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Correlations of Fault Rock Constitutive Properties Derived from Laboratory Retrieved Data of the North-Eastern Block of the Southern San Andreas Fault, Mecca Hills, CA via Computational Analysis.

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We aim to characterize fault-structure-related rocks via correlation between the various geophysical characteristics of samples retrieved from the southern San Andreas Fault (SSAF) near the Mecca Hills region in Southern California. Samples from this area were retrieved from the San Andreas Fault Observatory at Depth (SAFOD) near Parkfield, California at a depth of approximately 3km. Core samples of various lithologies were gathered from the borehole and analyzed using various geophysical methods. Emphasis was placed in possible correlations and relationships between varying lithologies and calculated values of unconfined compressional strength (UCS) and cohesion. Using retrieved data from the samples, as well as experimental data from previous experimental laboratory gathered data, values for strength and cohesion were calculated to demonstrate potential rock characteristics at in situ conditions. The geophysical and geomechanical values retrieved from these calculations were then correlated to damage zone dimensions via computational analysis in MATLAB. We also found frictional coefficients and shear strength and their empirical relationship with cohesion and UCS in order to demonstrate fundamental properties in rock strength.
1. Introduction

The San Andreas Fault (SAF) is a major right-lateral fault located in California. The fault accommodated $38 - 34 \, \text{mm yr}^{-1}$ of right-lateral motion with the Pacific Plate moving northwestward past the North American Plate. The fault is comprised of two major distinguishable segments. These segments, which are considered locked, are separated by a central, 150km creeping section. The two segments are comprised of two active shear zones and have proven to produce significant and disastrous earthquakes. The southwest deformation zone (SDZ) and the central deformation zone (CDZ) were the focus of the phase 3 experiments conducted at San Andreas Fault Observatory at Depth (SAFOD). The study, conducted in 2007, retrieved and analyzed the samples from a multilateral core drilling operation. The phase 3 experiment resulted in the retrieval of approximately 31m of core samples from across SDZ and CDZ, as well adjoining damage-zones.

SAFOD is a borehole located near Parkfield, California. The borehole reaches a vertical depth of approximately 2.7km and intersects the SAF at the southern end of a creeping zone that is approximately 150km long. SAFOD is the deepest land-based scientific experiment to intersect an active plate-boundary. Active fault zone observations are crucial to the understanding of the geomechanical nature of large earthquakes.

Recognizing the fault structure and lithologic properties of the studied portion of the SAF are critical to understanding the overall structure and movement of the SAF. This area in particular lies within a zone that displays significant slip deficit (Olsen et al., 2004). Geodetic analysis supports evidence that the southern SAF owes a 5–6m of slip deficit and thus is long overdue for a rupture that will lead to major ground movement (Weldon et al., 2004).

Fault zone architecture is dependent upon elastic-plastic properties comprised of velocity weakening and velocity strengthening materials. Experimental data from core samples retrieved from the deformation zone demonstrate in-situ strength characteristics of the lithology along the fault. Many models have been used to assume correlations of fault zone dimensions and rock rigidity; however, various values of elastic moduli and cohesion are typically not well constrained for fault-related rocks. Furthermore, many of these models rely upon assumptions that use a wide range of values for failure parameters, including cohesion and coefficients of friction in a Mohr-Coulomb condition that can be used to define the failure parameters for a Drucker-Prager plastic yield zone (Evans et al., 2014). The purpose of this experiment is to derive direct correlations of these values in a quantifiable manner that may be used to develop and refine earlier and more accurate predictions of ground motion.

Physical properties, such as shear strength and Young’s modulus, and the relationships between them are crucial to understanding the mechanics of rocks and rock deformation. Shear strength and Young’s modulus are of special interest to understanding rock deformation, as they are the determining factors in quantifying strength in situations of high shear situations such as those observed along faults similar to the SAF. Furthermore, calculations using these two physical values can be used to determine unconfined compressional strength (UCS) and cohesion ($C_o$), which further contribute to our understanding of rock deformation.
Figure 1: Schematic depiction of the study area. a) Geographic location on the borehole with the SAF highlighted as the gray and red line along the coast of California. The creeping segment of the SAF is shown as the gray line segment and the red line segments signify the locked portions of the fault. The locations of large rupture events are also noted on the map. b) Cross-section schematic representation of the main SAFOD borehole geometry (not to scale). The location of the 2007 phase 3 experiments at SAFOD is shown as it crosses the fault zone. General notation of the lithologies near the SAF and Buzzard Canyon Fault (BCF) is also shown. c) Map view schematic of the generalized location of the phase 3 experiments in respect with the SAFOD borehole (located at the origin). The shaded red region signifies the region of fault-related deformation with the red stippling signifying regions of microseismicity occurrences. d) Geophysical borehole log data demonstrated the region of low velocity structure near the fault (Bradbury et al., 2011).
2. Theory

Information was gathered from both core samples collected from the borehole as well as acoustic logs taken from within the borehole. Geophysical acoustic logs were used to gather in-situ geophysical data. The relationship of physical properties such as velocity, Young’s modulus, and friction, with UCS, are typically empirical in nature (Mavko et al., 2009).

