumulative Excavation Energy: 22J at 200mm, 41J at 400mm

**Wide Blade:**
Run IDs: 091130-1435, 091130-1536
Conditions: 60 Flat 0 Raked 1/8 JSC-1A

Cumulative Excavation Energy: 24J at 200mm, 55J at 400mm

**Raking 1/3/5/7:**
Run IDs: 081114-1551, 081118-1110, 081118-1147
Conditions: 30mm deep 1,3,5,7 Rake 0 Compacted JSC-1A
Cumulative Excavation Energy: 4J at 200mm, 8J at 400mm

**Raking 1/3/5/7:**

Run IDs: 091005-1309, 091005-1339, 091005-1412

Conditions: 30mm deep Rake 1/3/5/7 0 Compacted(100%50Hz30s) JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 6J at 400mm
Rake 1/3/5/7 (Loose/ Medium/ Dense):
Run IDs: 091005-1309, 091005-1339, 091005-1412
Conditions: 30mm deep Rake 1/3/5/7 0 Compacted(100%50Hz30s) JSC-1A
Run IDs: 090919-0943, 090919-1013, 090919-1042, 090919-1108
Conditions: 30mm deep Rake1/3/5/7/0 Compacted(20/40%15Hz45s) JSC-1A
Run IDs: 091018-1448, 091018-1513, 091018-1536
Conditions: 30mm deep Rake 1/3/5/7 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 1.7J at 200mm, 3J at 400mm
**Rake 1/2/3/4/5/6/7/8 (Loose/ Medium/ Dense):**

Run IDs: 081121-1617, 081121-1652, 081121-1714

Conditions: 30mm deep 1,2,3,4,5,6,7,8 Rake2 0 Compacted JSC-1A

Run IDs: 090919-1140, 090919-1201, 090919-1223

Conditions: 30mm deep Rake1/2/3/4/5/6/7/8 0 Compacted(20/40%15Hz45s) JSC-1A

Run IDs: 091018-1326, 091018-1348, 091018-1412

Conditions: 30mm deep Rake 1/2/3/4/5/6/7/8 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 3J at 200mm, 6J at 400mm
Rake 1/8 (Loose/ Medium/ Dense):
Run IDs: 090522-1416, 090522-1502, 090522-1536
Conditions: 30mm deep Rake 1/8 0 Compacted(100%) JSC-1A
Run IDs: 090920-1007, 090920-1040, 090920-1105
Conditions: 30mm deep Rake 1/8 0 Compacted(20/40%15Hz45s) JSC-1A
Run IDs: 091023-1240, 091023-1307, 091023-1350
Conditions: 30mm deep Rake 1/8 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 1.2J at 200mm, 2.3J at 400mm
Wide Blade (Loose/ Medium/ Dense):

Run IDs: 090925-1624, 090925-1648, 090925-1715
Conditions: 30mm deep Flat 0 Compacted(100%50Hz30s) JSC-1A

Run IDs: 090916-1535, 090916-1623, 090916-1647
Conditions: 30mm deep Flat 0 Compacted(20/40%15Hz45s) JSC-1A

Run IDs: 091017-1453, 091017-1603, 091017-1621
Conditions: 30mm deep Flat 0 Compacted(20%15Hz45s) JSC-1A

Cumulative Excavation Energy: 6J at 200mm, 15J at 400mm
Wide Blade (Dense):
Run IDs: 090925-1624, 090925-1648, 090925-1715
Conditions: 30mm deep Flat 0 Compacted(100%50Hz30s) JSC-1A
Run IDs: 090519-1620, 090521-0944, 090521-1007
Conditions: 30mm deep Flat 0 Compacted(100%) JSC-1A
Run IDs: 081106-1105, 081106-1227, 081106-1317, 081106-1453, 081113-1508, 081113-1538, 081113-1605
Conditions: 30mm deep Flat 0 Compacted JSC-1A

Cumulative Excavation Energy: 10J at 200mm, 21J at 400mm
Run IDs: 081119-1443, 081119-1509, 081120-1029

