Engineered Equestrian Riding Surfaces

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COMMITTEE PAGE

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ABSTRACT

Engineered Equestrian Riding Surfaces

By

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University of New Hampshire, May, 2018

Engineered equestrian surfaces are complex systems subject to unique loading. Interest in engineered surfaces has been growing since a properly designed surface boasts better performance, increased safety, and reduced maintenance as compared to other more traditional sand or turf riding surfaces. The goals of engineered riding surfaces are to improve the riding characteristics and horse performance and to reduce maintenance requirements. Research was undertaken to investigate how changes in surface material composition affect geotechnical properties of riding surfaces, and how changes in geotechnical properties affect the riding characteristics. Direct shear testing, Light Weight Deflectometer, and a new custom built Lab Drop Apparatus were used to characterize riding surface materials. Methods for quantitatively evaluating riding surface performance based on these tests are proposed. Two case studies were conducted to compare quantitative analysis methods to qualitative feedback from riders.
Equestrian riding surfaces are crucial to the performance and well-being of the horse and rider; just as synthetic turf is crucial to the performance of human athletes. Horses at the highest competition levels are very sensitive to the properties of the riding surface, and the riding surface, in turn, is very sensitive to its material composition. A poorly designed surface may also be linked to increased risk of injury in horses as well as a decrease in riding performance. Recent years have seen a dramatic increase in the use of engineered equestrian riding surfaces, especially at the highest levels of competition. An engineered riding surface is a sand-based mixture composed of one or more type of synthetic component, such as polymer fibers, geosynthetic fabric pieces, rubber pieces, and binding agents. When properly constructed and maintained, engineered riding surfaces boast enhanced riding performance, less variability, less maintenance, and the ability to be customized to a particular riding style or event. Their use, however, has outpaced the science: there is currently very little public knowledge regarding the role of surface components on riding performance. There is also a lack of standardized test methods and analyses for systematically characterizing, evaluating, and comparing the mechanical and functional properties of riding surface materials. Currently, the surface design and evaluation process is reserved for a select few individuals with years of experience and accumulated knowledge. Surfaces are compared using subjective evaluation by riders which, while rider opinions should be seriously considered when designing a surface, does not present a robust method for comparison moving forward. The lack of standards and general information
about surface properties also presents a problem for arena owners, who do not have simple and inexpensive tools at their disposal that can be used to verify manufacturers performance claims and develop appropriate maintenance plans. Developing standard test methods and generating public knowledge on the performance of equestrian surfaces will encourage data-driven innovation and development from manufacturers, empower arena owners, and provide safer riding conditions for horses.

Research presented in this thesis aims to expand knowledge of the geotechnical properties of riding surface materials, provide information on simple lab and field tests which can be used to characterize surfaces, investigate some of the physics of the horse-surface interaction, and relate functional properties to tangible, measureable, physical phenomena. Two case studies are also presented which demonstrate the applicability of some of the test methods.

Chapter 2 goes over background information on equestrian surface research, including different approaches by other researchers to characterize surfaces, and introduces the concepts of functional properties and the horse-surface interaction. Chapter 3 discusses the methodologies of lab and field tests used to characterize riding surfaces. Chapter 4 discusses two case studies undertaken as part of the research. Chapter 5 presents the results of this research. Chapter 6 summarizes the research and discusses important conclusions.
Most state-of-the-art engineered equestrian surfaces consist of a silica sand base of varying grain sizes and contain components from one or more of the following general categories: fibers, fabric pieces, rubber pieces, and/or a polymer-based binding agent. The components of an engineered surface are in themselves very specialized products, and their proportion in the riding surface mixture greatly affects riding characteristics and performance. Components are often tailor-made specifically for or by the surface manufacturer, and can be mixed at the factory or at the arena. Component specifications and mixture proportions are often proprietary, leading to expensive systems. Designing and developing a high performance riding surface is a complex process.

Little publicly available research has been done to date regarding the influence of the type and quantity of geosynthetic components on the riding characteristics of surfaces. Understanding the influence of the type and quantity of geosynthetic components on riding characteristics is crucial to encouraging data-driven innovation and advancement in the field of engineered equestrian surfaces.

Analysis of engineered equestrian surfaces is further complicated by the complex interaction that occurs between the horse hoof and the surface material, in addition to the interaction between the various component types. The complexity of the interaction results in many studies using
qualitative evaluation of riding surface characteristics instead of quantitative evaluation. Qualitative evaluation is typically done through the use of generally accepted terms, called functional properties, that aim to describe the characteristics of riding surfaces. The desire for more standardized quantitative evaluation methods has brought rise to a few tools developed specifically for engineered equestrian surfaces, such as the Orono Biomechanical Surface Tester, described in section 2.2.2.

Generally, a riding surface system may consist of three major layers: the riding surface and two support layers, all constructed on top of a natural or prepared base grade. A schematic is depicted in Figure 1.

![Schematic of riding surface system](image)

**Figure 1: Schematic of riding surface system**

The typical riding surface is three to five inches in depth, although depth may vary greatly from one arena to another as well as within a single arena, especially with time and use. The first support layer may be compacted stone dust, asphalt, or specialized rubber concussion mats. The second support layer may be compacted angular stone, and may or may not be present. The rough base grade is often compacted natural ground.
It is understood that the anatomy of the entire profile affects the overall riding characteristics, however most current research appears to focus primarily on the riding surface material.

2.1 – Genesis of Engineered Riding Surfaces

Horses historically rode on natural turf surfaces, however natural turf is difficult to maintain and may degrade over time, especially when exposed to high volume use. Additionally, using natural turf greatly limits where, geographically, such an arena can be built. In response to the growing demands being placed on natural turf surfaces, research and development of synthetic surfaces simulating natural turf started in the early to mid-1980’s. The first commercial installation of a synthetic coated sand surface, Polytrack, occurred in 1987 in the United Kingdom. Polytrack was a mixture of sand, synthetic fibers, and recycled rubber pieces that was coated in wax. Throughout the next two decades, more widespread installation of synthetic surfaces occurred globally, although primarily centered in the United States. Growth occurred despite continuing performance and maintenance issues. Many tracks eventually forwent their synthetic surface and installed a more traditional surface of just sand (Attwood Equestrian Surfaces, 2016).

It was clear from these early experiments that the current state of technology of engineered surfaces was not delivering the desired performance. Many surfaces were too hard and required excessive maintenance. In order to better understand engineered surface behavior, the International Equestrian Federation (FEI) funded several studies in the mid 2000’s aimed at understanding the role of surface properties in horse injury and connecting subjective evaluation to objective measurement of surface properties (Equestrian Surfaces – A Guide, 2014). One of such studies compared subjective evaluation of engineered surfaces to objective measurement (Hernlund et al., 2017). The results from that study showed that there was much variation in the
assessment of riding surfaces between riders, and that it may be possible to quantitatively evaluate some of the functional properties of riding surfaces.

2.2 – Literature Review

An overarching goal of equestrian surface research is developing standard test and analysis methods for characterizing the functional properties of surfaces by quantitative instead of qualitative means. Several approaches have been taken by different researchers in an attempt to reach this goal. This section discusses two of the most prominent approaches in the literature: instrumentation of the horse hoof for data collection during different riding conditions, and the development of a biomechanical test apparatus to simulate horse hoof loading.

2.2.1 – Equine Instrumentation

Several researchers (Robin et al., 2009; Chateau et al., 2009) have attached accelerometers and load cells to horses hoofs in order to better understand the load conditions during riding. The tests often focus on measuring peak loads and accelerations during the impact of the hoof with the surface while trotting, galloping, or jumping. Peak loads and loading rates are of interest because they may be connected to horse injury, and some studies have investigated how surfaces of different material composition affect peak loads on horses (Chateau et al., 2009). The study compared maximum impact accelerations between two surfaces: a crushed sand surface and a waxed sand surface. The study used an accelerometer attached to the horse hoof, and found that accelerations were significantly lower on the waxed sand surface. Many of these studies have been summarized by Hernlund et al. (2017), and an adapted version of their table appears in Table 1.
Table 1: Instrumented horse data (adapted from Hernlund et al. 2017)

<table>
<thead>
<tr>
<th>Study</th>
<th>Surface type</th>
<th>Speed / conditions</th>
<th>Peak vertical force (N)</th>
<th>Approximate time to peak vertical force (s)</th>
<th>Average Loading Rate (kN/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crevier-Denoix et al. (2015)</td>
<td>Good to soft turf</td>
<td>1 horse (524 kg), 8.3 m/s, 1m high jump</td>
<td>7000</td>
<td>0.075</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>Good to soft AirFibr</td>
<td></td>
<td>8000</td>
<td>0.075</td>
<td>106</td>
</tr>
<tr>
<td>Crevier-Denoix et al. (2010)</td>
<td>Firm Wet Sand</td>
<td>4 horses (550 kg), 7.21 m/s, trotting</td>
<td>7037</td>
<td>0.085</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>Deep Wet Sand</td>
<td>4 horses (550 kg), 6.65 m/s, trotting</td>
<td>6136</td>
<td>0.102</td>
<td>60</td>
</tr>
<tr>
<td>Robin et al. (2009)</td>
<td>Waxed sand</td>
<td>3 horses (533 kg), 9.78 m/s, trotting</td>
<td>9024</td>
<td>0.065</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>Crushed sand</td>
<td></td>
<td>9231</td>
<td>0.062</td>
<td>149</td>
</tr>
<tr>
<td>Setterbo et al. (2009)</td>
<td>Dirt</td>
<td>2 of 3 horses (486 kg +6.7), canter approx 6 m/s</td>
<td>6709</td>
<td>0.123</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Synthetic</td>
<td></td>
<td>5589</td>
<td>0.109</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Turf</td>
<td></td>
<td>7825</td>
<td>0.082</td>
<td>95</td>
</tr>
<tr>
<td>Schamhardt et al. (1993)</td>
<td>1.5 cm rubber on force platform</td>
<td>1 horse (652 kg+ rider 82 kg), 1.3 m high jump</td>
<td>2 x Body Weight = 14400</td>
<td>0.094</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>Canter</td>
<td></td>
<td>Est. 1.4 x BW = 10081</td>
<td>0.109</td>
<td>92</td>
</tr>
<tr>
<td>Meershoek et al. (2001)</td>
<td>Force platform + 4 cm sand</td>
<td>6 horses (599 ± 52 kg + rider 74 ± 14 kg), jump 1 m fence</td>
<td>9000</td>
<td>0.098</td>
<td>82</td>
</tr>
</tbody>
</table>

As would be expected, there is much variation in the loading of the surface. Variables such as horse mass, speed, and jump height all influence the dynamics of the interaction between hoof and surface. Values for peak vertical forces and average loading rate from these studies are often used as a benchmark for demonstrating the applicability of mechanical tools or tests. Measured peak vertical force ranges from approximately 5,600 to 9,200 N, approximately 1.1 to 1.6 times the body weight of the horses used for the study. Some estimated the load as high as twice the body weight at 14,400 N. The approximate time to the peak load from the onset of loading can
be used to calculate the average loading rate in kN/s. The average loading rate from the studies presented in Table 1 ranged from 51 to 153 kN/s. The average loading rate is often assumed to be constant from time zero to the time of maximum vertical force, and thus can be calculated as the maximum force divided by the time to impact. The loading rate is important, as certain characteristics of riding surface materials, such as maximum acceleration of an impact, may be sensitive to the loading rate.

Chateau et al. (2009) investigated acceleration of the horse hoof during impact and takeoff for horses trotting at approximately 10 m/s. For three horses, a total of 150 impacts were monitored with an accelerometer attached to the horse hoof. A graph of the acceleration time histories for the waxed sand and crushed sand riding surfaces is shown in Figure 2. Time is on the x-axis and is in milliseconds. The crushed sand riding surface is the solid line: waxed sand surface is the dashed line.

![Figure 2: Acceleration comparison between waxed and crushed sand surfaces (Chateau et al., 2009)](image)

The average maximum acceleration of the hoof when impacting the waxed sand riding surface was found to be approximately 170 G, where 1 G is equal to 9.81 m/s², the acceleration due to
gravity, with a standard deviation of approximately 68 G. The average maximum acceleration of
the hoof when impacting the crushed sand riding surface was found to be approximately 350 G,
with a standard deviation of approximately 114 G. The relatively high standard deviations
demonstrate that the loading imposed on the surface by the horse is highly variable, and the
resulting response from the surface, are highly variable.

2.2.2 – Orono Biomechanical Surface Tester

Another metric measured by several authors is the peak deceleration. A study by Holt et al.
(2014) found the peak acceleration of nine synthetic surfaces of varying moisture content and
density ranged from approximately 40 to 60 G, which is the acceleration in m/s\(^2\) divided by the
acceleration due to gravity. The study used the Orono Biomechanical Surface Tester (OBST) to
measure deceleration, among other parameters, of a synthetic hoof impacted on the surface
materials. The OBST is a system that simulates the initial impact of the horse hoof on the surface
(Peterson et al. 2008). The system was originally built by Michael Peterson while he worked at
the University of Maine, and was designed for use on race tracks, but was later modified for use
with show jumping arenas. The system drops an instrumented plastic hoof down a set of rails to
impact the surface, with the angle of the hoof and rails attempting to simulate the angle of the
horse’s hoof on impact, which of can vary widely depending on the horse and riding type. A
damping system is used to prolong the hoof-surface contact time. The OBST attempts to impact
the surface with a similar load and loading rate as that of an actual horse hoof, but does not
actually duplicate the exact complex loading mechanism of an actual horse. The current design
drops a 33 kg mass a height of 0.84 m, delivering approximately 272 Joules (J) of energy to the
surface on impact. A photograph of the OBST can be seen in Figure 3. The system is quite large
and has limited portability: it is mounted to the back of a truck so it can be transported to different locations. To the author’s knowledge, there are currently two systems in existence.

The system is equipped with a three-axis accelerometer, a load cell, and linear potentiometers. An example output of an acceleration time history is shown in Figure 4. The maximum acceleration of approximately 76 G is reached in under 10 ms.

Figure 3: Photograph of the OBST (from Hernlund et al. 2017)
The OBST has been used in several studies (Holt et al., 2014; Hernlund et al., 2017) to characterize surfaces or to provide a quantitative reference point to which qualitative evaluation of surface properties could be compared. The study by Hernlund et al. (2017) includes more detailed descriptions of the data analysis involved in using the OBST to quantify surface properties. Most often, the OBST is used to evaluate maximum vertical acceleration and force, as well as horizontal and vertical displacement during impact.

There are three parameters that are most often reported during equine instrumentation or biomechanical simulation studies: maximum vertical force, maximum vertical acceleration, and time from initiation of impact to the maximum force. Another parameter that is sometime used is the velocity of the hoof at impact with the surface. While understanding the loading characteristics of the hoof is undoubtedly important, it is unclear how closely the load conditions
must be simulated when designing mechanical instruments to test riding surfaces. Proponents of large biomechanical test equipment suggest the loading should be closely simulated so as to characterize surfaces under similar conditions as what the horse experiences. To do so, however, requires more energy and more complex mechanical systems and data analysis. In addition, the loading conditions are highly variable depending on such factors as horse mass, speed (i.e. trot or gallop), and activity (i.e. jumping or dressage). To truly characterize a surface under similar load conditions as a horse would require using several different pieces of equipment designed to simulate various loads, load angles, load rates, etc.; the resulting equipment would be a complex arrangement of spring-mass-dampers.

2.3 – Equestrian Surface Materials

Generally speaking, manufacturers of riding surfaces do not release specifications regarding the material properties of common riding surface components, and there is little incentive to do so: proprietary mixtures are trade secrets. As a result, there is little publically available information about the material properties of surface components or the quantities of each component in finished riding surfaces. Manufacturers use materials (fibers, fabric pieces, and rubber pieces for example) that are often made specifically for them. A typical engineered surface is composed of materials belonging to three main groups: sand, geosynthetic components, and binding agents. These are discussed in detail in the following sections. A photograph of an engineered riding surface developed by Premier Equestrian is shown in Figure 5.
Riding surfaces are typically prepared very loose as can be seen in the Figure 5, which depicts a freshly-groomed riding surface.

2.3.1 – Sands and Binders

Silica sand is typically desired for riding surfaces because of its mineral hardness and its resistance to weathering. Surface roughness of the silica sand can also increase the overall shear resistance of the material (Premier Equestrian 2014). Figure 6 shows a grain size distribution for a typical arena sand used in an engineered surface mixture, with geosynthetic components removed (adapted from Morganna Mendonca de Souza, 2016). The sand has a fines content of 1.8%, a coefficient of uniformity of ~2.5, and a coefficient of curvature of ~3.75. Both coefficients are shape parameters that may be used to estimate the gradation of a material. The coefficient of uniformity describes how uniform the size distribution is: smaller number suggest the material is poorly graded. A material with a coefficient of curvature is between 1 and 3 is considered well graded (Holtz et al., 2011). The sand would be classified as a poorly graded clean sand under the Unified Soil Classification System (USCS).
Chemical treatments and binders are designed to add cohesive resistance to a surface and aid in dust suppression. The treatments are hydrophobic and thus eliminate the need to water a surface. Water can, and commonly is, also be used for binding and dust suppression, even on surfaces with geosynthetic components such as sand-geotextile mixtures. Moisture surrounds the sand grains, causing capillary forces that hold the grains together (Hotlz et al., 2011), although this effect may be reduced in poorly graded materials. There are advantages and disadvantages to using water: there may be performance or safety issues if a surface is either too dry or too wet. Changes in water content over time may result in changes in performance, sometime rapidly if evaporation occurs. A distinct advantage is that the surface characteristics can be tweaked by adjusting the water content, although this may be less of an exact science and more of an experience-based endeavor. Often, the surface behaves very differently throughout a range of moisture contents, and is thus very sensitive to moisture changes. A study by Hernlund et al.
(2017) found that for 19 arenas tested, the water content ranged from 13% to 27% by mass with an average of 21.5%. Of the 19 arenas, 2 were sand, 2 were wax-coated sand with fiber, and 15 were sand with fiber. Two waxed surfaces were also analyzed and their wax content was found to be 1.3% by mass on average.

2.3.2 – Geosynthetic Components

Geosynthetics are playing an increasingly prominent role in the equestrian riding industry. Synthetic materials are incorporated into silica sand-based riding surfaces to improve shear characteristics and enhance other surface response characteristics, such as rebound and moisture retention. A wide variety of engineered components can be added to a surface to change its riding characteristics. Their use in riding surfaces generally consists of a combination of short polymer fibers and cut up pieces of recycled geotextile fabric along with other possible components such as rubber pieces. The resulting surface mixtures are complex, with fibers and / or fabric distributed throughout the three-dimensional sand matrix.