Full wave sonic logs were used to measure the acoustic characteristics of a formation. Principle acoustic waves are used in borehole logging to determine the slowness, or the reciprocal of velocity, through the material. In geophysical applications, both the compressional, or P-wave, and the shear, or S-wave types are of particular interest. Simple relationships using the two-way travel time can be used to determine velocity. From velocity, values of shear strength (µ), Lame’s constant (λ), and density (ρ) may be calculated as seen in Equation 1 and Equation 2, below.

\[
V_s = \frac{\mu}{\sqrt{\rho}} \quad (1)
\]

\[
V_p = \sqrt{\frac{K + 4\mu}{3\mu} \frac{\lambda + 2\mu}{\rho}} \quad (2)
\]

Where \( V_s \) is the S-wave velocity, \( V_p \) is the P-wave velocity, \( \rho \) is the density, and \( K \) is the bulk modulus.

In order to collect in situ data of the active fault zone from within the SAFOD borehole, and to further develop more accurate measurements from within the borehole, moduli data collected by Jeppson et al. (2010) was averaged at 100m intervals by Bradbury (2012).

Bradbury (2012) also used geophysical data collected at 15.25cm intervals combined with previous data from Jeppson (2010) to calculate averages for each structural unit within SAFOD. This data was used to determine values for elastic moduli via Equation 1 and Equation 2. Afterwards, using calculated values of \( \lambda \) and \( \mu \), values for Young’s Modulus (\( E \)) and Poisson’s ratio (\( v \)) were calculated using Equation 3 and Equation 4.

\[
E = \frac{\mu(3 \times \lambda \times 2 \times \mu)}{\lambda + \mu} \quad (3)
\]

\[
v = \frac{\lambda}{2(\lambda + \mu)} \quad (4)
\]

Where \( \mu \) is shear strength, \( \lambda \) is Lame’s constant, and \( \rho \) is density.

Typically, correlations between moduli and failure parameters needed for the construction of models are typically developed on a case-by-case occurrence. Particularly in the case of elasticity, these relationships are heavily dependent on specific lithologies and location (Mavko et al., 2009). For our study on the southern SAF, over 30 empirical relationships between UCS and wireline data of \( V_p, \Delta t, v, \rho \), or \( \phi \) (see Mavko et al., 2009; Tables 7.14) were analyzed. The relationship between cohesion and unconfined strength were calculated via a fundamental derivation of empirical relationship between the two values as well as with \( \mu \). This relationship is apparent below in Equation 5.
\[ UCS = 2C_o[(\mu^2 + 1)^{0.5} + \mu] \] (5)

Where \( C_o \) is the cohesion and \( \mu \) is the coefficient of friction.

By using the appropriate empirical relationships to define UCS, we can develop a set of values for cohesion that are more likely to represent the damage zone rocks associated with the SAF.

We derived further correlations between Young’s modulus and the unconfined strength using an empirical relationship from Chang et al. (2006) as well as Zoback (2007). This relationship is specific to “compact shale” which is a lithology that suitably represents the area of study on the SAF. The corresponding relation is apparent in Equation 6.

\[ UCS = 0.0528E^{0.712} \] (6)

Where \( E \) is Young’s modulus determined from the wireline log data.

\[ UCS = 2C_o[(\mu^2 + 1)^{0.5} + \mu] \]

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**Figure 2:** Schematic (not to scale) representation of core sample lithologies and rock deformation. Core Sample 1 was retrieved from Hole E and Core Samples 2 and 3 were retrieved from Hole G. Detailed sample locations and dimensions as well as lithologic and geophysical data are in Appendix A. Samples associated with sample deformation (SDZ and CDZ) are highlighted in red with the dashed red line notating a region of low velocity or a damage zone (Bradbury et al. 2011).