Conditions: 30mm deep Flat 0 1,8 Raked JSC-1A

Cumulative Excavation Energy: 7J at 200mm, 14J at 400mm
**Rake 1/8 (Dense) 60mm/45mm/30mm:**
Run IDs: 091130-1337, 091130-1413, 091130-1504
Conditions: 60 Rake 1/8 0 Compacted(100%50Hz75s10bf) JSC-1A
Run IDs: 090522-1602, 090525-0902, 090525-0944, 090522-1416, 090522-1502, 090522-1536
Conditions: 45 Rake 1/8 0 Compacted(100%) JSC-1A

**Wide Blade (Dense) 60mm/45mm/30mm:**
Run IDs: 091130-1435, 091130-1536
Conditions: 60 Flat 0 Raked 1/8 JSC-1A
Run IDs: 090522-1612, 090525-0920, 090525-0955
Conditions: 45 Flat 0 1/8 raked JSC-1A
Run IDs: 090522-1423, 090522-1514, 090522-1542
Conditions: 30mm deep Flat 0 1/8 raked JSC-1A
Wide Blade on JSC-1A with 5% Gravel

Run IDs: 100209-1528, 100209-1551, 100213-1315, 100213-1359

Conditions: 30mm deep Flat 0 Compacted(100%50Hz10bf70s) JSC-1A w/ 5% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 13J at 200mm, 30J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -13J at 200mm, -29J at 400mm
Rake 1/3/5/7 on JSC-1A with 5% Gravel

Run IDs: 100213-1508, 100213-1534, 100213-1558, 100213-1622, 100213-1636

Conditions: 30mm deep Rake 1/3/5/7 0 Compacted(100%50Hz10bf60s)

JSC-1A w/ 5% coarse

Cumulative Excavation Energy: 6J at 200mm, 13J at 400mm

Wide Blade on Raked JSC-1A with 5% Gravel

Run IDs: 100213-1519, 100213-1541, 100213-1605, 100213-1650

Conditions: 30mm deep Flat 0 Raked 1/3/5/7 JSC-1A w/ 5% coarse

Cumulative Excavation Energy: 8J at 200mm, 19J at 400mm
**Wide Blade on JSC-1A with 10% Gravel**

Run IDs: 100214-1504, 100214-1524, 100214-1541

Conditions: 30mm deep Flat 0 Compacted(100%50Hz10bf70s) JSC-1A w/ 10% coarse

**Horizontal Force Component:**

Cumulative Excavation Energy: 15J at 200mm, 39J at 400mm

**Vertical Force Component:**

Cumulative Excavation Energy: -18J at 200mm, -44J at 400mm
Rake 1/3/5/7 on JSC-1A with 10% Gravel
Run IDs: 100214-1558, 100214-1632, 100214-1659
Conditions: 30mm deep Rake 1/3/5/7 0 Compacted(100%50Hz10bf70s)
JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 6J at 200mm, 13J at 400mm

Wide Blade on Raked JSC-1A with 5% Gravel
Run IDs: 100214-1610, 100214-1638, 100214-1706
Conditions: 30mm deep Flat 0 Raked 1/3/5/7 JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 9J at 200mm, 20J at 400mm
**Rake 1/2/3/4/5/6/7/8 on JSC-1A with 10% Gravel**

Run IDs: 100220-1430, 100220-1452, 100220-1512, 100220-1532

Conditions: 30mm deep Rake 1/.../8 0 Compacted(100%50Hz10bf70s) JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 8J at 200mm, 21J at 400mm

**Wide Blade on Raked JSC-1A with 10% Gravel**

Run IDs: 100220-1438, 100220-1459, 100220-1518, 100220-1541

Conditions: 30mm deep Flat 0 Raked 1/.../8 JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 6J at 200mm, 16J at 400mm
Wide Blade on JSC-1A with 10% Gravel

Run IDs: 100221-1433, 100221-1457, 100221-1520

Conditions: 45 Flat 0 Compacted(100%50Hz10bf80s) JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 35J at 200mm, 71J at 400mm
Rake 1/3/5/7 on JSC-1A with 10% Gravel (45mm deep)
Run IDs: 100221-1601, 100221-1634, 100221-1659
Conditions: 45 Rake 1/3/5/7 0 Compacted(100%50Hz10bf80s) JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 10J at 200mm, 19J at 400mm

