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California Glacial Till and the Glaciated Valley Landsystem: Engineering Classification and Properties

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CALIFORNIA GLACIAL TILL AND THE GLACIATED VALLEY LANDSYSTEM: ENGINEERING CLASSIFICATION AND PROPERTIES

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by

Matthew M. Lattin

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CALIFORNIA GLACIAL TILL AND THE GLACIATED VALLEY LANDSYSTEM: ENGINEERING CLASSIFICATION AND PROPERTIES

by

Matthew M. Lattin

APPROVED FOR THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

SAN JOSÉ STATE UNIVERSITY

December 2013

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ABSTRACT

CALIFORNIA GLACIAL TILL AND THE GLACIATED VALLEY LANDSYSTEM: ENGINEERING CLASSIFICATION AND PROPERTIES

by Matthew M. Lattin

The engineering characteristics of glacial tills in the Sierra Nevada are difficult to determine due to the depositional nature of the material; however, testing methods unique to these dense materials can be utilized to obtain good engineering data. A literature review was conducted to determine testing methods and recommendations for engineering in glacial till. Further literature review revealed a significant amount of glacial deposits mapped by the USGS and CGS in the Sierra Nevada geomorphic province in California. Sierra Nevada glacial till field and lab data were obtained from Taber Consultants along with samples for further testing. Consequently, four significant conclusions were determined from testing and research. First, it was determined that Sierra Nevada glacial deposits may have large amounts of clay due to neoformation of the local volcanic rockform. As a result, plasticity and compressibility results ranged from low to high. Second, SPT *N* values for matrix material were correlated with depth. Third, unconfined compressive strength results for coarse-grained samples with no cohesive binding were independent of depth. Fourth, the matrix material dominated the engineering behavior of a given glacial till layer.

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to all those who helped me in the completion of this thesis. Special thanks go to my wife for her love and support during the past two years of graduate school and finalizing this thesis. I would also like to acknowledge Taber Consultants and its employees who assisted in research and understanding of geology and soils engineering: Martin McIlroy who has been an inspiration and mentor in the field of Geotechnical Engineering; Frank Taber and Ron Loutzenhiser who have mentored me in the intricacies of foundation design; Glen Wade who spent many hours the past three years assisting in deepening my knowledge of geology in California; and Ray Downes for assisting with soil samples and the understanding of soils testing. Lastly, I would like to acknowledge with much appreciation the role of Professor Laura Sullivan-Green, whose guidance throughout this thesis has been crucial. Without her guidance, review, and support this research would not have been completed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

Glacial till is one of the most common soils found in the Northern Hemisphere, and glacial deposits are one of the most difficult soils engineers encounter (Clarke, Hughes, & Hashemi, 2008). Engineering on glacial deposits is challenging due to the variable nature of the deposits. As a result, geotechnical cross-sections and engineering properties of glacial till can be highly variable and difficult to interpret. This is mainly due to till formed by glacial movement and deposition rather than fluvial or colluvial depositional processes. Trenter (1999) stated that, "Unlike a marine sediment, subject to one-dimensional consolidation during the sedimentation process, the conditions of deposition of a till are particularly complex" (p. 22). Consolidation and deposition complexities are due mainly to little or no sorting by water during the transport of sediment by glacier ice (Trenter, 1999). Using classical soil mechanics theories is challenging because of complex depositional properties associated with glacial till.

Methods of foundation design use the strengths of soils from in-situ and laboratory testing. For example, typical methods for soil bearing capacity analysis use the shear strength of soil determined from the test results of effective cohesion, friction angle, and unit weight. Because some glacial tills are unsorted mixtures of clay, sand, gravel, and boulders, it is much more difficult to determine a representative effective cohesion and friction angle. Unit weights of glacial till samples can be highly variable within the same glacial deposit unit. Engineering judgment must be used when soils are highly variable so that appropriate values for strength, cohesion, friction angle, and unit weight are selected.