Three sections of core were retrieved from the two boreholes, each corresponding to varying depths. Core Sample 1 was collected from a depth of 3141.4m to 3152.6m from Hole E. Two separate core sections were retrieved from Hole G, Core Section 2 was at a depth of 3186.7m to 3199.5m and contained deformed structure from the SDZ. Core Section 3 was also retrieved from Hole G at a depth of 3294.9m to 3312.7m and contained samples from the CDZ.
3. Computational Analysis

Following the derivation of values for UCS and cohesion, computational analysis via MATLAB models was conducted. In order to conduct the analysis, tabulated data was formatted into Comma Separated Values (.csv) files. From these files, calculations using a variety of scripts based upon the relations noted in Equations 3 - 6 were conducted.

Values for the average in-situ friction coefficient were based upon various results for friction as discovered by Lockner et al. (2011). As expected, active fault regions at the CDZ and the SDZ, had notably low strengths and also had low coefficients of friction. These values ranged from $\mu=0.4$ to $\mu=0.8$ for non-fault deformed areas but in regions where major fault related damage was noted, values of friction at $\mu=0.05$ were conducted for both core sections 2 and 3, where the CDZ and SDZ were located as well as frictional coefficients of $\mu=0.19$ and $\mu=0.16$ for the SDZ in core section 2 and the CDZ in core section 3, respectively.

From the various frictional coefficients, scripts were written in MATLAB to calculate the resulting values of UCS and cohesion. Additional scripts were written in order to plot values of cohesion and UCS versus depth. From the plots, comparison of the resulting UCS and cohesion values could be compared. Also, areas of notable deformation were highlighted in various colors.

4. Calculation Result Plots for Unconfined Strength

As UCS bears a distinct relationship with Young’s moduli, calculation and plotting was straightforward. Three plots were created to display the results for UCS vs depth. Core Sample 1 from Hole E, Core Samples 2 and 3 from Hole G. Figures 4 and 5 display the results of Core Samples 2 and 3, which contain samples from the SDZ and CDZ, respectively.

![Figure 3: Core Section 1 plot of Unconfomed Strength in MPa versus Depth in Meters in the first core section retrieved Hole E of SAFOD. This core section was retrieved from a depth of approximately 3141.4m to 3152.1m. Depths 3141.42 - 3144.6m consist of Sandstone. Depths 3144.6m - 3145.8m consists of Shale and underlying Siltstone. Depths 3145.8 – 3152.6m consists of Sandstone. Core Section 1 did not reveal any significant geomechanical values in relation to fault mechanics.](image-url)
Figure 4: Core Section 2 plot of Unconfined Strength in MPa versus Depth in Meters in the first core section retrieved Hole G of SAFOD. This core section was retrieved from a depth of approximately 3186.7m to 3199.5m. The blue denotes sections of Siltstone. Gray denotes Black Fault Rock. Red Foliated Fault Gauge correlated to the SDZ. It can be noted that the Black Fault Rock section displays a low UCS value.

Figure 5: Core Section 3 plot of Unconfined Strength in MPa versus Depth in Meters in the first core section retrieved Hole G of SAFOD. This core section was retrieved from a depth of approximately 3294.9m to 3312.7m. The first section from 3294.9 – 3296.6 consists of Siltstone. The red section consists of Foliated Fault Gauge (CDZ). The blue section consists of Sheared Siltstone/Mudstone. Depths 3301.5 – 3303.3 consists of Interlayered Siltstone and Sandstone Depths 3307.4 – 3311 consists of Claystone, Mudstone, and Siltstone. Depths 3311 – 3312.7 consists of Claystone and Mudstone gouge. Notice the drop in UCS at the boundary between the Fault Gouge and the Sheared Siltstone/Mudstone.
5. Calculation Result Plots for Cohesion

With cohesion and its relation with friction, calculations for cohesion required the use of multiple sets of data. As a result, 8 sets of data in total were created with 8 corresponding MATLAB models. From the 8 models, plots of each of the 3 core sections were created, which resulted in the creation of 12 plots. For the scope of this report, the plot of Core Section 2 from Hole G was of particular interest, as it contained the greatest amount of fault-related lithologic variety from the SDZ. The values for cohesion based off of the various frictional coefficients were plotted against each other in order to yield the best comparison.

Figure 6: Combined plots of Cohesion for Core Sample 2 from Hole G of SAFOD. This core section was retrieved from a depth of approximately 3186.7m to 3199.5m. The blue denotes sections of Siltstone. Gray denoted Black Fault Rock. Red Foliated Fault Gauge correlated to the SDZ. It can be noted that the Black Fault Rock section displays a low UCS value.

Each plot line denotes a cohesion trend based upon various frictional coefficients. Within the region containing Fault Gauge samples, the upper line denotes cohesion values derived from frictional coefficients 0.5, and the lower line denotes cohesion values calculated with a frictional coefficient of 0.19.