Wide Blade on Raked JSC-1A with 10% Gravel (45mm deep)
Run IDs: 100221-1610, 100221-1642, 100221-1707
Conditions: 45 Flat 0 Raked 1/3/5/7 JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 15J at 200mm, 32J at 400mm
**Rake 1/8 on JSC-1A with 10% Gravel**

Run IDs: 100226-1338, 100226-1401, 100226-1439, 100226-1515

Conditions: 30mm deep  Rake 1/8 0  Compacted(100%50Hz10bf80s)  JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 2.4J at 200mm, 5J at 400mm

**Wide Blade on Raked JSC-1A with 10% Gravel**

Run IDs: 100226-1345, 100226-1422, 100226-1453, 100226-1524

Conditions: 30mm deep  Flat 0  Raked 1/8  JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 9J at 200mm, 21J at 400mm
Rake 3/6 on JSC-1A with 10% Gravel
Run IDs: 100227-1316, 100227-1341, 100227-1420
Conditions: 30mm deep Rake 3/6 0 Compacted(100%50Hz10bf85s) JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 2.3J at 200mm, 4J at 400mm

Wide Blade on Raked JSC-1A with 10% Gravel
Run IDs: 100227-1323, 100227-1349, 100227-1427
Conditions: 30mm deep Flat 0 Raked 3/6 JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 12J at 200mm, 28J at 400mm
**Rake 4/5 on JSC-1A with 10% Gravel**

Run IDs: 100227-1458, 100227-1530, 100227-1606

Conditions: 30mm deep  Rake 4/5 0  Compacted(100%50Hz10bf80s)

JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 1.6J at 200mm, 3.5J at 400mm

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**Wide Blade on Raked JSC-1A with 10% Gravel**

Run IDs: 100227-1512, 100227-1541, 100227-1614

Conditions: 30mm deep  Flat 0  Raked 4/5  JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 14J at 200mm, 30J at 400mm
**Rake 4 on JSC-1A with 10% Gravel**

Run IDs: 100227-1632, 100227-1704, 100227-1729

Conditions: 30mm deep Rake 4 0 Compacted(100%50Hz10bf100s) JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 0.9J at 200mm, 2J at 400mm

**Wide Blade on Raked JSC-1A with 10% Gravel**

Run IDs: 100227-1647, 100227-1712, 100227-1736

Conditions: 30mm deep Flat 0 Raked 4 JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 14J at 200mm, 33J at 400mm
**Rake 2/7 on JSC-1A with 10% Gravel**

Run IDs: 100309-1442, 100309-1509, 100309-1532

Conditions: 30mm deep Rake 2/7 0 Compacted(100%50Hz10bf90s) JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 2J at 200mm, 4.5J at 400mm

**Wide Blade on Raked JSC-1A with 10% Gravel**

Run IDs: 100309-1450, 100309-1517, 100309-1539

Conditions: 30mm deep Flat 0 Raked 2/7 JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 13J at 200mm, 29J at 400mm
Rake 2/7 on JSC-1A with 10% Gravel

Run IDs: 100309-1450, 100309-1517, 100309-1539

Conditions:  30mm deep Flat 0  Raked 2/7  JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 13J at 200mm, 29J at 400mm
Rake 3/5 on JSC-1A with 10% Gravel

Run IDs: 100326-1410, 100326-1435, 100326-1459

Conditions: 30mm deep  Rake 3/5  0  Compacted(100%50Hz10bf90s)

JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 1.2J at 200mm, 2.7J at 400mm

Energy plot is unusual in that this plot is not linear. This might have been caused by compaction. On this day of experiment, we had hard time achieving level surface by compaction, so compaction was repeated 6 times before starting experiment.
Wide Blade on Raked JSC-1A with 10% Gravel