There is great variation in the type and quantity of geosynthetics used for surfaces. Some of the most common components are shown in Figure 7. Fiber type can vary widely, from thin monofilament (shown in Figure 8 mixed with geosynthetic fabric) to larger pieces of yarn. The fabric is typically a nonwoven geotextile and may be needle-punched or heat-bonded. Fabrics and fibers are used to add shear resistance, provide damping, and help control moisture content fluctuations. Rubber pieces are used to add rebound and help maintain a loose structure.
A study by Hernlund et al. (2017) found that for nine different synthetic surfaces the fiber content varied from 1.2% to 7.1% by mass, with an average of 3.9%. It can be seen that fiber content varies substantially. Research was undertaken at the University of New Hampshire during the summer of 2016 by Bruma Mendonca de Souza to explore the effects of various types and quantities of geosynthetic components on the shear behavior of riding surface materials.
Over 200 direct shear tests were used to evaluate the shear strength and compression / dilation behavior. The results suggest that riding characteristics of equestrian surfaces are very sensitive to changes in their material composition, and are discussed in the following section. The effect of geosynthetics on key functional properties of riding surfaces such as grip, responsiveness, and impact firmness is discussed in the results section.

2.4 – Index Properties

Extensive investigation into the index properties of engineered equestrian surface materials and their sensitivity to geosynthetic components was conducted by Bruma Morganna Mendonca de Souza at the University of New Hampshire during the summer of 2016. The investigation included sieve analysis, moisture content, proctor compaction, and direct shear testing to determine cohesion and friction angle. Ten unique surface samples were used, as identified in Table 2.

Table 2: Sample identification key

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Silica sand with fiber, fabric, and new polymer binder</td>
</tr>
<tr>
<td>B</td>
<td>Same as sample A, but one year older</td>
</tr>
<tr>
<td>C</td>
<td>High-end surface with fabric and rubber pieces, untreated</td>
</tr>
<tr>
<td>D</td>
<td>High-end surface with fabric and rubber pieces, treated with polymer binder</td>
</tr>
<tr>
<td>E</td>
<td>Same as sample C, without fabric</td>
</tr>
<tr>
<td>F</td>
<td>Economic surface with fabric and fiber, untreated</td>
</tr>
<tr>
<td>G</td>
<td>Economic surface with fabric and fiber, treated</td>
</tr>
<tr>
<td>H</td>
<td>Same as sample F, with rubber pieces</td>
</tr>
<tr>
<td>I</td>
<td>Sand and fiber surface with polymer binder</td>
</tr>
<tr>
<td>J</td>
<td>Typical arena sand, passing #4 sieve, no additives</td>
</tr>
</tbody>
</table>
Using treated and untreated versions of the same surface material allowed for the observation of the influence of binders. Testing on a broad range of surface materials allowed for establishing a range of typical values for some index properties. Table 3 shows values for effective cohesion and effective friction angle found through direct shear testing at a density of 1.7 g/cm³, which is the density of the sample after application of the normal stress. Effective values are used because the samples were dry when tested, with water contents less than 2%.

Table 3: Sample cohesion intercepts and friction angles

<table>
<thead>
<tr>
<th>ID</th>
<th>Cohesion Intercept (psi)</th>
<th>Friction Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.5</td>
<td>35.9</td>
</tr>
<tr>
<td>B</td>
<td>3.5</td>
<td>40.6</td>
</tr>
<tr>
<td>C</td>
<td>4.6</td>
<td>35.1</td>
</tr>
<tr>
<td>D</td>
<td>3.3</td>
<td>38.6</td>
</tr>
<tr>
<td>E</td>
<td>2.4</td>
<td>31.8</td>
</tr>
<tr>
<td>F</td>
<td>4.3</td>
<td>36.3</td>
</tr>
<tr>
<td>G</td>
<td>1.8</td>
<td>33.9</td>
</tr>
<tr>
<td>H</td>
<td>2.2</td>
<td>36.8</td>
</tr>
<tr>
<td>I</td>
<td>3.3</td>
<td>32.4</td>
</tr>
<tr>
<td>J</td>
<td>0.0</td>
<td>34.8</td>
</tr>
<tr>
<td>Average</td>
<td>3.4</td>
<td>35.6</td>
</tr>
</tbody>
</table>

Cohesion ranged from 1.8 psi to 5.5 psi, and friction angle ranged from 31.8° to 40.6° for surface mixtures (not including sample J, typical arena sand mixture with no additives, which had a
cohesion of 0 psi and friction angle of 34.8°). A scatter of maximum shear strength for some of the samples is shown in Figure 9.

![Shear strength vs normal stress graph]

**Figure 9: Shear strength data for some of the specimens, including average (“AVG”) constructed from Bareither et al., 2008**

Bareither et al. (2008) conducted direct shear tests on 30 different dry sand mixtures. The test density of the mixtures ranged from 1.63 to 1.95 g/cm³, with an average of 1.82 g/cm³, which is comparable to the test densities used for the riding surfaces, typically 1.70 g/cm³. The study found the intercept ranged from 0 to 1.2 psi, with an average of 0.52 psi, and friction angle ranged from 32.3° to 42.6°, with an average of 37.3°. Intercepts for the riding surface materials shown in Table 3 are higher than those obtained by Bareither et al. (2008), and friction angles of
the riding surfaces appear to be comparable. A failure envelope constructed using the average intercept of 0.52 psi and average friction angle of 37.3° is shown in Figure 9 as the line “AVG”.

An investigation was also conducted into the effect of moisture content on cohesion and friction angle. Sample C, which was an untreated sample, was subject to direct shear testing at three different moisture contents. Failure envelopes and the effect of moisture content and shear strength can be seen in Figure 10 and Figure 11, respectively. Normal stress appears to have very little influence on the rate at which moisture content effects shear strength. The average slope of the best fit lines for Figure 10 is 48°. Increasing the moisture content, up to a certain point, allows for the sample to become denser during application of the normal stress, resulting in higher shear strength. For this reason, a study of the effect of moisture content is really a study of the effect of density on the shear strength.

![Figure 10: Failure envelopes for different moisture contents](image)
The linearity of the materials in strength behavior throughout the tested range of normal stresses in all cases is demonstrated in Figure 10 and Figure 11. Cohesion for the lower moisture content specimen is likely due to the presence of geosynthetic components, as dry sand would otherwise be expected to have no cohesive strength. The cohesions and friction angles for Sample C at different moisture contents can be seen in Table 4, and graphs are shown in Figure 12.

Table 4: Effect of moisture on cohesion and friction angle for Sample C

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Cohesion $c'$ (psi)</th>
<th>Friction Angle $\phi'$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4%</td>
<td>4.6</td>
<td>35.1</td>
</tr>
<tr>
<td>7.4%</td>
<td>8.9</td>
<td>32.6</td>
</tr>
<tr>
<td>11.6%</td>
<td>10.1</td>
<td>31.2</td>
</tr>
</tbody>
</table>
Figure 12: Effect of moisture content on cohesion (left) and friction angle (right)

Increasing moisture content appears to increase the cohesion and decrease the friction angle of the material. Such an analysis could prove very useful in determining the appropriate moisture content of a surface or susceptibility to change in performance due to changes in moisture content.

Proctor compaction was also used to investigate the effect of moisture content on riding surface materials. Proctor compaction densifies a prepared sample by applying mechanical energy in the form of a free-falling mass. Two tests are available: standard proctor and modified proctor. The standard proctor uses a 5.5 lb. hammer dropped 25 times from a height of 12 inches onto a sample prepared in three layers. The modified proctor uses a 10 lb. hammer dropped from a height of 18 inches onto a sample prepared in five layers. The standard test methods are ASTM D698 and ASTM D1557 for standard and modified proctor compaction tests, respectively.
Moisture content is altered between tests in order to observe its effect on the dry density of the sample. For each test, one calculates the total density in the mold, the water content, and the dry density using the following equations, respectively:

\[
\begin{align*}
    w &= \frac{M_w}{M_s} \\
    \rho_t &= \frac{M_t}{V_t} \\
    \rho_d &= \frac{\rho_t}{1+w}
\end{align*}
\]

Where \(w\) is the water content, \(M_w\) is the mass of water in the specimen, \(M_s\) is the mass of solids in the sample, \(\rho_t\) is the total density of the sample in the mold, \(M_t\) is the total mass of sample in the mold, \(V_t\) is the total volume of the mold, and \(\rho_d\) is the dry density. Figure 13 shows several typical proctor compaction curves on various soil types. The optimum moisture content for each curve is the moisture content corresponding to the maximum dry density. As an example, curve 3 has a maximum dry density of approximately 1.92 Mg/m³ corresponding to an optimum moisture content of approximately 11.8%.

Figure 13: Typical proctor compaction curves for sand (adapted from Holtz et al., 2011)
Proctor compaction tests on the engineered surfaces suggested that there was not a significant effect of moisture content on dry density for moisture contents less than optimum. For moisture contents greater than optimum, there appears to be a significant decrease in dry unit weight with increasing moisture content. Proctor compaction curves for Sample C are shown in Figure 13. The zero air void curve represents the 100% saturation line for this material at a specific gravity of 1.90.

![Proctor compaction curves for Sample C](image)

Figure 14: Proctor compaction results for Sample C

The engineered riding surface appears to resemble the behavior of a poorly graded sand. Proctor compaction testing may prove useful for water-dependent arenas in determining the upper limit of moisture content at which the arena still maintains its desired performance characteristics. It should be noted, however, that proctor compaction has its limitations when working with poorly graded sands: water may segregate from the sand due to the narrow band of particle sizes.
2.5 – Horse-Surface Interaction

The horse-surface interaction describes how the hoof interacts with the surface. The interaction consists of four general phases: impact, braking, support, and takeoff. The exact loading mechanism of the hoof on the surface is very complex and subject to variation depending on the weight of the horse, type of riding, type of surface, and other factors. In fact, some research suggests that horses change their stride mechanics based on surface properties (Barrey et al., 1991; Northrop et al., 2013). The four phases were originally outlined by Hobbs et al. (2014) so that research could be targeted at specific phases of the interaction. A diagram of the four phases can be seen in Figure 15. Red arrows indicate acceleration and blue arrows indicate force on the horse, while the length of the arrow indicates the magnitude.

![Diagram of horse-surface interaction phases](image)

**Figure 15:** Four phases of the horse-surface interaction (adapted from Hobbs et al., 2014)

**Impact**

The impact phase represents the initial impact of the hoof on the surface and perhaps gets the most attention in the literature. During this phase, the hoof makes contact with the surface at
some initial velocity. The impact velocity varies depending on several factors, including the riding style, trotting, galloping, or jumping. Hernlund (2017) found mean hoof landing velocities to range from 4.4 to 7.1 m/s for horses jumping 1.3 to 1.5 m fences. After making contact, the hoof begins to decelerate as it compresses the material. The maximum vertical acceleration occurs during the impact phase.

**Braking**

During braking, the hoof continues to decelerate and compress the material vertically, but the weight and forward momentum of the horse also cause the hoof to slide horizontally into the surface. This results in both horizontal and vertical decelerations and forces. It is believed that some horizontal movement is desirable, as it reduces the maximum accelerations experienced by the horse (Hobbs et al., 2014). Too much however may over stress the horse mentally and physically or reduce confidence.

**Support**

During the support phase, the hoof comes to rest as the weight of the horse is transferred onto the hoof. Maximum vertical force occurs during the support phase as the hoof transitions from braking to takeoff (Hobbs et al., 2014). There is no substantial acceleration during this phase.

**Takeoff**

During takeoff, the heel of the hoof lifts up and the horse begins to propel itself forward. The surface must have sufficient shear resistance in order to reduce the deformation of the material and provide resistance as the horse pushes off (Hobbs et al., 2014).
The phases may not happen independently of one another, and there is likely some overlap between phases. The interaction occurs over a very short period of time, so each phase only occupies a very small time frame. Robin et al. (2009) measured the mean stance duration to be approximately 0.13 seconds for a horse trotting at 9.8 m/s. In addition, the motion of the horse is quite fluid, so the interaction likely moves smoothly from phase to phase with less distinction between individual phases. In addition, the hooves may be in different phases at any given time. Nonetheless, the four phases capture the four generally distinct components of the interaction. Understanding the phases of the horse-surface interaction is necessary to evaluating how the surface responds to the unique loading and unloading. The four phases of the horse-surface interaction are a simplification of the great variation in loading that a riding surface is subjected to. There are other loading scenarios that are not captured by the four phases, which assume loading only occurs vertically and horizontally either in the direction of movement or opposite the direction of movement. There may be lateral loading during the interaction, especially when a horse is turning. Turning may also subject the surface to rotational forces. The hoof may strike at an angle, causing stress concentrations and a non-uniform stress distribution across the surface area of the hoof. The variety and complexity of loading scenarios during the horse-surface interaction was perhaps the inspiration for the simplification presented in Figure 15. Analyzing surface performance based on this version of the horse-surface interaction, however, should be done with the understanding that it is a simplification that is not inclusive of the many different types of load scenarios that a riding surface may be subjected to by a horse.
2.6 – Functional Properties

Functional properties are qualitative terms that riders and industry professionals use to describe the riding characteristics of a surface. They do not describe the individual components of a riding surface, rather they describe the surface behavior as a whole. Functional properties are affected by many internal surface characteristics: material composition, water content, arena subbase, as well as external components such as arena maintenance, age, and event type. Functional properties have remained predominantly defined and evaluated qualitatively due to the lack of standardized testing equipment and methods for providing quantitative evaluations. Hobbs et al. (2014) set forth definitions for many functional properties based on what was commonly accepted in the industry at the time. Their definitions were adapted by Hernlund (2016) who offered summarized short descriptions for six functional properties: impact firmness, cushioning, grip, responsiveness, uniformity, and consistency. Each functional property had corresponding verbal anchors that suggest a range from high-end or low-end. Definitions for functional properties can be seen in Table 5.

Table 5: Functional properties from Hernlund (2016)

<table>
<thead>
<tr>
<th>Functional property</th>
<th>‘High-end’ verbal anchor</th>
<th>‘Low-end’ verbal anchor</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact firmness</td>
<td>Hard</td>
<td>Soft</td>
<td>The shock experienced by the horse and rider when the hoof contacts the surface.</td>
</tr>
<tr>
<td>Cushioning</td>
<td>Deep</td>
<td>Compacted</td>
<td>How much a surface is supportive compared to how much it gives when riding on it.</td>
</tr>
<tr>
<td>Grip</td>
<td>High grip</td>
<td>Slippery</td>
<td>How much the horse’s hoof slides during landing, turning and pushing off.</td>
</tr>
<tr>
<td>Responsiveness</td>
<td>Active</td>
<td>Dead</td>
<td>How active or springy the surface feels to the rider.</td>
</tr>
<tr>
<td>Uniformity</td>
<td>Uniform</td>
<td>Variable</td>
<td>How regular the surface feels when the horse moves across it.</td>
</tr>
<tr>
<td>Consistency</td>
<td>No change</td>
<td>Changeable</td>
<td>How much the surface changes with time and use.</td>
</tr>
</tbody>
</table>
**Impact Firmness**

Impact firmness is a measure of the shock, or deceleration, experienced when the hoof impacts the surface. The stiffness of a surface determines the impact firmness: hard surfaces, such as concrete, are very stiff and have high decelerations on impact. Soft surfaces, such as loose sand, are less stiff and have low decelerations on impact. High decelerations translate to high shock experienced by the horse, which in turn increases the risk of injury to the horse. Soft surfaces, while they may have more desirable shock absorbing properties, may lack sufficient support and put unnecessary stresses on the horse or expedite fatigue. Hard surfaces also increase the peak load and the average loading rate (Peterson et al., 2012). Shock absorbance and support are inversely related, therefore designing a surface for good impact firmness is to balance the tradeoff between the two. The OBST has been used by Hernlund et al., (2017) to define impact firmness as the peak vertical deceleration of the hoof on impact. Higher deceleration equates to higher impact firmness. It is also important to consider that the force imposed on the surface by the horse and the resulting acceleration are dependent upon the activity type and horse size.

**Grip**

Grip is how much the horse hoof slides during landing, turning, and takeoff. Grip is a manifestation of the shear resistance of the surface. The shear strength is the maximum shear resistance and is perhaps the most important material property of a riding surface (Peterson et al., 2012). The shear strength of a surface must be low enough to allow for horizontal shear displacement to occur while landing, but high enough to allow for effective takeoff and confident turning without slipping. Greater shear displacements during the initial impact and loading phase of the horse-surface interaction reduce the peak load and acceleration (shock) induced on the
hoof / limb. Too much shear displacement, however, and the surface will feel slippery to the rider and the horse may feel less sure-footed. Excessive shear displacement during takeoff may expedite fatigue and reduce jumping performance. Hernlund et al., (2017) proposed defining grip as the horizontal displacement of the hoof of the OBST corresponding to the time of the maximum vertical force. A graphical representation of this method is shown in Figure 16.

![Figure 16: Grip as defined using the OBST (Hernlund et al., 2017)](image)

This method evaluates grip as a distance, in mm, which attempts to capture the horizontal distance a hoof might slide when impact the riding surface. Shear resistance is highly sensitive to surface material composition, magnitude of the applied load, and load rate.

**Responsiveness**

Responsiveness, sometimes referred to as rebound, relates to how active the surface feels to the rider. The literature often refers to responsiveness as a function of the timing of both the initial impact and the elastic recovery. Active surfaces can be thought of as being “in tune” with the loading and unloading rate of the hoof. This is a difficult parameter to measure objectively, however, as many factors may influence the frequency of the surface response including the
loading rate, duration of impact, compaction of the surface, and gait frequency of the horse (Hobbs et al., 2014). Other extrinsic factors, such as arena maintenance and surface system substructure (most notably the presence of concussion mats below the riding surface) may also influence the dynamic response. Due to difficulties with evaluating the dynamic response characteristics of riding surfaces, responsiveness has been quantified using other means. The OBST has been proposed as one way to evaluate responsiveness. A method used by Hernlund et al., 2017 proposes evaluating responsiveness as the ratio of the spring compression and spring recoil times of the OBST, which results in a unit-less parameter. This analysis requires synchronized position and velocity data and is dependent on the stiffness of the spring damper. This approach is just one way to potentially evaluate responsiveness.

**Cushioning**

Cushioning appears to be a derivative of impact firmness, thus may not be an independent property of an engineered surface. In fact, a review of the literature would suggest that impact firmness and cushioning are both inversely proportional and interrelated. Hobbs et al. (2014) mention how high impact firmness equates to a supportive surface whereas low impact firmness equates to an unsupportive surface. Further investigation of current quantitative approaches to evaluating impact firmness and cushioning appear to satisfy this argument. Hernlund et al., (2017) used to OBST to define impact firmness as the peak deceleration and cushioning as the peak force during impact. High peak force equates to low cushioning. Because force and acceleration are related by the mass of the accelerating object, impact firmness and cushioning are also related. High deceleration (high impact firmness) would yield a high peak force (low cushioning). Based on the currently accepted definitions for impact firmness and cushioning, as
well as the physical relationships that govern the definitions, it can be seen that the two functional properties are interdependent.

**Uniformity and Consistency**

Uniformity and consistency are more broad evaluations of changes in surface performance that occur spatially and temporally. Uniformity is an evaluation of how all of the other functional properties change spatially across the arena. For this reason, uniformity should not be considered an independent property of the riding surface. Factors such as surface depth, moisture content, maintenance, and habitual use can all affect uniformity. Consistency relates to how the riding characteristics change temporally. Factors such as changes in surface depth or moisture content across the arena appear to be the most influential in determining consistency, but maintenance and habitual use also play a role (Hobbs et al., 2014). These two functional properties are perhaps the most difficult to evaluate, both qualitatively and quantitatively, since a lot of testing would be necessary to track changes in properties spatially and temporally. An approach to evaluating these properties is not well defined by the current literature.