For other regions of the damage zone that were not listed as being directly corresponding to the Fault Gauge, four different values for friction were applied. Again, these were plotted in comparison with each other and the results for Core Sample 2 are displayed in Figure 6. The black line denotes calculated values of cohesion based on a frictional coefficient of 0.8. The blue line denotes calculated values of cohesion based on a frictional coefficient of 0.6. The green line denotes calculated values of cohesion based on a frictional coefficient of 0.5. Lastly, the red line denotes calculated values of cohesion based on a frictional coefficient of 0.4.
6. Discussion

As expected, borehole-derived values for shear and Young’s modulus provided direct correlation with UCS and cohesion.

Cohesion values peaked within areas of significant deformation. Foliated Fault Gouge areas within the SDZ and CDZ displayed drastic spikes in cohesion. Values of ~42MPa to ~53MPa were seen dependent on frictional coefficients. Outside of the fault zone, we see lower cohesion values with values consistently between ~30MPa to ~45MPa.

In the case of unconfined strength, a similar trend with the relationship between cohesion and friction was noted. Fault gouge areas displayed a relatively high UCS, between ~125MPa and ~95MPa for the SDZ and between 100MPa and 80MPa for the CDZ.

Also of note, very low values of cohesion and UCS were calculated for the area neighboring the fault gauge of the SDZ, containing cataclasite. Calculations concerning this section yielded cohesion values between ~11MPa and ~17MPa and values of UCS as low as 45MPa.

Conclusion

Core sample analysis and in situ examination of the SAFOD boreholes revealed a multitude of geophysical values. Prior attempts to develop such correlations used predicted and inferred values to determine the empirical relations. Through this experiment, attempts to reduce fine-scale variability in rock property calculations were tested. From the collected data, of particular use were values of Young’s modulus and shear strength. From this data, we calculated empirical relationships with unconfined compressional strength and cohesion. Correlations of this data were tied directly to lithology as well as geologic dimensions from the borehole. These correlations are of critical importance for their use in understanding the mechanical deformation occurring in fault zones such as the San Andreas.

Acknowledgments

Special thanks to Bryce Mihalevich and his assistance in the writing and compilation of the numerous MATLAB scripts. Thanks also to Beth Shirley for her assistance in proofreading and reviewing this manuscript. Lastly, thanks to Erin Reeder for sharing her knowledge of Adobe Illustrator in the creation of the countless graphics in this manuscript as well as her constant emotional support.

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E.O. Lindsey, Y. Fialko, Y. Bock, D.T. Sandwell, and R. Bilham. Localized and distributed creep along the southern San Andreas Fault. (American Geophysical Union, 2014)


Appendix A: Lithologic and geophysical data for SAFOD Phase 3 Core.