Settlement due to soil deformation and consolidation under engineering loads is just as important to evaluate as strength. Short-term settlement occurs immediately upon load application with long-term settlement sometimes taking several years (Bardet, 1997). Typically, if estimates of settlement due to consolidation exceed a tolerable amount, settlement becomes the governing factor in foundation design. Also, settlement characteristics are different for fine-grained soils compared to coarse-grained soils (Bardet, 1997). The majority of settlement for fine-grained soils is long-term, whereas coarse-grained soil settlement is short-term.

Consolidation and shear strength can also be significantly affected if the till is fractured (Allred, 2000). Fracturing in till is closely linked to its depositional process due to the repetitive nature of glacial advance and retreat. The advancement and retreat of glaciers over pre-deposited till causes repetitive loading and unloading of overburden and can trigger fracturing in tills. However, fracturing is not present in all till and is dependent on the type and location of the till.

Shallow foundations are generally suitable in glacial till (Allred, 2000). Because of glacial till's high density and random distribution of soil particle size, particularly boulders, the use of driven piles and sheet piles may not be appropriate (Waltham, 2009). With the increased use of deep foundations in most areas, the most suitable deep foundation may likely be a type of cast-in-drilled-hole foundation. Where shallow foundations are suitable, mat foundations would be the likely choice so as to distribute the foundation's load over the varying soil conditions representative of glacial till.

Prior research concerning glacial till has been completed mainly in the United States, United Kingdom, and Canada. Research in the United States has been localized mostly to the Midwest due to the extent of glacial deposits over larger developed areas. Similarly, the United Kingdom is predominantly developed on glacial till and boasts a large amount of data concerning engineering properties of a wide variety of glacial till deposits. Canada has also experienced large amounts of development on glacial deposits, and considerable research has been completed in more populated areas.

In the Midwest United States, research has been completed by Finno on Chicago Clay (Finno, 2003a). Chicago Clay is a type of glacial till known as boulder clay. Haefner (2000) completed a literature review of the characterization methods of fractured glacial till in Ohio and Indiana. Brockman and Szabo (2000) completed research on fractures in Ohio glacial till. In general, some of the main concerns noted from research in the Midwest United States have been permeability due to the presence of fractures, or lack thereof, and sampling methods.

Research on glacial tills in the United Kingdom was compiled by Trenter, dating back to the 1970s. Trenter's work is the most comprehensive collection of glacial engineering research to date. In his report titled *Engineering in Glacial Tills*, Trenter successfully documented UK tills with respect to geology, engineering classification, engineering properties, site investigations, and various engineering applications. Additionally, engineering characteristics of glacial tills in other parts of Europe have been studied with respect to pile testing.

Little research as to the engineering of glacial till has been completed in California. For the most part, research completed in California concerning glacial till has been from a geologic perspective. As a result, there are three goals to this project. The first goal is to conduct a literature review to identify mapped areas and engineering data of glacial till from previous projects in California. Most of the mapping data gathered are from the United States Geological Survey (USGS) and California Geological Survey (CGS); however, there has been noteworthy research and mapping completed by others. The second goal is to identify semi-empirical relationships between strength and consolidation of glacial tills as compared to other soil parameters. This is mainly due to the depositional and the perceived over consolidated nature of glacial tills. Finally, the third goal of this project is to test known glacial till samples gathered in California and compare to empirical results.

Geology of Glacial Till

To understand the geology of California glacial till, inquiries into the formations of glacial till in general is necessary. Glacial till is mainly encountered in the northern hemisphere due to glacial movement during the Pleistocene Epoch, also known as the Great Ice Age, about 11,700 to 2.6 million years ago. During this time, glaciers advanced and retreated several times in the northern hemisphere (Till, 2013). Depending on the area, different types of glacial till were formed due to the glacial landsystem.

Definitions

Historically, researchers have identified different types of till. Evans, Phillips, Hiemstra, and Auton (2006) compiled common definitions of subglacial till types. Common definitions of subglacial till types are presented in Appendix A. When a definition is available, it will be noted as (Def: n), to denote the definition is available in Appendix A and it is term number n within Appendix A.