**Qualitative versus Quantitative Evaluation**

Defining functional properties qualitatively poses significant challenges for the industry. The ability of professional riders to sense the qualities of a riding surface should not be underestimated, however rider feedback often lacks consensus. Many factors may influence how a rider judges the quality of a surface via functional properties: their riding history, experience at other arenas, and their expectation of how a surface should ride (perhaps influenced by cost or prestige), to name a few. Additionally, the rider does not interact directly with the surface: rather
their perception of surface characteristics is through their interpretation of the horses riding behavior. This may pose some issues with using subjective evaluations, as horses likely adjust their gait to accommodate changes in surface conditions (Holt et al., 2014).

A study by Hernlund et al. (2017) compared subjective rider evaluation to objective measurements of functional properties. Subjective rider evaluation was collected by way of a questionnaire that had riders rate functional properties on a scale from 0-100. Objective evaluation was conducted using the Orono Biomechanical Surface Tester. The study found positive association between subjective and objective evaluation of impact firmness, meaning that rider evaluations of impact firmness generally agreed with evaluations made with the OBST. The study found negative association for responsiveness, meaning there was disagreement between rider evaluation and evaluation with the OBST. Notably, the study found that there was significant variation in the evaluation of functional properties between riders, despite using high-level professionals. Such variation could be due to the variables mentioned previously, such as riding history and experience, or could be attributed to non-standardized definitions of functional properties. While rider evaluation is important, there is a need for standardized, quantitative methods for evaluating functional properties. Ideally, each functional property would be defined by some measurable physical phenomenon that is related to the mechanical interaction between the hoof and surface. This would provide a means for measuring and comparing functional properties between surfaces.
3 – TEST METHODS

Extensive lab and field testing was conducted on a variety of engineered equestrian surfaces. The three primary tests used as part of this research were direct shear, light weight deflectometer, and a new custom designed laboratory drop apparatus. Other tests were conducted in order to determine common index properties such as field and lab density measurements and sieve analyses. Each test method provided a different approach to analyzing the properties of equestrian surface, and together they may provide a way to collect meaningful data that describes how engineered surfaces respond to loading.

3.1 – Direct Shear

Direct shear tests were chosen because the specimen is stressed in a way that shares a fundamental likeness to the phases of the horse-surface interaction, as discussed in Chapter 2. Direct shear tests can be used to measure the shear resistance of a material which may be mobilized during the horse-surface interaction. The changes in the vertical and horizontal displacements are also observed as the specimen is being sheared. Direct shear tests are also relatively simple, inexpensive, and adaptable to unusual materials.
3.1.1 – Description of the Direct Shear Test

Direct shear tests were used to evaluate the shear behavior and the compressive and dilative behavior of engineered surface materials. The direct shear test measures shear resistance under various normal stresses. The direct shear test consists of two phases: application of a normal stress and application of a shear stress. The normal stress acts down on the reconstituted specimen while applying a constant horizontal displacement rate generates the shear stress. A photograph showing the test machine, a Geocomp ShearTrac II, is shown in Figure 17 with arrows indicating the direction of application of the normal and shear forces. Linear potentiometers and load cells output position and force information, respectively, in both the horizontal and vertical directions. The material is first loaded into a shear box as shown in Figure 18, and prepared at a predetermined density and moisture content. Both density and moisture content can be modified as necessary. The shear box is a square metal box measuring 4 inches on each side, approximately 1.80 inches deep, and consisting of two halves which allows for one half to be moved relative to the other. After the normal stress has been applied, one half of the shear box is displaced horizontally, thus inducing a shear stress on the material. The standard test method used is ASTM D3080 (2011).
Tests can be conducted at different normal stresses and horizontal displacement rates, up to a maximum horizontal displacement of 1 inch. The software records data for both the normal
stress application phase and the shear phase. Normal stress application phase data includes time, vertical position, and normal stress. Shear stress phase data includes time, horizontal position, vertical position, and horizontal and vertical stresses. For this testing program the normal stress varied from 1 psi to 50 psi and the displacement rate was 0.10 in./minute.

The advantages of direct shear testing versus other laboratory shear tests, such as the triaxial test, must be weighed against the disadvantages. One limitation of the direct shear test is that it forces the failure plane to occur horizontally through the material. This forced failure plane may result in artificially high values for shear strength and friction angle. The triaxial test does not constrain where the failure plane occurs, but it usually occurs at an angle of approximately $45^\circ - \phi/2$.

Figure 19 shows a comparison of friction angle obtained using three different laboratory shear tests.

![Figure 19](image)

Figure 19: Comparison of friction angle obtained using various laboratory shear tests (from Holtz et. al., 2011)
Two sands were used for the comparison: Ottawa sand (O), which was poorly-graded ($C_u$=1.7) and had rounded particles, and Rainier sand (R), which was less poorly-graded ($C_u$ = 2.9) and had coarse, angular particles. It can be seen that for sand O, the friction angle obtained by triaxial was greater than the friction angle obtained by direct shear testing for normal stresses less than approximately 130 kPa (~20 psi). For sand R, direct shear testing appeared to produce greater friction angles for tests conducted at normal stresses above approximately 50 kPa (~7 psi).

Bareither et al. (2008) compared values of friction angle and cohesion measured using direct shear and triaxial tests on four sand and found that there was no statistically significant difference between values obtained with the two test methods. Resulting failure envelopes are shown in Figure 20.

![Figure 20: Comparison of failure envelopes for direct shear and triaxial tests (from Bareither et al., 2008)](image)

<table>
<thead>
<tr>
<th>Test Type</th>
<th>$\phi'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Shear</td>
<td>38.5</td>
</tr>
<tr>
<td>Triaxial Compression</td>
<td>39.5</td>
</tr>
</tbody>
</table>
The direct shear test represents only one potential failure plane and subjects the specimen to a very specific loading path. The triaxial test is capable of modeling various stress loading paths, which makes the test more versatile. In the arena there may be several different failure planes and stress paths that result from the complex and variable loading of the horse-surface interaction. A disadvantage of the triaxial test is that it requires more complicated specimen preparation and more time to run.

3.1.2 – Data Interpretation

From the test data, plots of shear stress and vertical displacement during the shear phase can be generated. Shear stress graphs were used to find maximum shear strength and to observe shear strength behavior. Vertical displacement graphs were used to observe the compression (sometimes referred to as contraction) and dilation behavior. Typical graphs of shear stress (top) and vertical displacement (bottom) of an engineered riding surface material can be seen in Figure 22. Compression is indicated by an increase in the vertical displacement and dilation is indicated by decrease in the vertical displacement. This sign convention is opposite of what is typically used in conventional geotechnical analyses, but was selected because it was how the raw data from the direct shear machine was output. Compression is a decrease in the volume of the sample that may occur during shearing, and is indicated here as a positive displacement. Compression can occur as a result of particles moving into void spaces, decreasing the void ratio, which is the ratio between the volume of the void spaces and the volume of solid particles in a specimen. Dilation is an increase in volume of the sample, and is indicated as a negative displacement. Dilation can occur as a result of particles rolling over one-another when sheared, causing a volume increase. Dilation is common in dense sands, since the particles are packed close together there must be some volume expansion in order for the material to deform in shear.
More details on the specifics of the data interpretation can be found in the results section. A depiction of dilation is shown in Figure 21.

![Dilation during shearing](from www.theartofdredging.com)

**Figure 21:** Depiction of dilation during shearing (from www.theartofdredging.com)

**Figure 22:** Typical shear stress (top) and vertical displacement (bottom) behavior
Maximum shear stress data can then be used to define Mohr-Coulomb failure envelopes, which were generated by fitting a linear regression to a plot of maximum shear stresses for different normal stresses. An example of shear stress graphs for different normal stresses is shown in Figure 23 and an example Mohr-Coulomb failure envelope is shown in Figure 24.

![Figure 23: Depiction of shear stress graphs for different normal stresses](image)

![Figure 24: Example Mohr-Coulomb failure envelope](image)
From the Mohr-Coulomb regression, the friction angle, $\phi$, and cohesion, $c$, can be determined, which define the Mohr-Coulomb linear failure envelope as expressed by the following equation:

$$\tau = c + \sigma \cdot \tan(\phi)$$  \hspace{1cm} (4)

Where $\tau$ is the shear stress, $\sigma$ is the normal stress, $\phi$ is the friction angle, and $c$ is the cohesion intercept. Shear stress behavior, compression / dilation behavior, friction angle, and cohesion are valuable for characterizing and comparing engineered equestrian surfaces.

3.2 – Light Weight Deflectometer

The Light Weight Deflectometer (LWD) is most commonly used for in situ quality assurance testing of roadway subgrade soils. The LWD can be used to evaluate a dynamic deflection modulus, $E_{vd}$, which is an index of bearing capacity (Zorn, 2005). A Zorn ZFG 2000 was used to carry out all LWD tests for this research. The test consists of dropping a 10 kg mass from a calibrated drop height of 71.5 cm onto a standard base plate, delivering a force of 7.07 kN. A set of steel springs act as a buffer for the impact. A typical force time history and frequency content is shown in Figure 25. High frequency noise in the raw signal is due to oscillations of the buffer springs. Most of the spectral energy is concentrated below 450 Hz.
An accelerometer in the base plate is used to compute deflections (Vennapusa, 2008). A schematic of the ZFG 2000 can be seen in Figure 26. Two different base plates with diameters of 200 mm and 300 mm were used; the smaller plate being used for stiffer surfaces. The accelerometer used by the ZFG 2000 is a Measurement Specialties 4000A MEMS accelerometer with a natural frequency of 6 kHz and sensitivity of 0.01974 V/G (Stamp, 2012). The ZFG 2000 applies a low pass filter of 200 Hz to the raw acceleration data to eliminate high frequency noise introduced by the buffer springs, and does not apply any corrections for phase or magnitude distortions (Stamp, 2012). The internal software then computes double integration to develop a displacement time history.

Figure 25: Zorn LWD force time history and spectral analysis (from Stamp, 2012)
3.2.1 – Test Procedure

To conduct a test in roadway applications, the plate is placed at the desired location and complete contact with the subgrade is ensured. The weight is raised to the calibrated height and three initial pulses, known as seating pulses, are executed. Seating pulses are used to further establish good contact between the plate and surface. After the seating pulses, three test pulses are executed. After successful completion of the test pulses, the plate can be moved to a new location. It is recommended that two tests be done on the same surface, and that the difference between average displacement readings for the tests be no more than $\pm 3\%$ (ASTM, 2015). For testing equestrian surfaces, due to the compressibility of the material compared to what the LWD was designed to test, the first three seating pulses are actually used for analysis.
Displacement and time data are collected for each pulse. Calculation of a dynamic deformation modulus uses the Boussinesq elastic half-space solution, adapted by Vennapusa (2008), can be seen in equation 5.

\[ E = \frac{(1-\nu^2)\sigma_0 r}{s} * f \]  
(Vennapusa, 2008) \hspace{1cm} (5)

Where \( E \) is Young’s modulus, \( s \) is the settlement, \( \nu \) is the Poisson’s Ratio, \( \sigma_0 \) is the applied stress, \( r \) is the radius of the plate, and \( f \) is a stress distribution shape factor. The ZFG 2000 assumes a Poisson’s ratio of 0.212 and a rigid plate with an inverse parabolic stress distribution shape factor \( f = \pi/2 \) (Stamp and Mooney, 2013). The device assumes an applied stress based on the plate diameter and assumed force from the calibrated drop height. Applied stresses are 0.10 MPa and 0.225 MPa for the 300 mm and 200 mm diameter plates, respectively. With these assumptions, dynamic deflection moduli can be calculated using equations 6 and 7 for the 300 mm and 200 mm diameter plates, respectively.

\[ E_{vd-300} = \frac{22.5}{s} \]  \hspace{1cm} (6)

\[ E_{vd-200} = \frac{33.76}{s} \]  \hspace{1cm} (7)

Where \( s \) is the settlement in mm and \( E_{vd} \) is the dynamic deflection modulus in MN/m². Issues may arise when testing soils with different Poisson’s ratio or stress distributions from what is assumed by the internal software. Settlement in the ZFG 2000 is calculated by double integration of the acceleration time history recorded by the accelerometer (Stamp and Mooney, 2013).
Displacement curves for three pulses conducted after the three initial seating pulses on packed gravel are shown in Figure 27.

![Displacement curve graph](image)

Figure 27: LWD test on packed gravel (from coursework for In Situ Geotechnical Testing Course, 2017, University of New Hampshire)

The results from each test include graphs of deflection versus time for each pulse, $E_{vd}$ and maximum deflection for each pulse, and average $E_{vd}$ for the entire test. Figure 28 shows deflection curves for six materials of different stiffness ranging from mulch to asphalt. LWD moduli corresponding to the tests are presented in Table 6. It can be seen that softer materials have greater displacements than stiffer materials, ranging from approximately 0.2 mm for asphalt to 8 mm for mulch. Additionally, softer materials also show greater negative displacement. Negative displacements are an indication that the base plate has lost contact with the material and has bounced past the initial height of the material. This may be the result of the action of the steel buffer springs. The buffer springs are designed to damp the load pulse for stiffer materials,
such as roadway subgrades, in order to simulate traffic loading. Because the springs themselves are very stiff, they may be less capable of damping the load pulse on softer materials, resulting in greater reflection of energy from the ground back to the base plate, causing the base plate to lose contact. It can be seen that softer materials have a longer time to the maximum displacement, and also demonstrate greater plate rebound.

Figure 28: Comparison of LWD results for different materials (from coursework for In Situ Geotechnical Testing Course, 2017, University of New Hampshire)
Table 6: LWD moduli for different materials of increasing stiffness (from coursework for In Situ Geotechnical Testing Course, 2017, University of New Hampshire)

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{vd}$ ($MN/m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mulch</td>
<td>2.9</td>
</tr>
<tr>
<td>Grass</td>
<td>6.3</td>
</tr>
<tr>
<td>Loose Gravel</td>
<td>12.6</td>
</tr>
<tr>
<td>Packed Dirt Path</td>
<td>22.7</td>
</tr>
<tr>
<td>Packed Gravel</td>
<td>27.2</td>
</tr>
<tr>
<td>Old Asphalt (200 mm)</td>
<td>185.6</td>
</tr>
</tbody>
</table>

3.3.2 – Applicability to equestrian surfaces

The LWD was chosen because it simulates the general mechanics of the impact phase of the horse-surface interaction. The LWD supplies an average force of 7,070 N to the base plate, which is well within the range of 5,600 N to 9,200 N measured during some equestrian instrumentation studies (see Table 1). Due to the size of the baseplate, however, average stresses may be lower than what is experienced by the horse hoof. From a usability standpoint, the LWD is very portable and can be operated by just one person.

3.4 – Lab Drop Apparatus

An experimental apparatus was designed in an attempt to establish a controlled laboratory environment in which surface materials could be tested. The Lab Drop Apparatus (LDA) is a cylindrical mold in which a specimen of riding surface material is placed at a desired density. A falling mass is used to deliver a load pulse to a metal plate placed on top of the specimen. A linear potentiometer measures displacement of the specimen during and after the impact. This
controlled environment facilitates linking the impact behavior of lab specimens to the phases of the horse-surface interaction. Inspiration for the design of the Lab Drop Apparatus (LDA) originated from testing with the LWD. The LDA and LWD share the same fundamental principle: a falling mass is used to impact the material, and a sensor measures, directly or indirectly, the deformation of the material. There are many unknown variables in LWD analysis, specifically the stress distribution shape factor and Poisson’s ratio. The LDA takes the mechanics of the LWD but operates in one-dimensional conditions, thus simplifying the analysis and eliminating assumed values involved in using the Boussinesq half-space theory. The LDA does not have buffer springs, which reduces the effect that relative stiffness between the springs and the material being tested may have on measured accelerations.

3.4.1 – Lab Drop Apparatus Design

A schematic of the LDA can be seen in Figure 29. Some guidelines for the design of the LDA were that it should be simple to operate, inexpensive, and have few unknown or assumed values in analysis. The LDA was prototyped in the lab using a standard 4” diameter proctor mold fitted with a linear potentiometer. A circular metal plate with an indent for a ball bearing was used as the impact plate. A 5.5 lb. (2.5 kg) proctor hammer was used to deliver the load pulse, ensuring consistent energy is being delivered each time. The linear potentiometer used was a Novotechnik TR-50, chosen because it can operate at high speeds (up to 10 m/s), and offers a stroke of 52 mm (Novotechnik, 2014). A schematic of the potentiometer setup, courtesy of Jim Abare from the Technical Service Center at UNH, is shown in Figure A 1.
Figure 29: LDA schematic
The potentiometer was powered by a constant 9 VDC power supply, and was connected to a National Instruments NI USB-6009 8 input, 14-bit multifunction I/O data acquisition unit, which was connected to a computer via USB and read into LabVIEW software. All of the components were attached to a board, making the system compact and mobile. A photograph of the system is shown in Figure 30.

![Figure 30: LDA setup](image)

LabVIEW was used to sample and record the potentiometer reading at a rate of 1000 Hz. Data collection ran continuously throughout the duration of a test, and results were exported to Microsoft Excel and/or MATLAB. The voltage output of the potentiometer is dependent upon the input voltage. The potentiometer was calibrated in the lab using a 9 VDC supply and a caliper to position the potentiometer at different increments. Output voltage corresponding to
sensor tip position was recorded and the calibration curve is shown in Figure A 2. The calibration equation, relating output voltage (V) to sensor tip position in millimeters (y) for 9 VDC input is:

\[ y = 9.1634 \times V - 15.114 \]  

(8)

Where y is the position of the tip of the sensor, with zero being fully retracted, and V is the output voltage of the sensor.

3.4.2 – LDA Operational Theory

Since 1-D conditions exist during the test, the gravitation potential energy of the hammer when it is raised (PE) can be related to the work done by the hammer on the soil (Ws):

\[ PE = W_s \]  

(9)

Breaking the terms down into their constituent components and solving for force yields the following:

\[ PE = mgh \]  

(10)

\[ W_s = Fd \]  

(11)

Therefore:

\[ mgh = Fd \]  

(12)

\[ F = \frac{mgh}{d} \]  

(13)
Where $m$, is the mass of the falling hammer, $g$ is the acceleration due to gravity, $h$ is the drop height of the proctor hammer, $F$ is the average impact force, and $d$ is the maximum displacement of the surface material. This relation ignores minor energy losses from drag and frictional forces and assumes 100% efficient load transfer. The mass and drop height for the proctor hammer are known and kept constant, and the displacement of the surface material is measured by the potentiometer.

Because the impact is not instantaneous and occurs over some period of time, the calculated force is an average force that is applied throughout the length of the displacement, $d$. As such, the acceleration is also an average acceleration for the impact, not the maximum acceleration. This is discussed further in the data analysis section.