Run IDs: 100326-1418, 100326-1442, 100326-1505

Conditions: 30mm deep Flat 0 Raked 3/5 JSC-1A w/ 10% coarse

Cumulative Excavation Energy: 12J at 200mm, 28J at 400mm
Rake 1/3/5/7 on JSC-1A with 30% Gravel
Run IDs: 100327-1524, 100330-1305, 100330-1443, 100330-1514, 100330-1557
Conditions: 30mm deep  Rake 1/3/5/7  0  Compacted(100%50Hz10bf100s)  JSC-1A w/ 30% coarse
Cumulative Excavation Energy: 8J at 200mm, 14J at 400mm

Wide Blade on Raked JSC-1A with 30% Gravel
Run IDs: 100327-1533, 100330-1315, 100330-1453, 100330-1525, 100330-1607
Conditions: 30mm deep  Flat  0  Raked 1/3/5/7 JSC-1A w/ 30% coarse
Cumulative Excavation Energy: 11J at 200mm, 25J at 400mm
**Rake 1/8 on JSC-1A with 30% Gravel**

Run IDs: 100331-1325, 100331-1359, 100331-1427

Conditions: 30mm deep Rake 1/8 0 Compacted(100%50Hz10bf100s) JSC-1A w/ 30% coarse

Cumulative Excavation Energy: 6J at 200mm, 12J at 400mm

---

**Wide Blade on Raked JSC-1A with 30% Gravel**

Run IDs: 100331-1340, 100331-1409, 100331-1436

Conditions: 30mm deep Flat 0 Raked 1/8 JSC-1A w/ 30% coarse

Cumulative Excavation Energy: 15J at 200mm, 31J at 400mm
**Rake 3/6 on JSC-1A with 30% Gravel**

Run IDs: 100331-1457, 100331-1523, 100331-1547, 100331-1615

Conditions: 30mm deep Rake 3/6 0 Compacted(100%50Hz10bf100s) JSC-1A w/ 30% coarse

Cumulative Excavation Energy: 4J at 200mm, 8J at 400mm

**Wide Blade on Raked JSC-1A with 30% Gravel**

Run IDs: 100331-1531, 100331-1557, 100331-1622

Conditions: 30mm deep Flat 0 Raked 3/6 JSC-1A w/ 30% coarse

Cumulative Excavation Energy: 12J at 200mm, 27J at 400mm
Wide Blade on JSC-1A with 30% Gravel

Run IDs: 100409-1302, 100409-1327, 100409-1350, 100409-1408

Conditions: 30mm deep Flat 0 Compacted(100%50Hz0bf30s) JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 18J at 200mm, 42J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -23J at 200mm, -53J at 400mm
Rake 4 on JSC-1A with 30% Gravel

Run IDs: 100409-1440, 100409-1507, 100409-1744, 100409-1807

Conditions: 30mm deep Rake 4 0 Compacted(100%50Hz0bf30s) JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 2J at 200mm, 4J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -2J at 200mm, -4J at 400mm
Wide Blade on Raked JSC-1A with 30% Gravel

Run IDs: 100409-1452, 100409-1518, 100409-1754, 100409-1816

Conditions: 30mm deep Flat 0 Raked 4 JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 14J at 200mm, 33J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -19J at 200mm, -42J at 400mm
Rake 1/2/3/4/5/6/7/8 on JSC-1A with 30% Gravel

Run IDs: 100413-1403, 100413-1431, 100413-1456, 100413-1519

Conditions: 30mm deep Rake 1/2/3/4/5/6/7/8 0

Compacted(100%50Hz0bf30s) JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 10J at 200mm, 23J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -7J at 200mm, -15J at 400mm
Wide Blade on Raked JSC-1A with 30% Gravel
Run IDs: 100413-1443, 100413-1505, 100413-1528, 100413-1552
Conditions: 30mm deep Flat 0 Raked 1/2/3/4/5/6/7/8 JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 5J at 200mm, 13J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -8J at 200mm, -18J at 400mm
**Rake 4/5 on JSC-1A with 30% Gravel**