<table>
<thead>
<tr>
<th>Core Interval &amp; Depth (m MD)</th>
<th>Depth (m MD) (ft MD)</th>
<th>Lithologic Unit</th>
<th>Geophysical Properties Averaged over core depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Interval 1 Hole E Runs 1 Sections 1-4</td>
<td>3141.42 – 3144.6 (10306.5 – 10316.8)</td>
<td>Greenish Gray Pebbly Arkosic Sandstone 7.5 % of total core sampled</td>
<td>$V_p$: 5.37 km/s $V_c$: 3.09 km/s $\rho$: 2.59 $\mu$: 23.87 $\lambda$: 31.82 E: 61.27 v: 0.28</td>
</tr>
<tr>
<td>Core Interval 1 Hole E Run 1 Sections 4-5</td>
<td>3144.6-3145.8 (10316.8-10,320.9)</td>
<td>Silty Shale and underlying Siltstone 3.2 % of total core sampled</td>
<td>$V_p$: 5.39 km/s $V_c$: 3.04 km/s $\rho$: 2.65 $\mu$: 20.98 $\lambda$: 30.44 E: 54.78 v: 0.30</td>
</tr>
<tr>
<td>Core Interval 1 Hole E Run 1 Sections 6-8, Run 2 Sections 1-6</td>
<td>3145.8-3152.6 (10,320.9-10,343.2)</td>
<td>Grayish-Red Pebbly Sandstone ~ 16.6 % of total core sampled</td>
<td>$V_p$: 5.00 km/s $V_c$: 2.98 km/s $\rho$: 2.59 $\mu$: 24.28 $\lambda$: 30.64 E: 61.87 v: 0.28</td>
</tr>
<tr>
<td>GAP IN CORE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core Interval 2 Hole G Core Run 1 Sec 1-6 to Core Run 2 Sec 1-3</td>
<td>3186.7-3193.9 (10455.2-10478.8)</td>
<td>Foliated Siltstone-Shale with Block-in-Matrix Fabric ~ 17.5 % of the total core</td>
<td>$V_p$: 4.79 km/s $V_c$: 2.85 km/s $\rho$: 2.57 $\mu$: 21.26 $\lambda$: 17.47 E: 51.68 v: 0.22</td>
</tr>
<tr>
<td>Core Run 2 Hole G Sec 4-5</td>
<td>3193.9-3196.4 (10478.8 -10486.8)</td>
<td>Black Fault Rock ~ 8.5 % of the total core</td>
<td>$V_p$: 3.69 km/s $V_c$: 2.17 km/s $\rho$: 2.59 $\mu$: 11.88 $\lambda$: 11.95 E: 29.4 v: 0.23</td>
</tr>
<tr>
<td>Core Run 2 Hole G Sections 6-9</td>
<td>3196.4-3198 (10,486.8-10,492.3)</td>
<td>Foliated Fault Gouge (SDZ) ~ 3.9% of the total core</td>
<td>$V_p$: 4.32 km/s $V_c$: 2.54 km/s $\rho$: 2.54 – 2.57 $\mu$: 17.25 $\lambda$: 14.41 E: 42.34 v: 0.23</td>
</tr>
<tr>
<td>Core Run 3 Hole G Section 1</td>
<td>3198.4-3199.5 (10,493.5-10,497.2)</td>
<td>Interlayered Siltstone &amp; Mudstone/Shale</td>
<td>$V_p$: 4.04 km/s $V_c$: 2.43 km/s $\lambda$: 11.74 E: 36.49 v: 0.21</td>
</tr>
<tr>
<td>GAP IN CORE</td>
<td>with Block-in-Matrix Fabric</td>
<td>~ 2.7% of the total core</td>
<td>( \rho ): 2.54 – 2.57</td>
</tr>
<tr>
<td>-----------------</td>
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</tr>
<tr>
<td>Core Interval 3 Hole G Runs 4.5.6 Core Run 4 Section 1 to the bottom of Core Run 4 Section 2</td>
<td>Siltstone</td>
<td>~ 4% of the total core</td>
<td>( V_p ): 3.95 km/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \rho ): 2.54 – 2.57</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( \nu ): 0.24</td>
</tr>
<tr>
<td>Core Run 4 Section 2 to the bottom of Core Run 4 Section 5</td>
<td>Foliated Fault Gouge (CDZ)</td>
<td>~ 6.2% of the total core</td>
<td>( V_p ): 3.90 km/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \rho ): 2.54 – 2.57</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( \nu ): 0.18</td>
</tr>
<tr>
<td>Core Run 4 Section 5 to the top of Core Run 5 Section 2</td>
<td>Sheared Siltstone/ Mudstone with Block-in-Matrix Fabric</td>
<td>~ 5.9% of the total core</td>
<td>( V_p ): 3.90 km/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \rho ): 2.54 – 2.57</td>
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<tr>
<td></td>
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<td></td>
<td>( \nu ): 0.18</td>
</tr>
<tr>
<td>Core Run 5 Section 2 to the top of Core Run 5 Section 4</td>
<td>Interlayered Siltstone to Very Fine-grained Silty Sandstone with Block-in-Matrix Fabric</td>
<td>~ 4.4% of the total core</td>
<td>( V_p ): 3.31 km/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \rho ): 2.54 – 2.57</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( \nu ): 0.27</td>
</tr>
<tr>
<td>Core Run 5 Section 4 to the bottom of Core Run 5 Section 7</td>
<td>Sheared and Fractured Siltstone to Very Fine-grained Silty Sandstone with Block-in-Matrix Fabric</td>
<td>~ 6.4% of the total core</td>
<td>( V_p ):</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \rho ):</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( \nu ):</td>
</tr>
<tr>
<td>Core Run 6 Section 1 to the top of Core Run 6 Section 5</td>
<td>Sheared and Fractured Claystone, Mudstone and Siltstone with Block-in-Matrix Fabric</td>
<td>~ 7.8% of the total core</td>
<td>( V_p ): 3.56 km/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \rho ): 2.54 – 2.57</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>( \nu ): 0.28</td>
</tr>
<tr>
<td>Core Run 6 Section 5 to the bottom of Core Run 6 Section 6</td>
<td>Sheared Claystone and mudstone gouge</td>
<td>~ 4.2% of the total core</td>
<td>( V_p ): 3.43 km/s</td>
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<td></td>
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<td>( \rho ): 2.54 – 2.57</td>
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<td>( \nu ): 0.28</td>
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