### 3.4.3 – Test Procedure

The desired test density and surface test height should be decided prior to placing the surface material in the mold. Test density and height are selected by the user, but it is recommended that an average density and average surface thickness as measured in-situ at the arena are used. The mass of surface material needed for the test can be calculated using the desired test density and surface test height:

$$m_{\text{specimen}} = \rho_{\text{specimen}} \times A \times h_{\text{specimen}}$$  \hspace{1cm} (14)

Where $m_{\text{specimen}}$ is the mass of the specimen at its desired moisture content to be placed in the mold in grams, $\rho_{\text{specimen}}$ is the desired test density of the specimen in g/cm$^3$, $A$ is the cross-
sectional area of the mold in cm², and \(h_{\text{specimen}}\) is the desired thickness of the specimen when placed in the mold in cm.

The calculated mass is then placed and compacted in the mold to the desired test height, ensuring that the desired test density is achieved. Once the specimen is properly prepared, the metal impact plate is placed on top of the sample, taking great care to ensure the specimen is level and does not get compressed. The potentiometer is then positioned with the tip in contact with the impact plate, and the power supply is turned on. The potentiometer’s initial position is taken as the point of zero displacement. Data collection is initiated in LabVIEW and the Proctor hammer is positioned on the metal impact plate, again with great care not to disturb the specimen. The mass is raised and then dropped, constituting one load pulse. A minimum of three load pulses is recommended, although many load pulses can be done as desired.

3.5 – Summary

Direct shear tests were chosen because the application of normal and shear stresses is similar to what the horse hoof applies to the riding surface. Direct shear can be used to observe changes in shear resistance and vertical displacement during shearing, and to develop failure envelopes. LWD tests were chosen as a way to observe how riding surfaces respond to impact loading. The Laboratory Drop Apparatus was designed to establish one-dimensional conditions for conducting impact testing of riding surface specimens prepared in the lab. The three test methods represent unique ways to evaluate riding surface characteristics.
4 – DIRECT SHEAR TESTING OF RIDING SURFACES: TWO CASE STUDIES

Case studies provided a great opportunity to assess the real-world applicability of the test and analysis methods developed to date. Importantly, the case studies helped develop a unique approach to analyzing the compression / dilation behavior of surface materials and further demonstrated the capability of direct shear testing in characterizing surface performance. Two case studies are presented in this research: Coyote Spring Farm surface remediation and an investigation into the performance issues of a riding surface from a Northern New England Farm.

4.1 – Coyote Spring Farm

An indoor arena in Lee, NH at Coyote Spring Farm (CSF) provided an ideal location for full-scale experimentation: the surface is highly controlled to ensure consistency, kept meticulously clean of contamination, and is mechanically groomed often to ensure consistent performance characteristics. In addition, the resident professional rider and other advanced riders could assist in providing subjective feedback on the riding characteristics of the surface and the material was readily available for geotechnical direct shear testing.

The study hoped to expand upon previous work (Morganna Mendonca de Souza, 2016, van der Heijden et al., 2017) by providing a further demonstration that direct shear tests can be used to
evaluate and compare the riding behavior and functional properties of surfaces with different material compositions. The study helped develop a unique approach to interpreting volume change during direct shear tests and included comparisons with subjective feedback from professional and advanced riders.

The case study at Coyote Spring Farm was outlined in a publication by van der Heijden et al. (2018).

4.1.1 – Surface Amendment and Remediation

Coyote Spring Farm wanted to amend their original riding surface in order to improve its performance. It was desired to increase the firmness of the surface while maintaining its grip and rebound characteristics. The surface was too compressible and the horse’s hooves were sinking too far into the surface on the initial impact. As a proposed solution, the surface was amended with additional fibers and fabric pieces. The goal of adding the fibers and fabric pieces was to reduce the compressibility of the surface and as a result increase the firmness. Part of what makes the surface compressible is the action of sand particles moving into void spaces when a load is applied. It can be hypothesized that fibers weave through the void spaces of the material, blocking some void spaces from being filled when a load is applied. Similarly, fabric pieces also block the motion of sand grains into void spaces by acting as barriers through which sand grains cannot freely pass. Fibers and fabric may also restrict lateral movement of sand grains, preventing collapse of void spaces. The preexisting surface already contained fiber and fabric but it was desired to increase the percentage of these materials. Shown in Figure 31 is the fiber
(white) and fabric pieces (blue) that were added to the original surface. It is interesting to note that the quantity itself seems relatively small compared to the scale of the arena.

Amending a surface in place is more difficult as compared to pre-manufacturing everything in a mixer with all the requisite components. The fibers and fabric pieces weigh significantly less than the silica sand, uniformly changing its percentage in the surface mixture (either by volume or weight) is quite difficult. The quantity of fiber and fabric added to the original riding surface proved to be excessive and the resulting riding behavior was highly unsatisfactory: a testament to the sensitivity of these systems to changes in their components. The fiber-saturated surface was balling-up and clumping in front of the horses’ hooves, causing tripping. The material lacked the ability to effectively “break over” during the takeoff phase of the horse-surface interaction. Break over is when the horse transitions from support to pushing off from the surface to propel
itself forward (See Figure 15). This adversely impacted the ability of the horses to effectively takeoff from the surface. A photograph of the fiber-saturated surface can be seen in Figure 32. It is quite apparent that the fibers and fabric pieces have caused clumping in the surface, making it both very difficult to groom and dangerous for the horse and rider.

Figure 32: Fiber-saturated surface

To remediate the fiber-saturated riding surface, some of the fibers and fabric pieces were carefully removed by a tedious process involving a Harley Rake, skimming the surface by creating windrows of mainly fibers. Excess fiber from the windrows was then removed by hand. This process continued through multiple runs until a sufficient amount of fiber was removed from the mixture. A coarse, manufactured washed sand was then added and the entire surface was reintegrated. To determine the amount of manufactured coarse sand to add, and the amount of fiber to remove, a number of small test sections were constructed in the arena with trial formulations. This was to simulate what would be the upcoming amendment process. Each
test area was formulated with different amounts of the manufactured coarse sand, while having excess fiber removed by hand. The results were noted and discussed with equestrian professionals. This then provided calculations for the “design target” for the overall arena (i.e., how much total sand to add, by weight, and how much fiber to remove, by volume). As a result, the riding behavior of the surface was greatly improved, restoring the break over ability and takeoff characteristics of the original surface while reducing the cushioning. A photograph of the remediated arena surface taken right after finishing the remediation process can be seen in Figure 33. Note the smooth and consistent surface as opposed to the fiber-saturated surface seen in Figure 32.

Throughout the process, two unique surfaces were created: fiber-saturated with the excessive quantities of fibers and fabric pieces, and the remediated surface with some geosynthetics removed and coarse sand added. The two new surfaces were then compared with the original,
allowing an excellent opportunity to assess the effect of fabric, fibers, and sand on the riding characteristics. Figure 34 shows a schematic of the three phases of the remediation process.

![Diagram of the remediation process](image)

**Figure 34: Schematic of amendment procedure**

The original CSF riding surface had been extensively studied prior to the amendment and remediation effort. Accordingly, there was a well-established geotechnical and riding condition background on the performance of the material both in the lab through more than 200 direct shear tests (Morganna Mendonca de Souza, 2016; van der Heijden et al., 2017) and in the arena. It was therefore decided to use the original material as the baseline to which the newly-created surfaces (fiber-saturated and remediated surface) would be compared. The goal of this comparison was to observe how the functional properties of the riding surface changed with changing material composition. The comparison was to be conducted in two ways: 1) estimating changes by observing how the direct shear behavior of the surfaces changed and 2) collecting subjective feedback from riders on the riding performance of each surface. This approach was designed to see if lab testing and analysis methods were capable of predicting changes in riding behavior.

Quantifying the direct shear behavior was necessary to better understand the contributions from the various components and how it affected the compression / dilation behavior, this would also
provide a method to compare surfaces in a less subjective way. Using experience gained through extensive previous testing of several professional-grade riding surfaces (Mendonca De Souza, 2016 and van der Heijden et al., 2017), surface parameters were established as shown in Figure 35. The parameters were established to highlight key characteristics of the typical compression / dilation behavior observed while testing riding surfaces.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V_{\text{max}}$</td>
<td>Maximum compression: relates to how compressible the surface is.</td>
</tr>
<tr>
<td>$\Delta V_{\text{min}}$</td>
<td>Maximum dilation: relates to how much rebound the surface supplies.</td>
</tr>
<tr>
<td>$\Delta V^*$</td>
<td>Vertical rebound parameter: total positive movement / volume increase after maximum compression, $\Delta V_{\text{max}} +</td>
</tr>
<tr>
<td>$\Delta H^*$</td>
<td>Horizontal rebound parameter: Horizontal displacement at which the original volume is restored.</td>
</tr>
</tbody>
</table>

Figure 35: Definitions of surface parameters
The curve demonstrates the typical behavior for test conducted at a normal stress of 1 psi, which was chosen because the balling-up of the surface was occurring during the takeoff phase when the hoof was dragging horizontally across the surface and there is little confining stress applied to the surface by the hoof. The materials initially compress before dilating. The magnitude of dilation is dependent upon surface material composition. The maximum vertical compression, \( \Delta V_{\text{max}} \), relates to the compressibility of the surface. Previous research has shown that higher values indicate a more compressible surface and relate to a deeper impact of the horse hoof. The maximum negative vertical displacement, \( \Delta V_{\text{min}} \), is the maximum dilation and has been shown to relate to the rebound behavior of the surface. It is important to note that \( \Delta V_{\text{min}} \) is taken as the vertical displacement corresponding to a horizontal displacement of 0.8 inches: \( \Delta V_{\text{min}} \) can be either positive or negative. The horizontal displacement of 0.8 inches was chosen as this is the wall thickness of the shear box, beyond which the material may spill out of the shear box. The parameter \( \Delta V^* \) represents the total absolute vertical movement of the material after the maximum compression has been reached. The parameter \( \Delta H^* \) is the horizontal displacement at which the net vertical displacement returns to zero, indicating a restoration of the original volume and density of the material. In cases where \( \Delta V_{\text{min}} \) is positive, full restoration of the original volume does not occur. These parameters can be used to compare the direct shear behavior of riding surfaces to each other.

Each phase was extensively studied in the lab using the established direct shear test and analysis methods. Feedback from multiple riders was collected during each phase, with riders reporting on their subjective experience with the surface. Feedback focused on how the current surfaces were riding and how they compared to the surfaces of the other phases.
4.1.2 – Results

Direct shear tests for each surface were conducted at a normal stress of 1 psi and with a constant rate of horizontal displacement of 0.10 in./minute. The normal stress was chosen because it provides minimal confinement to the specimen, allowing for subtle changes in compaction and dilation behavior to become more pronounced. The vertical behavior of the three materials for one test conducted at a normal stress of 1 psi are presented in Figure 36.

![Graph](image)

**Figure 36**: Compaction/dilation behavior for all phases

It can be seen that the original and the remediated surfaces have very similar behaviors. The fiber-saturated surface shows a significant amount of dilation as compared to the original and remediated surfaces. Small changes in the surface parameters between the original and
remediated surfaces hint at changes in the functional properties. Bar graphs showing the values for the surface parameters corresponding to tests as shown in Figure 36 are shown in Figure 37.

![Figure 37: Surface parameter bar graphs](image)

Figure 37: Surface parameter bar graphs

Again, the original and remediated surfaces show very similar values for $\Delta V_{\text{min}}$ and $\Delta V^*$, indicating that the takeoff / rollover performance of these surfaces is likely very similar. Looking at the fiber-saturated surface, $\Delta V_{\text{min}}$ shows that the dilation appears to be much greater when compared to the others. This is in line with the balling-up and clumping experienced by riders. A very low $\Delta V_{\text{max}}$ may indicate a very high impact firmness because the material does not compress much under the horse’s hoof.

Shear strength graphs were used in an attempt to better understand the clumping behavior experienced in the fiber-saturated surface. Figure 38 shows the direct shear behavior at a normal stress of 1 psi for all surfaces. As with the vertical behavior, the original and remediated surface surfaces show very similar behavior while the fiber-saturated surface is dramatically different.
The fiber-saturated surface appears to undergo several periods of strengthening and failing. The fiber and fabric in the soil matrix has made the material much stiffer and somewhat “brittle”, so the failure is more sudden and to a greater magnitude than what would be expected for a less stiff surface material. The re-strengthening suggests that fibers and fabric pieces are being reordered in the matrix after failure. This may be attributable to the interplay of the relatively large fabric pieces. Such a relatively high strength may indicate more difficult breakover of the surface. In addition, the higher strength and stiffness may also indicate a high impact firmness.
4.1.3 – Discussion and Conclusion

Changes in the direct shear surface parameters, as seen in Figure 37, were used to estimate changes in functional properties. Changes in the surface parameters between the original and remediated surfaces are well within the limitations of measurement of the direct shear machine, therefore no conclusions can be made regarding how the functional properties may have changed between these two surfaces Table 7 shows a summary of how the functional properties were estimated to change using the direct shear analysis and surface parameters. A decrease in $\Delta V_{\text{max}}$ implies a less compressive surface, meaning the material will compress less under the horses’ hooves. This may indicate a higher impact firmness. This is why the fiber-saturated surface, with the lowest value of $\Delta V_{\text{max}}$, is rated the hardest. Increased shear strength indicates a surface with more grip, which is why the fiber-saturated surface is rated as having the highest grip. Shear strength is very important, and too much or too little shear strength can lead to performance and safety issues.

Table 7: Changes in riding behavior estimated by direct shear tests

<table>
<thead>
<tr>
<th>Surface</th>
<th>Grip</th>
<th>Response</th>
<th>Impact Firmness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>High</td>
<td>Alive</td>
<td>Soft</td>
</tr>
<tr>
<td>Fiber-Saturated</td>
<td>↑ High</td>
<td>↑ High</td>
<td>↑ Hard</td>
</tr>
<tr>
<td>Remediated</td>
<td>O No change</td>
<td>O No change</td>
<td>O No change</td>
</tr>
</tbody>
</table>

Rider feedback was used as a comparison to the estimations made using direct shear tests. Professional and advanced riders are capable of detecting changes in surface performance by
interpreting the riding behavior. Feedback was focused on the impact of the hoof on the surface and the quality of the takeoff. The impact and takeoff phases are often the most critical determinants of the surfaces overall performance.

Of the original surface, riders said that overall it performed well, especially with decelerating the hoof on impact (desirable impact firmness). However, where the surface was lacking was in the takeoff / rollover phase: the grip was a little too high and the surface did not displace enough horizontally under the horse hoof during takeoff. Additionally, riders believed there was too much compression under the hoof, which was hindering takeoff.

Of the fiber-saturated surface, one rider said their horse was “tripping and stubbing his toes on the fiber-saturated surface”, and was showing signs that he was bracing himself against the surface. Such an action may indicate that the impact firmness was very high, resulting in the horse needing to brace against increased impact forces. Other riders agreed that they could not ride on the fiber-saturated surface due to similar problems.

Of the remediated surface, the same rider mentioned how “the tripping stopped immediately and…his stride was much more fluid.” Another rider said they were having good rides on it and their horse was also not tripping anymore. Another rider said how their horse “goes great on this surface,” and is now “the soundest he has ever been.”
It can be seen that there is great agreement between estimated surface performance using direct shear testing and the subjective interpretation of surface performance by the professional and advanced riders.

Using the established test parameters appears to be capable of comparing the performance of one surface to another, but should be used with caution, if at all, when attempting to estimate the performance of a stand-alone surface.

Changes in riding performance (and functional properties) are reflected in changes in the direct shear behavior of the materials, and thus in the surface parameters. The results suggest that it may be possible to estimate how the functional properties of a surface will change based on observed differences in the surface parameters relative to the original surface. Table 8 shows possible ways that changes in surface parameters may relate to changes in functional properties.

<table>
<thead>
<tr>
<th>Change in Parameter Value</th>
<th>Increases</th>
<th>Decreases</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V_{max}$</td>
<td>Lower impact firmness</td>
<td>Higher impact firmness</td>
</tr>
<tr>
<td>$\Delta V_{min}$</td>
<td>Increased responsiveness</td>
<td>Decreased responsiveness</td>
</tr>
<tr>
<td>$\Delta V^*$</td>
<td>Increased responsiveness</td>
<td>Decreased responsiveness</td>
</tr>
<tr>
<td>$\Delta H^*$</td>
<td>Increased responsiveness</td>
<td>Decreased responsiveness</td>
</tr>
</tbody>
</table>

It can also be noted that the system properties that affect performance (grip / shear resistance, responsiveness, and impact firmness) are not orthogonal. Orthogonality of the system would mean that changes to the characteristics of one component in the system would not create side
effects in other components of the system. That was not the case here. The change in cushion in the fiber saturated surface also resulted in a side-effect which changed the grip.

4.2 – Northern New England Farm

This section summarizes the results of a direct shear testing program conducted in June 2017 on the equestrian riding surface from a farm in Northern New England. The Northern New England Farm (NNEF) was experiencing difficulties with their riding surface. Maintenance was becoming increasingly more involved and frequent. More importantly their riding surface was lacking in performance from what they used to experience and from what the manufacturer claimed. Horses were tripping and riders claimed their hoofs were getting “stuck” in the surface. They became interested in our research and test methods after hearing of the success of the remediation of the Coyote Spring Farm riding surface. Samples of their riding surface were sent to our lab and extensive testing was done to obtain baseline measurements for comparison to other riding surfaces and to experiment with possible solutions to the problem.

4.2.1 – Baseline Testing

The goal of baseline testing was to observe how the surface in its as-delivered state compared to a range of previously tested materials that are known to ride well. This comparison arrived at identifying the root cause of the performance issues. Surface parameters (as established during the Coyote Spring Farm case study) were used to identify possible issues with the surface response. The material was tested at 15, 25, and 35 psi to develop failure envelopes and at 1 psi and 25 psi to observe compaction / dilation behavior. Based on testing by UNH of various
engineered riding surfaces using direct shear tests under confining pressures of 15, 25, and 35 psi, a strength performance range has been established (Morganna Mendonca de Souza, 2016; van der Heijden et al., 2017). Figure 39 shows the baseline material compared to the strength performance range. The upper bound is a silica sand with fiber, fabric, and a polymer binder; the lower bound is as silica sand with fiber and a proprietary binder.

The NNEF riding surface had a cohesion of 1.9 psi and a friction angle of 36°, at a density of 1.98 g/cm³ and moisture content of less than 1%. The density was higher than the tests used for the upper and lower bounds, which was 1.70 g/cm³. This was a result of the compressibility of the material: the material ended up compressing more than the others when applying the desired normal stresses. Since the density was higher, the measured maximum shear strengths may be higher than if tests were able to be conducted at the density of 1.70 g/cm³. Based on the baseline
testing, the problem with the material appeared to be that excessive compaction under the horse loading was causing the horse hoof to penetrate too far into the material, resulting in tripping during the takeoff phase when the hoof must release cleanly from the surface. Interestingly, the cause of tripping for the NNEF riding surface appeared to be opposite to the cause of tripping experienced with the fiber-saturated material at Coyote Spring Farm. At Coyote Spring Farm, too much dilation appeared to be causing excessive accumulation of material in front of the horse hoof, causing the toe to catch on the material during takeoff. Surface strength did not appear to be an issue since the strength of the material was within the range of previously tested materials, although the cohesion is lower than the average of 3.4 psi for the material tested (see Table 3). Therefore, an ideal amendment would decrease the compaction of the material without sacrificing strength.