**Run IDs:** 100418-1350, 100418-1427, 100418-1450, 100418-1514

**Conditions:** 30mm deep Rake 4/5 0 Compacted(100%50Hz0bf30s) JSC-1A w/ 30% coarse

**Horizontal Force Component:**

Cumulative Excavation Energy: 2.7J at 200mm, 6J at 400mm

**Vertical Force Component:**

Cumulative Excavation Energy: -2J at 200mm, -4J at 400mm
**Wide Blade on Raked JSC-1A with 30% Gravel**

Run IDs: 100418-1403, 100418-1435, 100418-1500, 100418-1522

Conditions: 30mm deep Flat 0 Raked 4/5 JSC-1A w/ 30% coarse

**Horizontal Force Component:**

Cumulative Excavation Energy: 12J at 200mm, 29J at 400mm

**Vertical Force Component:**

Cumulative Excavation Energy: -16J at 200mm, -35J at 400mm
Rake 2/7 on JSC-1A with 30% Gravel

Run IDs: 100418-1553, 100423-1428, 100423-1448, 100423-1509, 100423-1533, 100424-1351, 100424-1420

Conditions: 30mm deep Rake 2/7 0 Compacted(100%50Hz0bf30s)

JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 4J at 200mm, 8J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -2J at 200mm, -4J at 400mm
Wide Blade on Rake JSC-1A with 30% Gravel

Run IDs: 100423-1434, 100423-1454, 100423-1518, 100423-1541, 100424-1358, 100424-1428

Conditions: 30mm deep Flat 0 Raked 2/7 JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 12J at 200mm, 27J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -16J at 200mm, -36J at 400mm
Rake 3/5 on JSC-1A with 30% Gravel
Run IDs: 100424-1502, 100424-1523, 100424-1543, 100424-1604
Conditions: 30mm deep Rake 3/5 0 Compacted(100%50Hz0bf30s)
JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 4J at 200mm, 7J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -3J at 200mm, -5J at 400mm
Wide Blade on Rake JSC-1A with 30% Gravel

Run IDs: 100424-1509, 100424-1530, 100424-1551, 100424-1614

Conditions: 30mm deep  Flat 0  Raked 3/5  JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 13J at 200mm, 30J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -17J at 200mm, -39J at 400mm
Rake 1/8 on JSC-1A with 30% Gravel

Run IDs: 100513-1305, 100513-1332, 100513-1435, 100513-1459

Conditions: 30mm deep Rake 1/8 0 Compacted(100%50Hz0bf30s) JSC-1A w/ 30% coarse

Horizontal Force Component:

Cumulative Excavation Energy: 4J at 200mm, 9J at 400mm

Vertical Force Component:

Cumulative Excavation Energy: -3J at 200mm, -5J at 400mm
**Wide Blade on Raked JSC-1A with 30% Gravel**

Run IDs: 100513-1314, 100513-1341, 100513-1444, 100513-1507

Conditions: 30mm deep  Flat 0 Raked 1/8  JSC-1A w/ 30% coarse

**Horizontal Force Component:**

Cumulative Excavation Energy: 12J at 200mm, 26J at 400mm

**Vertical Force Component:**

Cumulative Excavation Energy: -16J at 200mm, -32J at 400mm
APPENDIX D.

EXCAVATION ENERGY DATA AT 200MM AND 400MM WAYPOINTS
Excavation Energy in J.

<table>
<thead>
<tr>
<th></th>
<th>at 200mm</th>
<th>at 200mm</th>
<th>at 200mm</th>
<th>at 400mm</th>
<th>at 400mm</th>
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<td>Total</td>
<td>Rake</td>
<td>Wide Blade</td>
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<td>JSC-1A</td>
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<td></td>
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<td></td>
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<td>11.3</td>
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<tr>
<td>Four tines(1/3/5/7)</td>
<td>4</td>
<td>4</td>
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<td>8</td>
<td>9</td>
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<tr>
<td>Two tines(1/8)</td>
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<td>16.3</td>
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<tr>
<td>Two tines(4/5)</td>
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<td>7.5</td>
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<td>27</td>
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<td>9.7</td>
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<td>11.5</td>
<td>10.5</td>
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<td>3.3</td>
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<td>8.3</td>
<td>6.7</td>
<td>13</td>
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Dense JSC-1A with 0% gravel, 30 mm deep