Present day surficial features of glacial movement prove to capture what the transport of rock and sediment may have looked like. Surficial features of glacial movement come in the form of distinct glacial deposits and erosion. These are convenient for geologists and engineers to help identify the extent of glacial movement in an area. Definitions of surficial features and erosion due to glacial movement are presented in Appendix A.

Glacial Landsystems

Historically Fookes, Gordon, and Higginbottom (as cited in Trenter, 1999) first introduced the glacial landsystem approach to simplify complex glacial sediment processes. Boulton and Paul (as cited in Trenter, 1999) modified the approach by suggesting that landsystems represented patterns due to glacial elements. Lastly, Eyles and Dearman (1981) developed it further by relating the type of glacier and the glacier bed. Trenter (1999) recognizes the three glacial landsystem types as Subglacial, Supraglacial, and Glaciated Valley. Rockhead (Def: 36), glacigenic sediments (Def: 16), and landform (Def: 26) characterize them. This is important to recognize due to the different types of tills formed by glacial movement. Figures 1, 2, and 3 and Tables 1, 2, and 3 display the distinctions between the three glacial landsystems by the aforementioned characteristics. The numbers located in the tables coincide with the numbers on the figures.

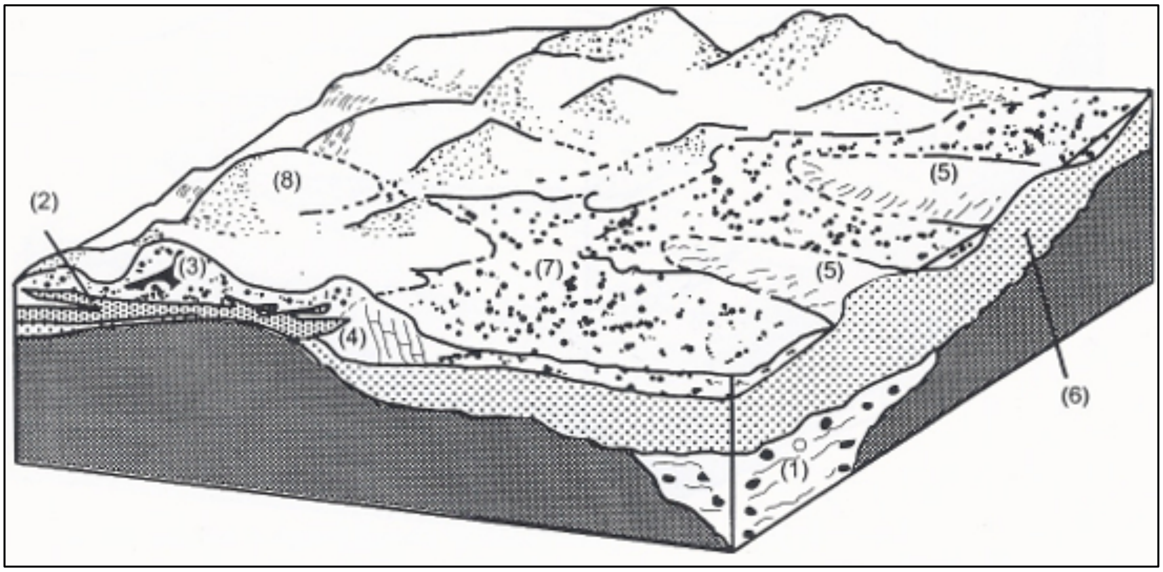

Figure 1. Supraglacial Landsystem Illustrative Example. Reprinted from *Engineering in glacial tills* (p. 30), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Table 1. Supraglacial Landsystem Characteristics. Reprinted from *Engineering in glacial tills* (p. 30), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Rockhead	Glacigenic Sediments	Landform
1. Subglacially cut buried channel, glacigenic debris (Def: 15) filled.	2. Crudely stratified melt-out till formed by meltdown of alternating debris-rich and debris-poor basal (Def: 1) ice with variable preservation of englacial (Def: 9) clast orientation; cobbles and boulders frequent. 3. Flow tills. 4. Strata deforming as a result of meltdown of adjacent ice-cores. 5. Drumlins. 6. Buried lodgement till (Def: 29). 7. Supraglacial melt-out and flow tills.	8. Hummocky (Def: 23) moraine (Def: 31) obscuring streamlined surface of lodgement till.