4.2.2 – Remediation Study

Four different materials were selected for amendment experiments in the lab: coarse sand, fibers, fabric, and rubber pieces. Each material was added individually to the as-delivered surface material and then tested to observe the influence of the amendment on the characteristics of the surface. The effect of the amendment on riding performance was then estimated using changes in surface parameters developed during the Coyote Spring Farm case study. The experiments were also compared to previously tested surfaces with known performance characteristics as a point of reference. Tests were conducted at 1 psi normal stress, which is designed to simulate the later part of the takeoff phase when there is little confining pressure on the surface.
Only one mixture with each amendment material was created in the lab. The percentages by mass of each amendment material in the final mixture can be seen in Table 9.

<table>
<thead>
<tr>
<th>Amendment</th>
<th>% by mass in mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>20%</td>
</tr>
<tr>
<td>Fiber</td>
<td>0.3%</td>
</tr>
<tr>
<td>Fabric</td>
<td>1.0%</td>
</tr>
<tr>
<td>Rubber</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

Fabric pieces were approximately 0.55 to 0.60 mm thick and had an average mass of 0.056 g, but varied greatly from approximately 0.030 g to 0.30 g. They also varied greatly in dimensions: some were 1 cm to a side, while others were 2 cm wide and 6 cm long. Fibers had an average length of 2.5-3.0 cm and diameter of approximately 0.01 mm. The size distribution for the rubber pieces can be seen in Table 10. Sieve analysis for the coarse sand used in the experiment is shown in Figure 40. The coefficient of uniformity, $C_u$, is 1.7 and the coefficient of curvature, $C_c$, is 0.9, which classify the material as a poorly graded sand.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>% Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8&quot;</td>
<td>22.4%</td>
</tr>
<tr>
<td>1/4&quot;</td>
<td>71.8%</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>5.8%</td>
</tr>
</tbody>
</table>
Sieve analysis of the baseline material itself was not possible due to the binder used in the material. The binder adds cohesion between particles, causing them to “stick” together and to occasionally clog the sieves, resulting in a material with an artificially large average particle size.

The four mixtures were then tested using the direct shear test. The results are presented in Table 11 in terms of shear strength and in Figure 41 in terms of shear stress under a confining pressure of 25 psi. The amendments did not appear to have a substantial effect on the maximum shear strength of the material for a normal stress of 25 psi.

Table 11: Maximum shear strength comparison

<table>
<thead>
<tr>
<th>Test</th>
<th>Shear Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>20.4</td>
</tr>
<tr>
<td>+ Sand</td>
<td>18.6</td>
</tr>
<tr>
<td>+ Fiber</td>
<td>20.8</td>
</tr>
<tr>
<td>+ Fabric</td>
<td>19.8</td>
</tr>
<tr>
<td>+ Rubber</td>
<td>20.2</td>
</tr>
</tbody>
</table>
Additions of fiber, fabric, and rubber appeared to reduce the initial stiffness of the material, but they appear to level off at higher horizontal displacements. The sand has less of an effect on the initial stiffness, but appears to have a lower stiffness at higher horizontal displacements. The most drastic effect appears to be in the compression / dilation behavior. Figure 42 shows vertical displacement during shear of the amendments compared to the baseline, conducted at a normal stress of 1 psi.
It can be seen that adding sand, fiber, and fabric increased the maximum compaction as the material is sheared, but adding rubber pieces resulted in substantial dilation. Similar trends were observed at higher normal stresses, although somewhat muted in comparison to 1 psi normal stress. Compression / dilation of the baseline and amendments at a normal stress of 25 psi is shown in Figure 43.
The size of the rubber pieces is likely to be the cause of the dilation. As the material is sheared, rubber pieces at or near the failure plane roll over the sand, fiber, and other rubber pieces. This rolling action results in dilation. The elasticity of the rubber pieces may also play a role. The rubber pieces may be acting like a spring: they become compressed during application of the normal stress, decreasing their volume. As particles shift and roll during the shearing, some of this stored energy in the compression of the rubber pieces may be released, resulting in dilation.

Figure 43: Compression / dilation of baseline and amendments at 25 psi
4.2.3 – *Discussion and Conclusion*

Experimenting with the NNEF riding surface showed the capability of direct shear testing to distinguish between surfaces with different material compositions. The lab testing proved capable of identifying the underlying issues with the surface material and proposing a general framework for a possible solution. Before the findings could be pursued further, however, there was an incident at the farm that led the managers to decide to abandon the surface all together. The incident was directly attributed to the poor performance of the surface. Nonetheless, the lab testing of the material provided a critical understanding of the influence of certain geosynthetic components on the shear behavior of surfaces, from which inferences could be drawn to the changes in riding behavior.

In addition, the effect of four common surface additives on shear behavior and riding behavior were explored. Fabric, fiber, and sand additives, in the proportions used, appeared to have the same effect on the shear characteristics of the material, slightly increasing compression. Rubber pieces had a very strong influence on shear characteristics, resulting in substantial dilation. Based on the lab testing, adding rubber pieces appeared to be the most appropriate option as it is the only amendment that decreased compression and increased dilation. The next step would be determining if the quantity of rubber pieces added was appropriate. A comparison between the surface with rubber pieces and surfaces from the Coyote Spring Farm remediation case study was made. Figure 44 and Figure 45 show dilation and strength performance comparisons between the baseline, added rubber, and CSF fiber-saturated and remediated surfaces, respectively. The tests were all conducted at 1 psi normal stress.
Figure 44: Strength comparison between baseline, rubber amendment, and CSF

Figure 45: Compression / dilation comparison between baseline, rubber amendment, and CSF
Baseline material with added rubber dilates about twice as much as the CSF remediated surface, approaching that of the fiber-saturated surface. A comparison of surface parameters for the four surfaces is shown in Table 12 and Figure 46.

Table 12: Surface parameters for baseline, added rubber, and CSF surfaces

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>+ Rubber</th>
<th>CSF Fiber-Saturated</th>
<th>CSF Remediated</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta V_{\text{max}})</td>
<td>0.036</td>
<td>0.012</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td>(\Delta V_{\text{min}})</td>
<td>n/a</td>
<td>0.09</td>
<td>0.14</td>
<td>0.04</td>
</tr>
<tr>
<td>(\Delta V^*)</td>
<td>n/a</td>
<td>0.10</td>
<td>0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>(\Delta H^*)</td>
<td>n/a</td>
<td>0.39</td>
<td>0.08</td>
<td>0.26</td>
</tr>
</tbody>
</table>

As for the strength, a sudden failure of the baseline with added rubber surface can be seen around 0.45 inches of displacement. This is reminiscent of, although to a lesser magnitude than, the strengthening and failing cycles of the CSF fiber saturated surface. Sudden shear failure coupled with high dilation both suggest that the added rubber in the surface material may be causing too much dilation. Further testing would be needed to determine the appropriate quantity of rubber pieces.

![Figure 46: Surface parameter bar graphs for baseline, added rubber, and CSD surfaces](image)

The amendment testing suggests that rubber pieces could be added to decrease the compression of the riding surface material.
5 – RESULTS

5.1 – Direct Shear

A good understanding of the general shear behavior of riding surface materials has been established through an extensive series of direct shear tests on four unique and commercially available engineered surfaces:

B – Sand with fiber and a proprietary wax binder.
C – An economic surface option with sand, fibers, fabric pieces, and binder.
D – A high-end surface with sand, fibers, fabric pieces, rubber pieces, and binder.

Figure 47 shows shear strength results for the four different samples conducted at normal stresses of 15 psi, 25 psi, and 35 psi. The results fall within a relatively narrow band, although their differences are not insignificant in terms of shearing resistance when considering the contributions of cohesion and friction angle. All specimens had a consolidated density of approximately 1.70 g/cm³. Specimen A had moisture content of approximately 2%, while others had moisture contents of less than 1%. Test data for the specimens is shown in Figures B2 through B5 in the Appendix B.
Specimen D had the highest apparent cohesion while specimen C had the lowest. Cohesion values and friction angles for the specimens are shown in Table 13. Water content for each sample was less than 2%.

Table 13: Cohesion and friction angle for specimens A, B, C, and D

<table>
<thead>
<tr>
<th>Surface</th>
<th>Consolidated Density (g/cm³)</th>
<th>Cohesion c’ (psi)</th>
<th>Friction Angle φ’ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.70</td>
<td>4.4</td>
<td>39.1</td>
</tr>
<tr>
<td>B</td>
<td>1.70</td>
<td>3.8</td>
<td>31.1</td>
</tr>
<tr>
<td>C</td>
<td>1.65</td>
<td>2.7</td>
<td>33.5</td>
</tr>
<tr>
<td>D</td>
<td>1.70</td>
<td>6.3</td>
<td>34.3</td>
</tr>
</tbody>
</table>
Specimen B showed the lowest friction angle value but a similar cohesion to specimen C, which has a much higher friction angle. The difference in friction angle between the two surfaces may be attributed to the lack of geosynthetic fiber pieces in specimen B, which contribute additional shear resistance.

The materials show shear behavior that is more typical of very loose soils, mainly that there is no well-defined peak in the maximum shear stress. In fact, it is quite typical to not reach a maximum shear stress, even with one inch of horizontal displacement. There was typically a gradual change in slope that occurred between approximately 0.2 to 0.3 inches of horizontal displacement, after which small increases in the induced shear stress resulted in substantial horizontal displacements. Typical shear stress graphs for an engineered riding surface, in this case surface B, are shown in Figure 48 at different normal stresses, $\sigma_n$.

![Shear Stress vs. Horizontal Displacement](image.png)

**Figure 48**: Typical shear stress graphs for an engineered riding surface, specimen B
The riding surface is initially very stiff at low displacements, but stiffness quickly decreases as the material is sheared. It can be seen that higher normal stress results in greater shear resistance. In addition, the riding surface material under higher normal stress appears to remain stiffer over a greater horizontal displacement.

The effect of geosynthetic components on shear behavior was also explored. Surface materials were tested with different geosynthetic components as well as with some geosynthetic components removed. Figure 49 shows shear strength envelopes for specimen D both in its as-delivered condition with binding agent, fibers, fabric, and rubber pieces, and in a modified condition without a binding agent and with the geosynthetics removed.

![Graph showing shear strength envelopes for specimen D](image)

**Figure 49:** Effect of geosynthetics and binder on shear strength, specimen D
The strength advantages of adding geosynthetics is quite evident. Cohesion increases from 2.4 to 5.1 psi and friction angle increases from 31.8° to 37.1° when the geosynthetics and binding agent are present. Figure 50 shows a comparison between specimen B in its as-delivered state and with the fibers removed manually but keeping the binding agent. There is little difference in the cohesive strength of the material, since the binder is left in place, but there is a substantial decrease in the friction angle (from 31° to 23°) with the removal of the fibers.

This would suggest that binding agents appear to be predominantly responsible for cohesive strength, whereas geosynthetic components, such as fabric pieces and fibers, appear to be predominantly responsible for changes in the frictional resistance. This makes sense physically,
as there is increased frictional resistance at the interface between the soil particles and the geosynthetics.

Vertical displacement (compression / dilation) during the shear phase was also an important component of the analysis. Vertical displacement is a manifestation of a change in volume, and therefore density, of the specimen during shearing. Vertical displacement results, conducted at a normal stress of 25 psi, are shown in Figure 51.

![Figure 51: Vertical displacement for specimens A, B, C, and D](image)

The compression / dilation behavior of the four specimens were quite different. Specimen B shows the least compression, whereas specimen D shows significantly more compression than the others. Specimens A and C, which show about the same compression, demonstrate different
dilation behaviors: A dilates while C continues to compress. Specimen B dilates substantially, almost returning to its original height. Specimen D also shows some dilation.

The testing, along with many others conducted on these materials at different normal stresses, suggests that surface material compression / dilation behavior can be sorted into three categories: compressive, partially dilative, and fully dilative, all of which are demonstrated in Figure 52.

![Graph showing compression / dilation behavior categories for an engineered surface](image)

**Figure 52: Compression / dilation behavior categories for an engineered surface**

Compressive surfaces exhibit no dilation during direct shear testing. Partially dilative surfaces exhibit compression and dilation, but have a net-compressive behavior (compression exceeds dilation). Fully dilative surfaces exhibit substantial dilation that exceeds compression, thus the surface has a net-dilative behavior.
The compression / dilation behavior category may suggest how the surface behaves during the impact and braking phases of the horse-surface interaction. The magnitude of compression that occurs during the shear test may indicate if a surface will be more or less compressive during the impact phase. During braking the hoof slides horizontally into the surface, shearing the material. Compressive surfaces may continue to compress throughout the entirety of the braking phase, while partially and fully dilative surfaces may begin to rebound.

The magnitude of compression during the impact and braking phases has repercussions for the takeoff phase. If the hoof is further into the surface the horse may experience more difficulty in taking off. A compressive surface may result in the hoof sliding further into the surface, potentially leading to takeoff problems, whereas a partially dilative or fully dilative surface may rebound more.

Of course, the compression / dilation response of surface materials is dependent on the confining pressure used in the direct shear test. Low confining pressures exaggerated the compression or dilation behavior while high confining pressures (i.e. 35 or 45 psi) resulted in more muted behavior. Regardless of the confining pressure, surfaces trended the same relative to one another: for example, a surface that was more compressible than another at 5 psi normal stress would also be more compressible at 45 psi, only the difference may be less noticeable. Figure 53 shows the compression / dilation behavior of surface B at three different normal stresses.
As expected, higher normal stresses reduce the magnitude of dilation. A normal stress of 1 psi was often used because the compression / dilation behavior may be exaggerated due to the low confining stress.

5.1.1 – Observations

Some of the riding surfaces test have relatively large geosynthetic components. The dimensions of the shear box, 10 cm square, may present repeatability issues when testing riding surface that contain fabric pieces that can be 5 cm long. In response to these potential scale issues, initially three tests of each riding surface specimen were conducted for each normal stress (i.e. 15, 25, or 35 psi). This was done to observe if there was substantial variation in the shear strength between
tests conducted at the same normal stress. Of 36 tests conducted on specimens A, B, C, and D, the average standard deviation for shear strength was 0.87 psi, with the maximum being 2 psi for Specimen A at a normal stress of 35 psi. Test data for all four specimens is shown in Tables B1 through B4 in Appendix B. Low standard deviations may suggest that there is little effect of the relative size of some geosynthetic components to the size of the shear box. It was decided going forward to conduct only one test at each normal stress.

Bareither et al. (2008) investigated potential effects on friction angle of the relative size of large particles in sand mixtures to the size of the direct shear box. 30 clean sand materials with gravel contents (particles greater than 4.75mm) ranging from 0% to 30% were tested using a small-scale 6.4 cm (2.5 inch) square direct shear box and a large-scale 30.5 cm (12 inch) square direct shear box. 24 of the sands tested classified as poorly-graded, the same classification for the riding surface material shown in Figure 6. They found that there was no statistically significant difference in friction angles obtained using the small scale and large scale shear boxes. Bareither et al. (2008) also investigated the repeatability of direct shear tests, conducting five replicate tests one of the sand specimens and found no statistically significant difference in the friction angle between the tests. The study found friction angle to be repeatable within ± 0.25°.

It is important to note that the clean sand materials used in the study by Bareither et al. (2008) may behave differently than riding surface materials. The relatively large gravel particles in the clean sand mixtures are rigid whereas large fabric pieces commonly found in riding surfaces are flexible.
5.2 – LWD

The LWD data that was primarily used was the displacement of the first pulse, maximum acceleration of the first pulse, and frequency of the impact. Tests were conducted on five different high-level riding surfaces, shown in Table 14. Two different base plates were used: the standard 300 mm diameter base plate and a customized baseplate with a horse shoe bolted on the bottom, approximately 120 mm in diameter (iEquiTek Patent Pending Horse Shoe Impact Head). The customized plate was provided by iEquiTek, the firm that designed and created it. The 300 mm diameter plate was used to test the riding surface and support layer of Arena 1, and the support layers of Arenas 2, 3, 4, and 5. The horse shoe plate was used to test the riding surface of all arenas.

Table 14: Arenas tested with LWD

<table>
<thead>
<tr>
<th>Arena</th>
<th>Surface Description</th>
<th>Support Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Indoor arena. Sand with fiber, fabric, and binder</td>
<td>Rubber Concussion Mats</td>
</tr>
<tr>
<td>2</td>
<td>Indoor arena. Sand with fiber, proprietary wax binder</td>
<td>Asphalt</td>
</tr>
<tr>
<td>3</td>
<td>Indoor arena. Sand with fiber, fabric, rubber pieces, and binder</td>
<td>Stone Dust</td>
</tr>
<tr>
<td>4</td>
<td>Outdoor arena, moisture dependent. Sand with fabric and yarn, no binder</td>
<td>Stone Dust</td>
</tr>
<tr>
<td>5</td>
<td>Outdoor arena, moisture dependent. Sand with fabric, no binder</td>
<td>Geotextile over compacted gravel</td>
</tr>
</tbody>
</table>

Figure 54 shows LWD displacement results for six pulses conducted at the same location in the center of Arena 1. The first three pulses show decreasing displacement as the material is compacted under each consecutive load pulse. Displacements appear to converge at around 3 mm with pulses 4, 5, and 6. The 300 mm diameter base plate was used, applying a stress to the surface of approximately 100 kPa. Each pulse was conducted approximately 10 seconds apart.
Displacement time histories from the LWD start at approximately 3 milliseconds. This is because there is loss of data at the ends of the signal due to the double differentiation conducted by the LWD to generate displacement from acceleration. Negative displacement indicates that the plate is losing contact with the surface and bouncing back. There is visible confirmation of this occurring when conducting a test. One possible reason for this behavior is that the surface thickness itself is relatively thin (2-4 inches typically), at least from a geotechnical perspective, and is underlain by a stiff base layer. The stiffness of the base layer causes a reflection of the pulse energy back to the plate, resulting in the plate losing contact with the surface. For the tests shown in Figure 54, the base layer was rubber concussion mats, however the same bouncing behavior has been observed on surfaces underlain by compacted stone dust and asphalt. This reflection of energy may also be responsible for the bump in the displacement signal that is seen.
in pulses 3 through 6. Another possible cause could be the action of the buffer springs, and this is explored in greater detail later. It can also be seen that the time to the maximum displacement decreases with the first four pulses before leveling off. As shown in Figure 55, the relationship between pulse displacement and time to peak appears to be linear for the range of displacements measured during the tests.

![Graph showing pulse displacement versus time to peak displacement](image)

**Figure 55: Pulse displacement versus time to peak displacement**

The same trend was observed for other tests conducted on engineered riding surfaces, and are shown in Figures C5 and C6 in Appendix C.