Energy at 200mm (Dense JSC-1A)

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<td>No raking</td>
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<tr>
<td>Eight tines(1/2/3/4/5/6/7/8)</td>
<td>Eight tines(1/2/3/4/5/6/7/8)</td>
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<tr>
<td>Four tines(1/3/5/7)</td>
<td>Four tines(1/3/5/7)</td>
</tr>
<tr>
<td>Two tines(1/8)</td>
<td>Two tines(1/8)</td>
</tr>
<tr>
<td>Two tines(1/8)</td>
<td>Two tines(1/8)</td>
</tr>
<tr>
<td>Two tines(2/7)</td>
<td>Two tines(2/7)</td>
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<tr>
<td>Two tines(2/6)</td>
<td>Two tines(2/6)</td>
</tr>
<tr>
<td>Two tines(3/6)</td>
<td>Two tines(3/6)</td>
</tr>
<tr>
<td>Two tines(3/5)</td>
<td>Two tines(3/5)</td>
</tr>
<tr>
<td>Two tines(4/5)</td>
<td>Two tines(4/5)</td>
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<tr>
<td>One tine(4)</td>
<td>One tine(4)</td>
</tr>
<tr>
<td>One tine(8)</td>
<td>One tine(8)</td>
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</table>

Unit of energy is J.

Energy at 400mm (Dense JSC-1A)

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<tbody>
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<td>No raking</td>
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<tr>
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<td>Eight tines(1/2/3/4/5/6/7/8)</td>
</tr>
<tr>
<td>Four tines(1/3/5/7)</td>
<td>Four tines(1/3/5/7)</td>
</tr>
<tr>
<td>Two tines(1/8)</td>
<td>Two tines(1/8)</td>
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<td>Two tines(1/8)</td>
<td>Two tines(1/8)</td>
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<td>Two tines(2/7)</td>
<td>Two tines(2/7)</td>
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<tr>
<td>Two tines(2/6)</td>
<td>Two tines(2/6)</td>
</tr>
<tr>
<td>Two tines(3/6)</td>
<td>Two tines(3/6)</td>
</tr>
<tr>
<td>Two tines(3/5)</td>
<td>Two tines(3/5)</td>
</tr>
<tr>
<td>Two tines(4/5)</td>
<td>Two tines(4/5)</td>
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<td>One tine(4)</td>
<td>One tine(4)</td>
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<tr>
<td>One tine(8)</td>
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</table>

Unit of energy is J.
Dense JSC-1A with 0% gravel, 30 mm deep

Excavation energy in J.

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<th>at200mm</th>
<th>at200mm</th>
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<th>at400mm</th>
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<td>Rake</td>
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<td>Total</td>
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<td>-</td>
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<tr>
<td>Eight tines(1to8)</td>
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<td>10.5</td>
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<td>11.3</td>
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<tr>
<td>Four tines(1/3/5/7)</td>
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<td>4</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>17</td>
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<tr>
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<td>2.5</td>
<td>6</td>
<td>8.5</td>
<td>4.8</td>
<td>14</td>
<td>18.8</td>
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<tr>
<td>Two tines(3/6)</td>
<td>2.5</td>
<td>7.5</td>
<td>10</td>
<td>4.5</td>
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<td>One tine(4)</td>
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<td>8.5</td>
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<table>
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<td>Total</td>
<td>Rake</td>
<td>Wide</td>
<td>Total</td>
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<tr>
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<td>6</td>
<td>8.5</td>
<td>4.8</td>
<td>14</td>
<td>18.8</td>
</tr>
<tr>
<td>Two tines(2/7)</td>
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<td>8.4</td>
<td>4.2</td>
<td>15</td>
<td>19.2</td>
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<td>10</td>
<td>4.5</td>
<td>16.3</td>
<td>20.8</td>
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</table>
Medium Dense JSC-1A with 0% gravel, 30mm deep

Excavation energy in J.