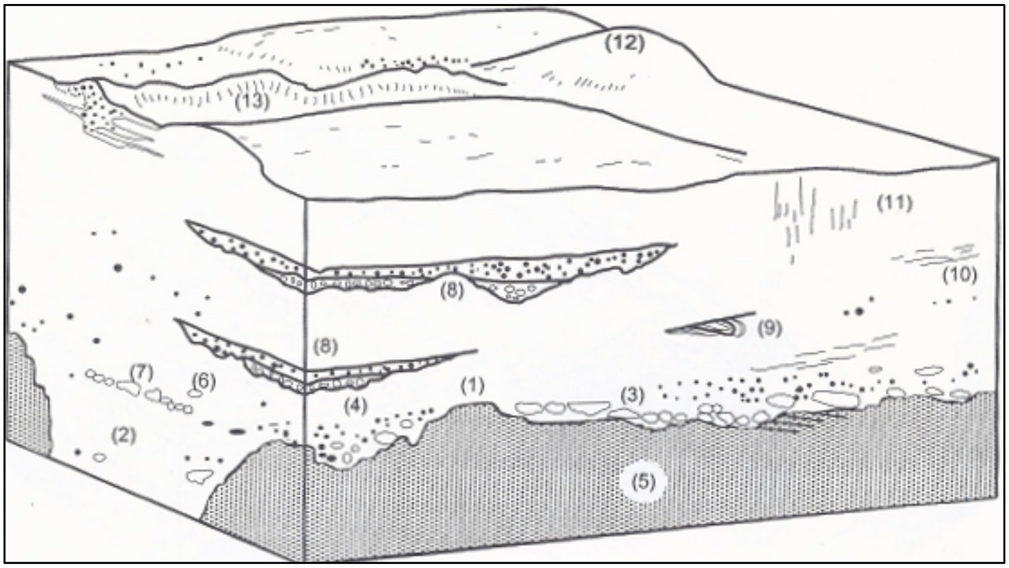

Figure 2. Subglacial Landsystem Illustrative Example. Reprinted from *Engineering in glacial tills* (p. 29), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Table 2. Subglacial Landsystem Characteristics. Reprinted from *Engineering in glacial tills* (p. 29), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Rockhead	**Glacigenic Sediments**	**Landform**
1. Striated (Def: 40) rockhead surface locally overdeepened by subglacial erosion. 2. Buried channel over-steepened by subglacial meltwaters (Def: 30) and filled with subglacially derived sediments. 3. Rock rafts (Def: 35), glaciotectonised rockhead and deformation till (Def: 5) depending on bedrock lithology. 4. Bouldery unit of scree-like (Def: 37) debris filling lee-side cavities (Def: 27) in rockhead surface. 5. Bedrock.	6. Preferentially oriented clast (Def: 2) along axis. 7. Distinct flat iron shaping of clasts composed of fine-grained lithologies; coarse-grained lithologies produce clasts of higher sphericity, frequently found as boulder pavements. 8. Cut and fill fluvial sediments deposited as sand and gravels in interconnected subglacial channels or as laminated clays in subglacial ponds (Def: 43). Lenses of resedimented till may be incorporated into fluvial sediments. 9. Fluvial sediments reworked, deformed, and incorporated in subsequent tills. 10. Slickensided (Def: 38) bedding plane resulting from subglacial shear. 11. Near vertical en-echelon joints (Def: 8) orientated with respect to glacier flow direction.	12. Drumlinised, streamlined, low relief surface. Where rockhead is close to the surface, rock-core drumlins (Def: 7) and crag and tail (Def: 4) landforms may develop. 13. Esker (Def: 10) ridge; a subglacial channel fill that survives as a positive topographic feature not having been sheared off and buried by till.