### 5.2.1 – Effect of Different Locations in Arena

Figure 56 shows LWD tests conducted on Arena 1 at three different locations: at the center, along the kick wall, and at the quarter turn line. The track along the kick wall sees a high volume of traffic concentrated in a small area, so the surface there is typically more compacted than at
other areas in the arena. The quarter turn line may be looser than the kick track or center, since horses tend to shove the material up in the corner. The center does not see much concentrated traffic.

![Graph showing LWD tests at different locations in an arena](image)

**Figure 56: LWD tests at different locations in an arena**

The average first pulse displacement of the three locations at the arena is 8.51 mm, with a standard deviation of 0.29 mm. For the first and second pulses, the quarter line has the greatest displacement and the kick wall has the smallest displacement. This makes sense since the kick wall generally consists of a more compacted surface, whereas the quarter line is looser. Second pulse displacement at all locations is almost half that of the first pulse, which suggests that the first pulse compacts the material substantially. There also appears to be more plate bounce for the first pulse than at consecutive pulses at all locations. This may be a result of the buffer springs compressing more on the compacted surface of the second and third pulses.
5.2.2 – LWD Tests for Maximum Acceleration

The LWD was also used to investigate changes in maximum acceleration. As discussed in Section 3.2, the LWD uses an accelerometer to measure acceleration for each pulse, then internally transforms the acceleration time history into a displacement time history using proprietary software. Since the LWD does not output raw acceleration data, the deflection time history must then be differentiated twice back to acceleration. Integrating from acceleration to deflection, then differentiating back to acceleration likely introduces substantial processing errors in the signal. In order to confirm the accuracy of this method, an accelerometer was temporarily attached to the baseplate of the LWD to observe if the measured acceleration was similar to that of the differentiated deflection time history. Six pulses were conducted on grass and the acceleration from the accelerometer ranged from 26 to 28 G and from the LWD, 26 to 37 G. This appears to confirm that using the displacement time history to calculate maximum acceleration is an acceptable method. Typical displacement, velocity, and acceleration time histories from an LWD test on an engineered riding surface are shown in Figure 57. No additional filtering or conditioning is applied to the displacement time history output from the LWD. The acceleration time history shows that the plate initially has a positive acceleration downward corresponding to when the falling mass impact the plate and the plate accelerates downward from rest. The maximum acceleration from the impact occurs upward, thus the sign is negative. Acceleration should be 1 G at time zero, but this cannot be seen due to loss of data points from differentiation.
Figure 57: LWD time histories

The LWD outputs displacement signals with typically only 15 to 30 data points, and the data points are not output at evenly spaced time intervals. An example of raw output from the LWD is shown in Table C 1 in Appendix C. This results in a very low resolution displacement time...
history which, when double-differentiated, results in a low resolution acceleration time history. There is also a loss of one data point each time the signal is differentiated, which is substantial for a signal composed of so few data points to start. This is why the first few data points of the acceleration time history are missing.

If the displacement time history were sinusoidal, the corresponding velocity and acceleration time histories would have a 90° and 180° phase difference from the displacement time history. Therefore, the maximum positive displacement would correspond to a velocity of zero and the maximum negative acceleration. The maximum acceleration corresponds to the maximum displacement, which occurs when the mass and base plate system has come to rest. The maximum acceleration occurs at this point because the base plate is changing direction from downward to upward motion. This change in direction is responsible for the spike in acceleration during the impact.

All five arena surfaces were tested with the LWD and analyzed for maximum acceleration using double differentiation. Differentiation was conducted using MATLAB. The results are shown in Table 15. Arena 1 was tested with the 300 mm diameter plate, while arenas 2 through 5 were tested with the horse shoe plate. Averages and standard deviations for each arena are shown in Table 16. It is interesting to note that there is less variation in the displacements at Arena 1 than at Arenas 2, 3, 4, and 5. A possible explanation is that the horse shoe base plate, which is much smaller than the 300 mm diameter plate, is more susceptible to local variation in the test location.
Table 15: LWD test results on five unique arena surfaces

<table>
<thead>
<tr>
<th>Arena Test #</th>
<th>Location</th>
<th>Plate</th>
<th>Notes</th>
<th>Displacement (mm)</th>
<th>Acceleration (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>300 mm</td>
<td>4” surface depth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Center</td>
<td>300 mm</td>
<td>4” surface depth</td>
<td>8.44</td>
<td>64.3</td>
</tr>
<tr>
<td>1</td>
<td>Quarter line</td>
<td>300 mm</td>
<td>4” surface depth</td>
<td>8.82</td>
<td>106.7</td>
</tr>
<tr>
<td>1</td>
<td>Kick track</td>
<td>300 mm</td>
<td>2.5” surface depth</td>
<td>8.26</td>
<td>56.1</td>
</tr>
<tr>
<td>2</td>
<td>Quarter line</td>
<td>Horse Shoe</td>
<td>Fresh groomed surface</td>
<td>10.92</td>
<td>48.9</td>
</tr>
<tr>
<td>2</td>
<td>Quarter line</td>
<td>Horse Shoe</td>
<td>Fresh groomed surface</td>
<td>10.80</td>
<td>47.7</td>
</tr>
<tr>
<td>2</td>
<td>Near kick track</td>
<td>Horse Shoe</td>
<td>Groomed, very loose</td>
<td>13.34</td>
<td>45.5</td>
</tr>
<tr>
<td>2</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>Loose for kick track</td>
<td>8.06</td>
<td>36.4</td>
</tr>
<tr>
<td>2</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>Fairly compacted</td>
<td>7.56</td>
<td>42.6</td>
</tr>
<tr>
<td>2</td>
<td>Center</td>
<td>Horse Shoe</td>
<td>Very loose</td>
<td>11.05</td>
<td>49.5</td>
</tr>
<tr>
<td>3</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>Fresh groomed surface</td>
<td>9.91</td>
<td>51.5</td>
</tr>
<tr>
<td>3</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>3.5” surface depth, very loose</td>
<td>16.38</td>
<td>68.1</td>
</tr>
<tr>
<td>3</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>2.75” surface depth, very loose</td>
<td>14.10</td>
<td>63.1</td>
</tr>
<tr>
<td>3</td>
<td>Center</td>
<td>Horse Shoe</td>
<td>2.75” surface depth</td>
<td>10.71</td>
<td>55.3</td>
</tr>
<tr>
<td>4</td>
<td>Center</td>
<td>Horse Shoe</td>
<td>Dry, 4” surface depth</td>
<td>9.02</td>
<td>60.1</td>
</tr>
<tr>
<td>4</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>Dry, 2.5” surface depth</td>
<td>16.64</td>
<td>89.8</td>
</tr>
<tr>
<td>4</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>Dry, 2.5” surface depth</td>
<td>12.32</td>
<td>81.3</td>
</tr>
<tr>
<td>4</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>Dry, 2.5” surface depth</td>
<td>16.51</td>
<td>65.1</td>
</tr>
<tr>
<td>4</td>
<td>Kick track</td>
<td>Horse Shoe</td>
<td>Wet, 2.5” surface depth</td>
<td>13.34</td>
<td>60.9</td>
</tr>
<tr>
<td>5</td>
<td>Near jump take off</td>
<td>Horse Shoe</td>
<td>Fresh groomed, 3.25” surface depth</td>
<td>12.98</td>
<td>78.5</td>
</tr>
<tr>
<td>5</td>
<td>Near jump take off</td>
<td>Horse Shoe</td>
<td>Fresh groomed</td>
<td>9.65</td>
<td>57.9</td>
</tr>
<tr>
<td>5</td>
<td>Near jump take off</td>
<td>Horse Shoe</td>
<td>Fresh groomed</td>
<td>10.67</td>
<td>74.7</td>
</tr>
<tr>
<td>5</td>
<td>Center</td>
<td>Horse Shoe</td>
<td>Fresh groomed, very loose</td>
<td>11.30</td>
<td>74.6</td>
</tr>
</tbody>
</table>

Table 16: Average and standard deviation of LWD displacement and acceleration

<table>
<thead>
<tr>
<th>Arena # Tests</th>
<th>Average Displacement (mm)</th>
<th>Average Acceleration (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.5 +/- 0.3</td>
<td>76 +/- 27</td>
</tr>
<tr>
<td>2</td>
<td>10.3 +/- 2.1</td>
<td>44 +/- 5</td>
</tr>
<tr>
<td>3</td>
<td>12.8 +/- 3.0</td>
<td>60 +/- 7</td>
</tr>
<tr>
<td>4</td>
<td>13.6 +/- 3.2</td>
<td>71 +/- 13</td>
</tr>
<tr>
<td>5</td>
<td>11.2 +/- 1.4</td>
<td>71 +/- 9</td>
</tr>
</tbody>
</table>

A plot of all tests conducted with the horse shoe base plate is shown in Figure 58, with a linear regression and 95% confidence interval for the fit. The coefficient of fit is very low (R = 0.24), but the results do appear to follow a trend of increasing acceleration with increasing first pulse displacement. The scatter is not unexpected given the variability of the tested materials.
The results suggest that, in general, greater first pulse displacements may have higher impact accelerations. This may be a result of the relative stiffness between the riding surface and the buffer spring. The relative stiffness affects compression of the buffer spring and the duration of the load pulse. The buffer springs is designed to compress when testing stiff surfaces, such as compacted roadway base layers. Compression of the buffer spring results in a load pulse that occurs over a longer period of time than if the springs were not in place and the falling mass impacted directly with the baseplate. Greater spring compression results in a longer load pulse, since the impact is damped by compression of the spring. Stiffer materials, such as compacted gravel, result in greater spring compression versus softer materials, such as riding surfaces, which results in minimal spring compression. This can be visually observed during the test by
the rebound height of the LWD mass. Tests on concrete result in the mass rebounding at least 75% of the drop height, whereas some riding surfaces showed little to no rebound of the LWD mass, as was observed during tests 2.3, 3.2, 3.3, and 5.4., which all showed very little mass rebound, approximately less than 10 %, and some of the largest displacements. Other tests showed large displacement as well, but the rebound height was not noted. This observation, coupled with the relatively high displacements for each of the tests, would suggest that the loose riding surface has a very low stiffness. This appears to contradict the higher acceleration values for these tests, as higher accelerations are typically associated with stiffer surfaces. However, for the tests on very loose high displacement riding surfaces, there is less compression of the buffer springs which shortens the duration of the load pulse. With denser, lower displacement riding surfaces, the material may be stiffer so the buffer springs displace more, elongating the duration of the load pulse. Since acceleration describes change in velocity with respect to change in time, increasing the time over which the impact occurs will result in a lower acceleration. A demonstration is shown in Figure 59.

![Figure 59: Idealized impact pulse duration depiction](image-url)
If this hypothesis is correct, it would be expected that the tests on the support layer materials would result in low accelerations because of the elongation of the load pulse from increased compression of the buffer springs. Figure 60 shows four tests on different riding surface support layer: stone dust, rubber mat, compacted gravel, and asphalt, all shown as red open circles. Displacement and acceleration of the four different support layers is discussed in further detail later in this section, and is shown in Table 17.

![Graph showing the relationship between first pulse displacement and acceleration for different support layers.](image)

Figure 60: LWD horse shoe base plate test results with arena support layer test results

Tests conducted on the support layer materials, which are very stiff compared to the loose riding surfaces, result in lower accelerations, trending well with the results from the horse shoe base plate tests. These results seem to support the hypothesis that the relative stiffness between the
surface and the buffer springs has a significant influence on the resulting impact acceleration. Accelerations on stiffer surfaces tended to be lower than those on softer surfaces due to the influence of the buffer springs.

5.2.3 – Effect of Different Base Plates

Tests were conducted to compare the 300 mm base plate with a horse shoe bolted to the bottom. The diameter of the horse shoe base plate was 120 mm, and with the load from the LWD this resulted in an applied stress of approximately 625 kPa, versus the 100 kPa of the 300 mm base plate. While the surface area of the horse shoe itself was smaller than that of the horse base plate, when it is placed on the riding surface the entire plate makes contact with the riding surface. The horse shoe was used because it was believed that the stress may be more representative of that induced by a horse. A comparison between the first pulse of a test conducted on an engineered riding surface with the 300 mm plate and with the horse shoe plate is shown in Figure 61.
The tests were conducted along the kick track and the surface depth was approximately 3.5 inches. The horse shoe results in greater displacement than the 300 mm plate, as would be expected with the increase in stress. Rebound with the horse shoe is very different: values remain positive suggesting that there is no loss of contact between the shoe and the surface, although it is not possible to be certain. Accelerations for the two base plates were very different, as was expected given the increase in stress and displacement. The acceleration for the 300 mm base plate was 64 G, and for the horse shoe was 146 G, which is much closer to the average acceleration of 170 G found by Chateau et al. (2009) on their work with instrumented horse hoofs. This would suggest that the horse shoe base plate for the LWD is capable of testing riding
surfaces and producing impact accelerations that are within the range of accelerations that have been measured on real horses.

Both the 300 mm diameter plate and the horse shoe plate were modeled in Rocscience Settle 3D software (copyright 2018, Rocscience). The plates were modeled as rigid plates with their corresponding applied stresses: 100 kPa for the 300 mm plate and 625 kPa for the horse shoe plate. The soil profile was split into two layers: a 10 cm thick top layer for the riding surface and a 40 cm thick bottom layer for the support layers. The top layer was given a unit weight of 12 kN/m$^3$ and an elastic modulus of 1,000 kPa; the bottom layer was made to be ten times as dense and stiff as the top layer and had a unit weight of 18 kN/m$^3$ and elastic modulus of 10,000 kPa. The reason for this was to investigate how the relative stiffness between the riding surface and the support layer affects the stress distribution under the two plates. The software uses Boussinesq methods for calculating stress distributions, which are derived from the theory of elasticity. Curves of vertical loading stress with depth for the two plates are shown in Figure 62. Loading stress is the stress induced on the soil by the plates. This is different from total stress, which would include the contribution of the self-weight of the soil, which is not significant considering the riding surface is very thin.
The horse shoe plate has a significantly higher loading stress in the top 0.1 m of the soil layer than the 300 mm plate, but loading stress for the two plates converges around 0.4 m. Higher loading stress from the horse shoe plate is a result of its higher applied stress of 625 kPa as compared to 100 kPa for the 300 mm diameter plate. The reason the loading stress converges instead of remaining higher throughout the profile is due to the difference in diameter of the two
plates. This is best visualized by comparing loading stress as a percent of applied stress for both plates, as shown in Figure 63.

Figure 63: Vertical loading stress as a percent of applied stress for the 300 mm plate and the horse shoe plate

It can be seen that the loading stress attenuates quicker with depth for the horse shoe plate than the 300 mm plate. This would suggest that under identical applied stress conditions the horse shoe base plate would have a shallower influence depth than the 300 mm diameter base plate due
to its smaller diameter. Therefore, the properties of the support layers, and perhaps the native soil underneath the arena, may be exercised more by the larger diameter 300 mm plate than the horse shoe plate. It should be noted that the software only allows for the application of static loads. The stress distribution may be different under dynamic loading, as the soil tends to be stiffer when subjected to a dynamic load than a static load. In addition, application of the theory of elasticity for stress distribution purposes requires that stress and strain are proportional. This requirement can be assumed met for applied loads below failure loads of the soil (Holtz et al., 2011). It is reasonable to assume that the loading stress from the base plates on the support layers of the arena is well below failure. It is unclear how well this assumption holds for the riding surface material, however, which is very loose and can incur substantial strain (typically on the order of 10% to 20%) under these loads. This may have implications for the stress distribution through the top 0.1 m of the profile.

5.2.4 – Effect of Arena Support Layer Material

Arenas 1, 2, 3, and 5 had different support layer materials: Arena 1 had rubber concussion mats, Arena 2 had asphalt, Arena 3 had compacted stone dust, and Arena 5 had compacted gravel. The compacted gravel base of Arena 5 was overlain with a geotextile fabric to prevent the surface material from working its way into the void spaces in the gravel layer. Tests were conducted with the 300 mm plate on the support layer of each arena, and the results for the first pulse can be seen in Figure 64. Maximum displacement and acceleration for each material are shown in Table 17. All three pulses for each base material are shown in Figures C2 through C4 in Appendix C.
Table 17: Displacement and acceleration of arena support layers

<table>
<thead>
<tr>
<th>Support Layer</th>
<th>Displacement (mm)</th>
<th>Acceleration (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone Dust</td>
<td>1.34</td>
<td>19.9</td>
</tr>
<tr>
<td>Compacted Gravel</td>
<td>3.00</td>
<td>13.7</td>
</tr>
<tr>
<td>Rubber Concussion Mat</td>
<td>1.37</td>
<td>20.5</td>
</tr>
<tr>
<td>Asphalt</td>
<td>0.37</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Figure 64: LWD tests on different support layers, 300 mm plate

Displacements for the rubber mat and stone dust base are very similar, while the compacted gravel showed the most displacement and the asphalt shows the least. The displacement of the stone dust base appears to hold relatively steady for approximately 10 ms. The displacement time history of the rubber mat shows a similar trend as that of the stone dust, but with one notable difference. Instead of flattening out like the stone dust base, the rubber mat appears to rebound...
slightly before flattening, after reaching the maximum displacement. This suggests that the rubber concussion mats have an elastic behavior, supplying rebound without damping. The use of rubber base mats may improve the rebound characteristics of a riding surface system as compared to a stone dust base. The displacement of the asphalt base was significantly less than both the rubber mat and the stone dust, suggesting that the base may contribute to increasing the impact firmness of a surface, especially in shallow areas of the arena. The support layer materials have significantly lower accelerations than riding surfaces, despite being much stiffer. As discussed earlier, this is likely a result of increased compression of the buffer spring and elongating the load pulse, which reduces the maximum accelerations.

5.2.5 – Effect of Moisture

The effect of moisture on Arena 4, which is an outdoor, moisture sensitive arena, was explored. The arena was nearly dry when first tested, so water was added in order to make the comparison. The exact moisture content after addition of water was not known and a sample was not taken at the time. However, the arena manager was present to confirm that the level of moisture appeared to be representative of what was typically used. First pulse displacements with the hoof base plate are shown in Figure 65, with tabulated results shown in Table 18.
Adding water increased the displacement by 34% and reduced the maximum acceleration by 20%. Water also appeared to reduce the rate of compaction of the riding surface: the displacement of second pulse on the wet surface was 68% of the first pulse, and on the dry surface was 76%, suggesting that the dry surface may become compacted more quickly.
5.2.6 – LWD Impact Frequency

The frequency of the impact pulse was also investigated as a potential way to quantitatively evaluate responsiveness. Because the riding surface response appears to be sinusoidal in the shape, the following general equation for a sinusoid was used to analyze the frequency of the impact:

\[ d = A \sin(2\pi \omega t + x) + y \]  

(15)

Where \( A \) is the amplitude, \( \omega \) is the frequency, \( t \) is time, and \( x \) and \( y \) are constants used to shift the sinusoid horizontally or vertically to ensure a better fit. The duration of the impact represents half of one period of a sine wave, so frequency of the impact was estimated as half the inverse of the time corresponding to the maximum displacement. Amplitude was estimated as half the maximum displacement:

\[ f_{impact} = 0.5 \times \frac{1}{t_{impact}} \]  

(16)

\[ A = \frac{d_{\text{max}}}{2} \]  

(17)

Where \( d_{\text{max}} \) is the maximum displacement and \( t_{\text{impact}} \) is the time corresponding to the maximum displacement. The coefficient \( y \) was set to be equal to the amplitude, which sets the axis of oscillation for the wave to half the maximum displacement. Microsoft Excel Solver plug-in can then be used to determine the coefficient \( x \) by minimizing the initial displacement of the sinusoid to zero. Example data for a sinusoid fit is shown in Table 19. Figure 66 shows an
example of the LWD displacement with an impact sinusoid fit. The test was conducted on an
erengineered riding surface of Arena 1.