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<th>at200mm</th>
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<td>-</td>
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<td>5</td>
<td>9</td>
<td>14</td>
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<td>Four tines(1/3/5/7)</td>
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<td>4</td>
<td>5.6</td>
<td>3</td>
<td>11</td>
<td>14</td>
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<tr>
<td>Two tines(1/8)</td>
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<td>5</td>
<td>6.1</td>
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<td>13</td>
<td>15</td>
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<td>One tine(8)</td>
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Loose JSC-1A with 0% gravel, 30mm deep

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<td>Wide</td>
<td>Total</td>
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<td>Four tines(1/3/5/7)</td>
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Data on Dense JSC-1A with 5% to 30% gravel.

Excavation energy in J.

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<th>Gravel content, %</th>
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<th>Wide Blade</th>
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<td>at200mm</td>
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<td>2.4</td>
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<td>Rake 1/2/3/4/5/6/7/8</td>
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<td>10</td>
<td>8</td>
</tr>
<tr>
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<td>30</td>
<td>10</td>
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</table>
Data on Dense JSC-1A with 5% to 30% gravel (continued).

Excavation energy in J.

<table>
<thead>
<tr>
<th>Different number</th>
<th>Rake</th>
<th>Depth, mm</th>
<th>Gravel content, %</th>
<th>at200mm</th>
<th>at400mm</th>
<th>Wide Blade</th>
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<th>at400mm</th>
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<td>4</td>
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<td>4</td>
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<tr>
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<td>30</td>
<td>4</td>
<td>9</td>
<td>12</td>
<td>12</td>
<td>26</td>
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<tr>
<td>Rake 1/8(*)</td>
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<td>30</td>
<td>6</td>
<td>12</td>
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<td>8</td>
<td>14</td>
<td>11</td>
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<tr>
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<td>23</td>
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<td>4</td>
<td>9</td>
<td>12</td>
<td>12</td>
<td>26</td>
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</tbody>
</table>

| Two tines        | Rake 1/3/5/7 | 30 | 0 | 4 | 8 | 4 | 9 |
| Rake 1/3/5/7     | 30 | 5 | 6 | 13 | 8 | 19 |
| Rake 1/3/5/7     | 30 | 10 | 6 | 13 | 9 | 20 |
| Rake 1/3/5/7     | 30 | 30 | 8 | 14 | 11 | 25 |
Data on Dense JSC-1A with 5% to 30% gravel (continued).

Excavation energy in J.

<table>
<thead>
<tr>
<th>Depth, mm</th>
<th>Gravel content, %</th>
<th>Rake</th>
<th>Wide Blade</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>at 200mm</td>
<td>at 400mm</td>
<td>at 200mm</td>
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<tr>
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<td>Specific Energy</td>
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<td>0</td>
<td>-</td>
</tr>
<tr>
<td>No Raking</td>
<td>30</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>No Raking</td>
<td>30</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>No Raking</td>
<td>30</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>No Raking</td>
<td>45</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>No Raking</td>
<td>45</td>
<td>10</td>
<td>-</td>
</tr>
</tbody>
</table>

![Specific Energy Diagram]

- **Specific Energy (@200mm), J/m3**
- **Specific Energy (@400mm), J/m3**
BIBLIOGRAPHY


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³ A newsletter not in publication as of 2003. Formally called Curatorial Newsletter. See appendix B to know which issue has data for which Apollo core sample.


VITA

Masafumi Iai was born in Tokyo. He received Bachelor of Engineering in Mechanical Engineering (2001-03-26), and Master of Engineering in Mechanical Engineering (2003-09-30) from Tokyo Institute of Technology. He visited Sharif University of Technology from 2002-04-12 to 2003-06-04. He served as a lecturer at Tokyo Metropolitan College of Aeronautical Engineering, Department of Aeronautical Engineering, from 2004-04-01 to 2005-03-31. At Missouri University of Science and Technology, he was awarded Master of Science in Civil Engineering (2010-05-15) and PhD in Geological Engineering (2010-12-18).