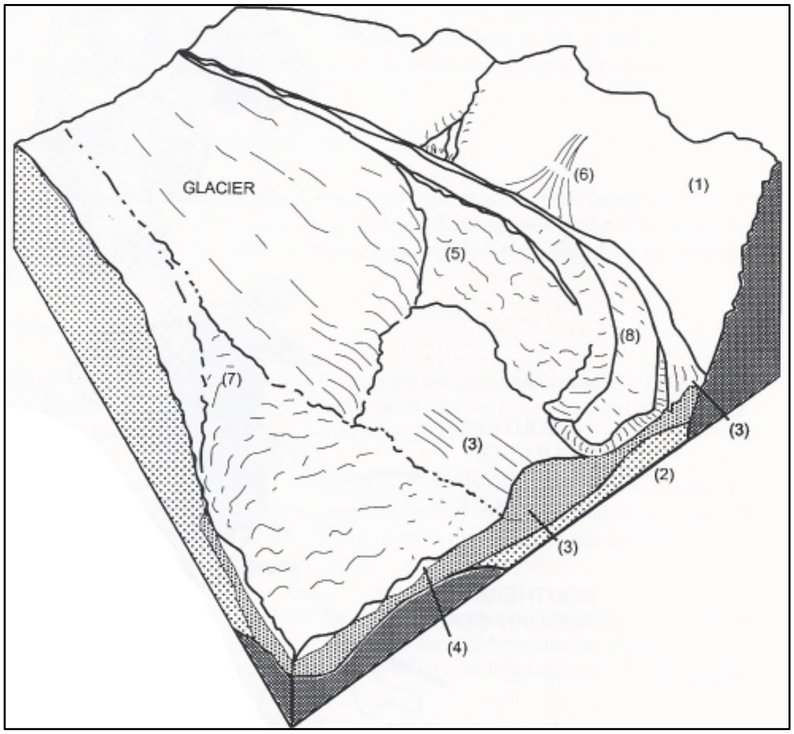

Figure 3. Glaciated Valley Landsystem Illustrative Example. Reprinted from *Engineering in glacial tills* (p. 31), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Table 3. Glaciated Valley Landsystem Characteristics. Reprinted from *Engineering in glacial tills* (p. 31), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Rockhead	Glacigenic Sediments	Landform
1. Striated and polished with roches moutonnées (Def: 33) and oversteepened basins. Loading and unloading due to glacial movements induce stress relief joints, which may be exploited by subsequent frost action. 2. Buried channel filled with glacigenic debris often fragmented from scree avalanched from valley sides and reworked by glacial advance and retreat. Coarse angular cobbles and boulders frequent.	3. Lodgement till often hard or dense with streamlined drumlinised surface containing cobbles and boulders. 4. Thick hummocky sequences of supraglacial melt-out straddle valley floor and overlie lodgement tills in places; coarse debris including far travelled clasts, cobbles, and boulders. 5. Complex glaciofluvial (Def: 17) sediments and flowed tills deposited in kettle (Def: 24) holes or against lateral moraines. 6. Valleyside fans discharging large quantities of coarse debris to lateral moraines.	7. Medial moraine. 8. Lateral moraine ridge.

The Glaciated Valley in California

Alpine Glaciers, also known as Highlands Glaciers, have formed the glacial tills encountered in California. An Alpine Glacier valley can be distinguished by its u-shaped valley appearance. This differs from a valley created by stream erosion, which takes on a v-shaped appearance. Other names for this glacier type have been given in various literature as Confined Glaciers and Mountain Glaciers and are identified as two types, those being valley and cirque glaciers as illustrated in Figure 4. These correspond with the Glaciated Valley landsystem mentioned previously.