Table 19: Example data for a sinusoid fit to LWD impact pulse

<table>
<thead>
<tr>
<th>LWD</th>
<th>Sinusoid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>Displacement (mm)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.001792</td>
<td>0.134</td>
</tr>
<tr>
<td>0.00336</td>
<td>0.737</td>
</tr>
<tr>
<td>0.004704</td>
<td>1.675</td>
</tr>
<tr>
<td>0.006272</td>
<td>3.35</td>
</tr>
<tr>
<td>0.009184</td>
<td>6.901</td>
</tr>
<tr>
<td>0.010304</td>
<td>7.906</td>
</tr>
<tr>
<td>0.0112</td>
<td>8.375</td>
</tr>
<tr>
<td>0.011872</td>
<td>8.442</td>
</tr>
<tr>
<td>0.013439999</td>
<td>8.107</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 66: Impact sine fit to LWD result
It was not expected that the shape of the displacement time history be perfectly sinusoidal. The amplitude and frequency line up with the initial point (0,0) and the maximum displacement \((t_{impact}, d_{max})\), since these parameters were used to define equation.

As previously discussed, negative displacement indicates that the plate has lost contact with the surface. This loss of contact makes the displacement time history after the maximum displacement unreliable. In the rebound, the measured displacement is not representative of the actual surface displacement, but rather of the plate itself. There may be a portion of the displacement time history where the plate is in contact with the surface, but it is not possible to determine. For this reason, frequency of the rebound was not determined.

There was little variation in impact frequency across surfaces 1, 2, and 3. For a sample of nine tests, the average impact frequency was 42.5 Hz with a standard deviation of 3 Hz. This consistency may be a product of the loading delivered by the LWD, and not a measure of surface properties. The LWD delivers very consistent load pulses, which are controlled by the buffer springs. The duration of the impact may be a function of the relative stiffness between the riding surface and the buffer spring. The difference in stiffness between the buffer springs and riding surfaces is significantly greater than the difference in stiffness between one riding surface and another. Therefore, the buffer spring likely controls the duration of the load pulse, and small changes in surface stiffness are not significant enough to have a measureable effect on the duration of the load pulse.
A possible solution to this problem would be to select buffer springs that have a similar stiffness to riding surfaces. Doing so may allow for small differences in riding surface stiffness to influence the load duration.

5.2.1 – Observations

There are several limitations to using the LWD in its current state on engineered equestrian surface, some are limitations with the design and theory of the LWD and some are limitations introduced by the material properties.

The ZFG 2000 used for this research applies some signal processing to the acceleration data before outputting displacement data. The exact details of the signal processing are proprietary. Some degree of low-pass filtering is applied in order to remove high frequency noise in the signal. The filtering is likely fine-tuned to work best with anticipated signal from materials whose stiffness lies within the typical range the LWD was designed to test, and may not be suitable for the signal resulting from testing on equestrian surfaces, which are considerably softer than roadway subgrades.

The influence zone of the LWD is another important consideration. The influence depth can be assumed to fall between 1.5 and 2 times the diameter of the plate. For the 300 mm diameter plate, this would be 0.45 to 0.6 m (~ 1.5 to 2.0 feet). This means the influence depth may extend well into the graded natural ground under the arena surface. The advantage of such a deep influence depth is that the LWD may be capable of testing the response of the entire surface system as a whole. This is important, since the support layer of the arena likely have a substantial
influence on the riding performance of the horse. The disadvantage is that the LWD, at least in its current setup, may not be capable of isolating the surface material, so changes in surface material composition may not be distinguishable, and the influence depth may not be representative of that of a horse hoof. If it was desired to use the LWD to test only the riding surface, changes to the base plate buffer springs, and the mass may be necessary. Using a base plate that approximates the surface area of a horse hoof may improve the performance of the LWD application in testing equestrian riding surfaces.

While the force of impact is representative of that of a horse, the time to impact appears to be significantly shorter, approximately 12 ms as compared to the range of 62 to 123 ms from the studies previously shown in Table 1. The use of softer springs, if any springs at all, may improve the performance of the LWD in riding surface applications by lengthening the time over which the load pulse is applied. The use of buffer springs introduces effects on the load pulse characteristics depending on the relative stiffness between the riding surface material and the buffer. Stiffer riding surfaces will result in more compression of the buffer spring, elongation of the load pulse, and lower accelerations than softer riding surfaces.

5.3 – LDA

The LDA was investigated a potential tool for characterization of equestrian riding surfaces. Several different parameters may be obtained from an LDA test, depending on the analysis type. Two analysis approaches are outlined here: a simple analysis based on one-dimensional mechanics and a more complex analysis involving differentiating the output signal. Together,
they show that the LDA has potential as a tool for obtaining mechanical properties of surface materials and quantitatively evaluating some functional properties.

5.3.1 – Simple One-Dimensional Analysis

The test conditions established with the design of the LDA allow for the use of one-dimensional analysis to calculate mechanical properties of the test specimen. Under the assumption of 1-D conditions, Equation 18 can be used to calculate the force of impact:

\[ F = \frac{mgh}{d} \]  

(18)

Where \( F \) is the force of impact, \( m \) is the mass of the proctor hammer, 2.45 kg, \( g \) is the acceleration due to gravity, 9.81 m/s\(^2\), and \( h \) is the drop height of the proctor hammer, 0.305 m. Equation 18 can be solved for force:

\[ F = \frac{2.5 \text{ kg} \times 9.81 \text{ m/s}^2 \times 0.305 \text{ m}}{d} \]  

(19)

\[ F = \frac{7.48 \text{ N} \times m}{d} \]  

(20)

Where \( F \) is the average force required to displace the surface material the distance \( d \). A curve of the relationship between impact force and displacement using Equation 18 can be seen in Figure 67.
The relationship makes sense rationally. For example, a stiffer material such as concrete will displace less under a given load, resulting in higher average impact forces than softer materials, such as foam, which will displace more under the same load. The corresponding average vertical stress can be calculated by dividing the impact force by the area of the metal impact plate, $A_p$:

$$\sigma = \frac{F}{A_p}$$  \hspace{1cm} (21)

Total strain during a pulse can be calculated using the known initial height of the sample and the measured displacement:

$$\epsilon = \frac{d}{h_o}$$  \hspace{1cm} (22)
Where $\epsilon$ is the strain, $d$ is the measured displacement, and $h_o$ is the initial height of the sample.

The instantaneous velocity of the falling mass at impact ($v$), the deceleration of the mass during impact ($a$), and the equivalent G-force of the deceleration can all be calculated as defined using basic physics principles:

\[
v = \sqrt{2gh}
\]  
\[
a = \frac{v^2}{2d}
\]  
\[
G = \frac{a}{g}
\]

The instantaneous impact velocity is only a function of the drop height, $h$, which is fixed by the proctor hammer, thus it is constant between tests. Equations for instantaneous velocity and average acceleration become:

\[
v = \sqrt{2gh} = \sqrt{2 \times 9.81 \frac{m}{s^2} \times 0.305m} = 2.45 \frac{m}{s}
\]

\[
a = \frac{2.45^2}{2d} = \frac{3.00}{d}
\]

Where $v$ is the impact velocity, $g$ is the acceleration due to gravity, 9.81 m/s\(^2\), and $h$ is the drop height of the proctor hammer, 0.305 m. The deceleration is therefore only a function of the deformation of the material: it can be seen that large deformations will result in a lower deceleration than smaller deformations. Equation 27 is shown graphically in Figure 68.
Another characteristic included in the analysis is the impact time, which is the time from the initial impact of the mass to the maximum displacement. A constrained modulus, can also be estimated by dividing the impact stress by the total strain. This is different from Young’s Modulus, which is applicable if the specimen can freely deform in accordance with the effect of Poisson’s ratio. The mold, however, constricts lateral deformation of the specimen during the impact test. An equation relating constrained modulus to Young’s Modulus as a function of Poisson’s Ratio is shown below:

\[ M = \frac{E(1-v)}{(1+v)(1-2v)} \]  

(28)
Where $M$ is the constrained modulus, $E$ is Young’s Modulus, and $\nu$ is Poisson’s Ratio.

Constrained modulus values are higher than Young’s Modulus, because the material will be stiffer when lateral deformation is constrained.

An example of the results for a typical LDA test using the simple 1-D analysis methods are shown in Table 20.

<table>
<thead>
<tr>
<th>Pulse</th>
<th>Displacement (d)</th>
<th>Impact Time (t)</th>
<th>Decel. (a)</th>
<th>Decel. (G)</th>
<th>Impact Force (F)</th>
<th>Stress ((\sigma))</th>
<th>Strain ((\varepsilon))</th>
<th>Modulus (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.9</td>
<td>0.016</td>
<td>202</td>
<td>21</td>
<td>611</td>
<td>78</td>
<td>18.6%</td>
<td>419</td>
</tr>
<tr>
<td>2</td>
<td>3.80</td>
<td>0.010</td>
<td>790</td>
<td>81</td>
<td>2388</td>
<td>304</td>
<td>5.8%</td>
<td>5216</td>
</tr>
<tr>
<td>3</td>
<td>2.18</td>
<td>0.005</td>
<td>1377</td>
<td>140</td>
<td>4163</td>
<td>530</td>
<td>2.9%</td>
<td>18538</td>
</tr>
</tbody>
</table>

Displacement of the first pulse is substantially greater than for the second and third pulse, since the material is still very loose. As the material densifies under the applied load, the maximum acceleration, force, and stress increase. The modulus of the material increases by several orders of magnitude.

Deceleration may be used to describe the impact firmness of a surface, with higher decelerations implying a firmer surface. Modulus may be used to describe the stiffness of a surface. Figure 69 shows plots of stress versus strain for the three load pulses shown in Table 20, which can be used to demonstrate the stiffening rate of a riding surface.
It can be seen that the surface gets stiffer with each consecutive load pulse. The stiffening rate of a surface could be explored as a metric used to determine the required maintenance frequency. For example, surfaces that get stiffer faster may require more frequent grooming to maintain acceptable impact firmness performance.

5.3.2 – LDA Analysis by Differentiation

For the data acquisition system, it was important to ensure that the:

- A/D converter has sufficient resolution to capture the smallest signal level
- A/D converter has enough range to capture the highest signal level
- Sampling rate is in accordance with the Nyquist Criterion
The bit resolution describes the number of discrete intervals the A/D converter can produce over a range of input analog values. The number of discrete intervals can be calculated using the following equation:

\[ N = 2^M \]  

(29)

Where \( N \) is the number of discrete intervals and \( M \) is the resolution of the A/D converter in bits. Resolution may be expressed in terms of voltage by dividing the voltage range, in this case 9 V, by the number of discrete intervals. A 14-bit A/D converter was used, which has \( 2^{14} \) discrete intervals, resulting in a voltage resolution of \( 5.5 \times 10^{-4} \) V. The smallest displacement that can be captured with this system is equal to the displacement range of the potentiometer, 52 mm, divided by the number of discrete intervals, which results in approximately 0.0032 mm.

The Nyquist Rate is the lowest sampling rate required to avoid aliasing of the signal, and is equal to twice the highest frequency desired to capture. An idea of an appropriate sampling rate was first estimated using first principles. LDA tests were conducted and the displacement of the first pulse was measured manually using a ruler. The average of three first pulse displacements was 12.4 mm. Equation 27 could be rearranged to estimate the time of an impact based on the initial velocity of the falling mass and the displacement of the first pulse:

\[ a = \frac{v^2}{2d} = \frac{\Delta v}{\Delta t} \]  

(30)

Rearranging and solving for \( \Delta t \) yields:

\[ \Delta t = \frac{2d}{v} = \frac{2 \times 0.0124 \text{ m}}{2.45 \text{ m/s}} = 0.0101 \text{ s} \]  

(31)

The frequency of the impact is the reciprocal of the time of the impact:

\[ F_{\text{impact}} = \frac{1}{\Delta t} = \frac{1}{0.0101 \text{ s}} = 99 \text{ Hz} \]  

(32)
In order to avoid aliasing when sampling the signal, the sampling rate should be at least twice this estimated frequency desired to capture, thus the sampling rate should be approximately 200 Hz. Since the method used to estimate the frequency of the impact was very crude, tests were initially oversampled at 5 kHz in order to observe if this estimation was correct. The displacement time history of the test sampled at 5 kHz is shown in Figure 70.

![Figure 70: LDA displacement time history sampled at 5 kHz](image)

Discrete Fourier Transform was then conducted using MATLAB software in order to observe the frequency content of the signal, and is shown in Figure 71.
Figure 71: Discrete Fourier Transform of LDA displacement time history sampled at 5kHz

It can be seen that the spectral energy is concentrated at relatively low frequencies, with most of the spectral energy occurring below 200 Hz. The result demonstrates that a sampling rate of 5 kHz is more than sufficient to capture the range of frequencies present in the signal.

In order to get more comprehensive results from the LDA, a complete look at the displacement and acceleration time histories is necessary. MATLAB was used to filter and differentiate the raw output signal. Filtering was conducted using a third-order low pass filter with a stopband frequency of 200 Hz. The signal was also shifted to account for any delay introduced by the filter. Filtering was necessary to remove electrical noise from the signal, which becomes magnified when differentiating the signal. A comparison of the raw and filtered signals is shown in Figure 72.
High frequency noise is filtered out very well, with only a minimal decrease in the maximum displacement (5.6% in this case). The filtered displacement is then differentiated once to produce a velocity time history and once again to produce an acceleration time history. The resulting signals are shown in Figure 73.
Figure 73: Displacement, velocity, and acceleration time histories for LDA test
The maximum acceleration during impact can be found using the acceleration time history. In this example, the maximum acceleration is 46.6 G, corresponding to when the falling mass comes to rest, which occurs at the maximum displacement.

In order to check the integrity of acceleration values obtained using the filtering and differentiation method, an accelerometer was used to compare measured acceleration to the calculated value. An LDA test was conducted on an engineered riding surface specimen with an accelerometer attached to the impact plate. The accelerometer measured a maximum acceleration of 220 G. The maximum acceleration after filtering and differentiating the displacement signal was only 50 G. The differentiation was run again, this time without filtering, and the calculated acceleration was 120 G, shown in Figure 74.

![Acceleration Time History](image)

Figure 74: LDA test at 1 kHz sampling rate, unfiltered
While the value for maximum acceleration obtained from the unfiltered signal is closer to the measured value, there was still a substantial discrepancy. A possible explanation could be that the sampling rate was too low: it can be seen that there are only two data points that define the impact pulse for acceleration, and this may not be sufficient to capture the extent of the impact pulse. The sampling rate must be very high in order to capture detail during an impact, and acceleration, which is time-dependent, may be sensitive to the sampling rate. A test was conducted on the same engineered riding surface as that from Figure 73, prepared to the same specification of a thickness of 8 cm and a density of 1.10 g/cm$^3$. A higher sampling rate of 5 kHz was used and no filtering was applied to the raw signal. The resulting acceleration time history is shown in Figure 75.

![Acceleration Time History](image)

**Figure 75:** LDA acceleration time history at 5 kHz sampling rate, unfiltered
A distinct spike in acceleration corresponding to the impact, which takes place from approximately 40 to 55 milliseconds, is not distinguishable. The maximum calculated acceleration was over 1000 G and it occurred at approximately 23 milliseconds, which was well before the start of the impact. At this higher sampling rate, filtering is necessary to cut through the signal noise. The same low pass filter was used as before, with a stopband frequency of 200 Hz, to filter the displacement signal prior to differentiation. The resulting acceleration time history is shown in Figure 76.

![Acceleration Time History](image)

**Figure 76:** LDA acceleration time history at 5 kHz sampling rate, filtered

There is now a distinguished spike in acceleration corresponding to the impact. The maximum acceleration is 237 G, which is very close to the 220 G measured with the accelerometer. This suggests that the 200 Hz low pass filter is appropriate for this signal.
Much care must be taken when filtering signals, especially when taking derivatives of a signal. Differentiating a signal amplifies the influence of small aberrations such as noise or signal bias. Small changes to the displacement time history can result in large changes to the acceleration time history, thus the maximum acceleration value is dependent upon the filter parameters. Changing filter parameters, especially the stopband frequency, can drastically change the maximum acceleration. The test conducted for Figure 76 was subjected to several different stopband frequencies in order to observe the effect on maximum acceleration. Figure 77 shows a comparison of the original 200 Hz filter and a 300 Hz filter. It can be seen that increasing the stopband frequency leads to a reduction in the maximum acceleration, in this case from 237 G to 179 G, a substantial reduction.

![Figure 77: Comparison of 200 Hz and 300 Hz stopband frequencies](image)
Lowering the stopband frequency to 130 Hz proved insufficient at removing signal noise, resulting in several acceleration peaks in excess of 300 G, and a maximum acceleration for the impact that was not well distinguished. A stopband frequency of 180 Hz still showed substantial noise in the signal, as shown in Figure 78.

![Graph showing comparison of 200 Hz and 180 Hz stopband frequencies](image)

Figure 78: Comparison of 200 Hz and 180 Hz stopband frequencies

A stopband frequency of 200 Hz appears to be a reasonable frequency to use, as it results in good filtering of noise and a clearly distinguishable peak corresponding to the impact.
5.3.3 – Displacement Time History

The displacement time history from an LDA test may be used to observe how the riding surface materials respond to impact loading. One parameter the may be useful is the percent recovery. Percent recovery is how much the riding surface rebounds after impact as a percentage of the total impact displacement. A graph depicting this is shown in Figure 79.

\[
\% \text{Recovery} = \frac{\text{rebound displacement} - \text{impact displacement}}{\text{impact displacement}} \times 100\% \tag{33}
\]

There is a measured rebound that occurs immediately after the maximum impact displacement. After the rebound, the displacement levels off to some value. It is likely that the rebound spike is likely from plate bounce.
a consequence of the impact plate losing contact with the riding surface material and “bouncing”. For this reason, the rebound spike is not considered, and the rebound displacement is taken as the displacement at which the signal has leveled off. Nonetheless, the magnitude of the rebound spike may be an indication of the ability of the surface to return energy to the horse hoof: a surface with greater plate bounce may absorb less energy from the impact, returning more energy to the horse than a surface with less plate bounce.

5.3.4 – Comparison to Equine Instrumentation

Time histories from the LDA tests were used to examine the horse-surface interaction and compare impact testing to measured force and acceleration time histories from equestrian instrumentation studies. Robin et al. (2009) measured vertical force during the horse-surface interaction. Two graphs showing different load behavior are shown in Figure 80. The horizontal axis is percentage of the stance phase duration. The left figure is the average of 90 strides with one horse and the right figure is the average of 30 strides with another. Two graphs showing acceleration time histories are shown in Figure 81, from Chateau et al. (2009). The solid line is an engineered riding surface and the dotted line is a crushed sand riding surface. The two papers are based off of the same study.
Figure 80: Different load patterns during horse-surface interaction. Horse 1 (90 strides) is on the left and Horse 2 (30 strides) is on the right (from Robin et al., 2009).

Figure 81: Acceleration time histories from horse shoe accelerometer (from Chateau et al., 2009)

It can be seen that the load pulse is very uniform and takes the general shape of a half-sine load pulse, which is commonly assumed for impact type analyses. There is a spike in the vertical force around 5% of the stance phase duration. The spike is more pronounced in the right figure than the left figure, and this may be a result of averaging. This spike in force that occurs around 5% stance duration corresponds with the maximum measured acceleration in Figure 81, and it can be seen that the more pronounced spike corresponds to a significantly higher acceleration.
The maximum acceleration, however, does not occur at the maximum force. While force and acceleration are related in classical mechanics, the duration of the load pulse plays a very important role in the resulting accelerations. As mentioned in the LWD results, a load pulse with a short duration will result in higher acceleration than a load pulse of a longer duration. This explains why the initial spike from impact, despite not representing the maximum force, results in the maximum acceleration. After this initial impact, the surface is slowly loaded as the horse’s weight is transferred on to the hoof. This occurs over a comparatively long period of time, so there are no significant accelerations.

Because there is no spring damper in the LDA system, the support phase of the horse-surface interaction is not present. However, Figure 81 suggests that there are no significant accelerations that occur during the support phase. In addition, simulating the entire loading scheme of the horse-surface interaction is very complex, and appears unnecessary since maximum acceleration is often of most interest and this occurs during the impact phase.

5.3.4 – Observations

Using displacement measurements to estimate maximum acceleration of an impact introduces many opportunities for error. Due to the double differentiation involved, acceleration time histories are very sensitive to small changes in the displacement time history. Care must be taken when processing and filtering the output signal. The simplest way around this problem is to equip the system with an accelerometer, since calculating acceleration from indirect measurements may introduce errors. Short of using an accelerometer, increasing the sampling rate appeared to be capable of capturing more detail during the impact, resulting in a signal that
required filtering but could produce acceleration values similar to those measured by an accelerometer.

For the one-dimensional analysis approach, the acceleration values were significantly lower than those from the differentiation method. This is because the one-dimensional approach assumes that the rate of acceleration is constant throughout the entire time of impact, which may not be the case. Additionally, the one-dimensional approach utilizes static analysis, which does not consider the potential effects of dynamic loading on soil properties. Soils are stiffer under dynamic loading than under static loading, so values calculated using static analysis methods may underestimate the stiffness.

5.4 – Comparison of Test Methods

All three test methods – direct shear, LWD, and LDA – were used to analyze two surface materials of very different riding behavior, referred to here as Surface 1 and Surface 2. Estimations of the functional properties of each surface from the three test methods were compared.

Surface 1 contains fabric pieces and fibers, all held together by a binding agent. Surface 2 contains only fiber and a proprietary wax binding agent. The two surfaces exhibit very different riding behavior. Surface 1 is a firmer surface that offers good grip. Surface 2 offers a very soft (low impact firmness) riding experience, but has had issues with excessive compressibility and low grip (too much hoof slide).
5.4.1 – Direct Shear Testing

Direct shear testing included development of strength envelopes for the two surfaces as well as compression / dilation analysis at 1 psi normal stress. Strength envelopes are shown in Figure 82.

![Shear strength envelopes for Surfaces 1 and 2](image)

**Figure 82**: Shear strength envelopes for Surfaces 1 and 2

The consolidated density of the samples was approximately 1.70 g/cm³. Cohesion values for Surface 1 and 2 was found to be 4.4 psi and 3.8 psi, respectively and friction angles were found to be 39° and 31°, respectively. While cohesion is more or less comparable, the higher friction angle of Surface 1 would suggest that it is stronger than Surface 2, thus it would have more grip. The disparity in strength between the two surfaces becomes greater with increasing normal
stresses due to the $8^\circ$ difference in friction angle. It is likely that the fabric in Surface 1 is contributing to its increased frictional resistance.

Compression / dilation performance was evaluated at a normal stress of 1 psi to evaluate the rebound potential of the surfaces. Figure 83 shows compression / dilation behavior for the two surfaces.

![Figure 83: Compression / dilation for surfaces 1 and 2](image)

It can be seen that Surface 2 exhibits mostly compressive behavior, whereas Surface 1 exhibits fully dilative behavior. This would suggest that Surface 1 may have greater rebound than Surface 2, thus it would be more responsive. Additionally, surfaces that exhibit compressive behavior have been known to have issues during the takeoff phase of the horse-surface interaction; too
much compression without substantial rebound may result in the hoof getting “stuck” in the surface.

5.4.2 – LWD Testing

The LWD was used on both surface materials, and the displacement time histories are shown in Figure 84.

![Displacement Time Histories](image)

**Figure 84:** Surfaces 1 and 2 displacement time histories and sinusoid fits

Impact frequencies are nearly the same for the two surfaces. The main difference in the LWD result is the maximum displacement and the maximum acceleration, which are shown in Table 21.
Table 21: LWD results for surfaces 1 and 2

<table>
<thead>
<tr>
<th>Surface</th>
<th>Displacement (mm)</th>
<th>Maximum Acceleration (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.4</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>11.0</td>
<td>50</td>
</tr>
</tbody>
</table>

The higher displacement for Surface 2 implies that the surface is more compressible, which is in agreement with observations of the direct shear behavior. Lower maximum acceleration for Surface 2 suggests it has a lower impact firmness than Surface 1. It also appears that the magnitude of rebound for Surface 1 is much greater than that of Surface 2, which does not show much rebound occurring. This is in agreement with the results of the compression / dilation testing that also suggest Surface 1 has greater rebound than Surface 2.

5.4.3 – LDA Testing

Results from LDA testing, shown in Figure 85, show similar behavior as the LWD displacement time histories. Each riding surface material was placed to a thickness of 8 cm at a density of 1.10 g/cm³. The sampling rate was 5 kHz and displacement time histories were processed with a 200 Hz low pass filter.
Figure 85: LDA displacement time histories for Surfaces 1 and 2

A summary of LDA test results for the two surfaces can be seen in Table 22. Percent recovery is a measure of the ratio of the rebound to the impact displacement. It can be seen that Surface 2 is more compressive than Surface 1, has a lower maximum acceleration, and has a substantially lower percent recovery.

Table 22: Surfaces 1 and 2 LDA comparison

<table>
<thead>
<tr>
<th>Surface</th>
<th>Displacement (mm)</th>
<th>Impact Time (ms)</th>
<th>Acceleration (G)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.2</td>
<td>13</td>
<td>289</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>10.1</td>
<td>15</td>
<td>237</td>
<td>4.5</td>
</tr>
</tbody>
</table>
The LDA tests show similar displacements as those from the LWD, but much higher maximum accelerations. There could be a combination of factors that explain why the acceleration is very different between the LWD and LDA, including interference of the buffer spring as discussed previously.

The one-dimensional analysis approach from LDA also produces significantly lower acceleration values than those found through double differentiation, and the results are shown in Table 23. The reason may be that the one-dimensional approach assumes a constant acceleration throughout the entire displacement, which may not be representative.

<table>
<thead>
<tr>
<th>Displacement (d)</th>
<th>Accel. (a)</th>
<th>Accel. (G)</th>
<th>Average Force (F)</th>
<th>Average Stress (σ)</th>
<th>Strain (ε)</th>
<th>Modulus (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>m/s²</td>
<td>G</td>
<td>N</td>
<td>kPa</td>
<td>%</td>
<td>kPa</td>
</tr>
<tr>
<td>9.2</td>
<td>325</td>
<td>33.1</td>
<td>1057</td>
<td>135</td>
<td>11.6%</td>
<td>1166</td>
</tr>
<tr>
<td>10.1</td>
<td>297</td>
<td>30.3</td>
<td>967</td>
<td>123</td>
<td>12.6%</td>
<td>976</td>
</tr>
</tbody>
</table>

One-dimensional approach shows that surface 1 has a greater modulus than surface 2, which may have implications for the surfaces strength during takeoff or in cornering.

5.4.4 – Summary

Estimates of the quality of the surfaces functional properties can be made based on the testing conducted by all three instruments. There is much agreement in the conclusions drawn from each test. In fact, all three tests indicate that Surface 1 is less compressive and has more rebound than
Surface 2. Table 24 summarizes how the two surfaces compare on strength, compression, and rebound based on the testing.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Strength</th>
<th>Compression</th>
<th>Rebound</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Higher</td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td>2</td>
<td>Lower</td>
<td>More</td>
<td>Less</td>
</tr>
</tbody>
</table>

Results from the test methods may be used to quantitatively compare functional properties between surfaces. Grip can be related to shear strength: surfaces with higher shear strength have more grip. Impact firmness can be related to the maximum acceleration recorded using either the LWD or the LDA: a surface with higher acceleration has a higher impact firmness. Responsiveness can be related to the compression / dilation behavior from direct shear testing, displacement time histories from the LWD or LDA, and percent recovery from the LDA: more dilation and greater percent recovery indicate a more responsive surface. These proposed methods for evaluating functional properties are shown in Figure 86. Estimations of how the functional properties compare between Surface 1 and surface 2 using these methods are shown in Table 25.
Using direct shear testing and LWD or LDA testing allows for a comprehensive report on an engineered surface, including development of a shear strength envelope, finding the maximum acceleration, and observing trends in the displacement time histories.
6 – SUMMARY AND CONCLUSION

6.1 – Summary

This research project involved investigation into the geotechnical and functional properties of engineered equestrian riding surfaces. Three test methods were conducted: direct shear, lightweight deflectometer and a custom-built laboratory drop apparatus. Tests were conducted on several unique materials both in the lab and at riding arenas around the North Eastern United States. The results of these test methods may be used to redefine three functional properties using measurable quantities instead of qualitative evaluations: grip, impact firmness, and responsiveness.

Case studies conducted as part of this research showed that amending riding surfaces is not straightforward. Functional properties are interdependent on each other and there are clear tradeoffs when adjusting their properties. Thus, the elusive “perfect” riding surface boils down to a desirable balance between grip, responsiveness, and impact firmness, a balance that may vary from rider to rider and sport to sport (for example, training arenas versus international competition arenas). Being able to observe, adjust, and fine-tune this balance is necessary to advancing surface performance and understanding. The methods outlined in the case studies presented in this thesis appear to be capable of observing differences in the shear behavior of riding surfaces. The Coyote Spring Farm case study demonstrated the ability of direct shear testing to distinguish between riding surfaces with different material compositions and helped
develop methods for relating shear behavior to functional properties. Lab experimentation with the Northern New England Farm riding surface showed the sensitivity of riding surfaces to relatively small additions of fiber, fabric pieces, and rubber pieces. Rubber pieces appeared to have the most drastic influence on the shear behavior of the riding surface material to which they were added.

Important findings from this research include:

**Direct Shear**

- Addition of binding agents increases cohesive strength of riding surfaces
- Addition of geosynthetic fabric pieces and fibers increases the frictional resistance of riding surfaces and may make the surface more brittle, and may contribute to the cohesive strength
- Deformation behavior of riding surfaces in direct shear can be organized into three categories: compressive, partially dilative, and fully dilative
- Addition of geosynthetic fabric pieces and fibers may reduce compression by restricting lateral movement of sand grains
- Addition of rubber pieces may decrease compression and increases dilation

**Light Weight Deflectometer (LWD)**

- Surface displacement initially decreases with consecutive load pulses, until the material has been compacted to the point where there is no change in displacement between consecutive load pulses
• Maximum accelerations from LWD tests tended to increase with increasing first pulse displacement due to the relative stiffness between the riding surface and the buffer springs

• The relative stiffness between the riding surface and the LWD buffer springs affects the maximum acceleration. Softer riding surfaces result in less compression of the buffer springs, which results in a shorter load pulse and a higher maximum acceleration than a stiffer surface where the buffer springs compress more

• The influence depth of the LWD is dependant upon the applied stress and the size of the base plate. For the two base plates tested, and under their respective applied stresses, the horse shoe base plate loads the surface with greater stress throughout the top 0.4 m of the profile. Under identical applied stress conditions, the horse shoe plate would be more well suited to isolating the riding surface material. With the 300 mm base plate the LWD exercises the support layers and base grade of an arena, which allows the LWD to tests the entire riding surface profile

Laboratory Drop Apparatus (LDA)

• Constrained modulus may be estimated using one-dimensional conditions, and has been shown to increase with consecutive load pulses due to compaction and densification of the material

• Displacement time histories showed that different riding surface materials have different compression and rebound behavior. Percent recovery of the rebound was calculated as 4.5% for one surface tested and 33% for another.
Functional Properties

- Grip may be defined by direct shear strength envelopes
- Impact firmness may be defined by the magnitude of compression from direct shear tests and by the maximum acceleration values from LWD or LDA tests
- Responsiveness may be defined by the compression / dilation behavior from direct shear tests and by the rebound from LWD or LDA tests

6.1.1 – Recommended Amendment Process

Combining the test methods outlined in this thesis allows for estimating how functional properties change when material composition changes. There are no standard “target values” for the shear or impact performance of riding surfaces that will tell the user if their surface is “good” or “bad”, although this thesis does present general shear behavior performance ranges. Thus, using direct shear testing to amend or remediate a riding surface is a comparative study: how does the original material compare to other riding surfaces? Likewise, when amendments are added to and / or removed from the original surface, how do these proposed surface mixtures compare to the original? Observing changes in shear behavior can help determine potential changes in functional properties.

When undertaking a surface amendment or remediation, the first step is to communicate with the arena owner and riders who use the arena. Communication with the owner and riders is crucial in properly understanding the current state of the arenas functional properties and the performance goal the owner wants to achieve. Perhaps the surface has a performance issue that the owner wants to fix (remediation), or the owner just wants to improve one or more of the functional
properties (amendment). A goal could be, for example, increasing impact firmness or increasing responsiveness.

The next step is to sample the arena surface and begin baseline testing. Direct shear testing is conducted to obtain baseline strength and compression / dilation performance. This should include a shear strength failure envelope (composed of at least three normal stresses, i.e. 15, 25, and 35 psi) and tests conducted at 1 psi normal stress. Other tests can be included as well, such as LWD or LDA testing. The baseline results can be compared to the performance of other surfaces (some of which are outlined in this thesis) for assistance in identifying the potential causes of performance issues and / or areas where the surface performance can be improved. Experimental batches can then be made that incorporate different types and / or quantities of amendments. Amendments should be selected based on how the baseline behavior compares to that of the performance goals. The experimental batches can then be put through the same testing regime as the baseline so that performance comparisons can be made. If the performance goals are not met, the type and quantity of the amendment should be adjusted. If the performance goals appear to have been reached, the proposed solution should be tested by creating a test patch in the arena. The test patch should be evaluated and qualitatively assessed by the arena owner and / or riders. Any outstanding performance issues based on rider feedback can be addressed by adjusting the proposed recipe and returning to lab testing. Figure 87 shows a flow chart of the recommended process when amending or remediating a surface. Changes to the riding surface material composition should be done incrementally. For example, if lab testing and analysis suggest the addition of a certain quantity of a certain component, that component should be added to the arena riding surface in increments, with testing conducted after each addition. Doing
so allows for adjustments to the final quantity of the added component to be made as necessary, or for the progression of changes in riding performance from the additions to be tracked and observed by riders.

Figure 87: Proposed amendment process flow chart

Ultimately, functional properties estimated in the lab through testing must be evaluated by riders, since they are the ones who will be using the surface and can feel differences in surface behavior. The riders should be familiar with the original surface and its performance issues, therefore they should be able to determine if the performance goal has been reached or not.

There are two main advantages to using a controlled remediation / amendment process such as the one proposed here: the ability to fine-tune and experiment with different mixtures, and to potentially avoid costly full-scale procedures that do not turn out as originally intended.
6.2 – Conclusion

Characterizing the properties of riding surfaces is complicated by the wide variability in loading conditions that horses impose on the surface. In order to compare the functional properties of surfaces, repeatable and consistent test methods must be used so that the same loading mechanism is used on all surfaces. Important characteristics of riding surfaces, such as displacement and maximum acceleration during an impact, are dependent upon the magnitude and duration of the load. For this reason, comparing values for displacement or acceleration must be done under consistent load conditions.

Each test method represents just one way of evaluating riding surfaces. The test methods are suggested as potential ways to evaluate and characterize surface behavior under specific, repeatable loading, not as ways to simulate the actual loading a horse may subject to a riding surface.

A few important takeaways from this research include:

1. The geotechnical and functional properties of engineered riding surfaces are sensitive to changes in material composition with the addition of some amendments. Addition of 7.7% by mass rubber pieces resulted in a decrease in compression and increase in dilation for one riding surface material tested.

2. Important characteristics of engineered surfaces obtained from impact testing, such as displacement and maximum acceleration, are dependent upon the magnitude and duration of the load pulse.
3. The test methods outlined in this thesis appear capable of observing changes in material and functional properties. Comparisons between the three test methods revealed good agreement from the results of their individual analysis approaches.

4. Three functional properties, grip, impact firmness, and responsiveness, may be defined by quantitative measurements. The measurements are of physical phenomena closely related to the mechanics of the horse-surface interaction that the functional property aims to describe.
REFERENCES


Novotechnik. 2014. Position Transducer Information Sheet, Series TR/TRS. Novotechnik US Inc. 155 Northboro Road, Southborough MA 01772, USA.


APPENDIX A – LABORATORY DROP APARATUS

Figure A 1: Schematic of potentiometer used for LDA
Figure A 2: LDA potentiometer calibration curve

$y = 9.1634x - 15.114$

$R^2 = 1$

Net Position (mm)

Voltage Output (VDC)

9.05 VDC Input
Figure B 1: Shear stress behavior at different normal stresses for eight unique engineered riding surfaces (from Morganna Mendonca de Souza, 2016)
Figure B 2: Specimen A test data
Figure B 3: Specimen B test data
Figure B 4: Specimen C test data
Figure B 5: Specimen D test data
Table B 1: Direct shear results for Specimen A

<table>
<thead>
<tr>
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<th>Average Shear Strength psi</th>
<th>Standard Deviation</th>
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Table B 2: Direct shear results for Specimen B

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Table B 3: Direct shear results for Specimen C

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Table B 4: Direct shear results for Specimen D

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APPENDIX C – LIGHT WEIGHT DEFLECTOMETER

Figure C 1: LWD test on stone dust base, all three pulses
Figure C 2: LWD test on compacted gravel base, all three pulses

Figure C 3: LWD test on asphalt base, all three pulses
Figure C 4: LWD test on rubber concussion mat, all three pulses

Figure C 5: Pulse displacement versus time, kick wall
Figure C 6: Pulse displacement versus time, quarter line

Table C 1: Example raw output from LWD

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