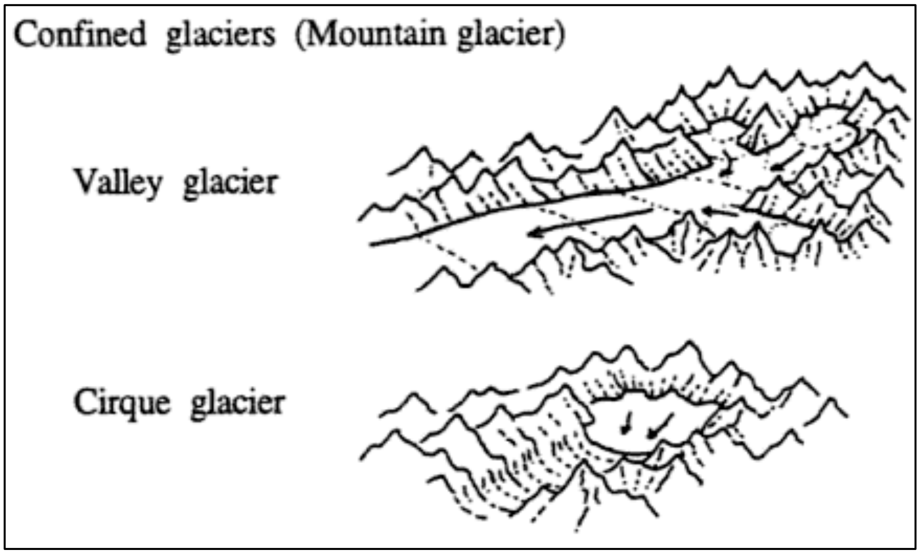

Figure 4. Confined Glacier Types. Reprinted from *Glaciers of California: Modern glaciers, ice age glaciers, the origin of Yosemite Valley, and a glacier tour of the Sierra Nevada* (p. 8), by B. Guyton, 1999, London, England: University of California Press. Copyright 1999 by the Regents of the University of California. Reprinted with permission.

The Glaciated Valley landsystem is unique in that glacial tills were formed at higher elevations compared to tills that were created over larger lower elevation areas, such as those encountered in the Midwest United States. Harden (1998) stated that geologists recognized that during the Pleistocene Epoch, mountain ranges including the

Sierra Nevada, Rocky Mountains, and the Alps of Europe were covered by Alpine Glaciers. Therefore, California glacial tills are unique in that they were derived at high elevations, thusly correlating to the Glaciated Valley landsystem. Three examples of the typical Glaciated Valley landsystem in California are the Yosemite Valley, Tahoe Lake, and areas westerly of Mono Lake located in the Sierra-Nevada, California. These areas have been studied at great depth.

Soils located in the Glaciated Valley landsystem are complex due to fluvial, colluvial, and glacial erosion. For example, during the advancing and retreating of glaciers during the Pleistocene Epoch fluvial erosion changed to glacial erosion during climatic cooling (Brocklehurst, 2002). This change from fluvial to glacial erosion is one major cause of considerable deviations in the lithologies that are seen presently in California tills. These processes of erosion loosen and remove material; however, they are very different processes. Fluvial erosion is related to the flow processes of rivers that erode river channels by water and sediment movement, whereas colluvial erosion is the deposition of sediment by gravity (Plummer, Carlson, & McGeary, 2007). On the one hand, glacial erosion is related to the flow processes of glaciers, which erode soils in a much different manner. On the other hand, deposition of sediments by glacial movement consists of transporting materials that have been trapped within the glacier, fallen on top of the glacier, and gouged from beneath the glacier (Trenter, 1999). Meltwater movement above or below the glacier can also transport glacial sediments (Evans, Phillips, Hiemstra, & Auton 2006). Because these erosional processes are located in the same general area, over time the lithology becomes very erratic.

Lithologies in Glaciated Valleys, although erratic, tend to be made up of the local rockform. In the Sierra Nevada, for example, the rockform is regionally homogeneous granitoids that may have experienced rapid glacial erosion (Brocklehurst, 2002). Similarly, the USGS identifies a wide variety of volcanic rocks in the Sierra Nevada. Brocklehurst (2002) explained that the degree of jointing in bedrock correlates with the amount of glacial debris. In areas such as this it can be expected that the lithology of glacial tills will contain boulders and cobbles originating from volcanic rocks and may be generally clastic in nature.

Till has been mapped throughout California in the Basin and Range, Sierra Nevada, Transverse Ranges, Great Valley, Coast Ranges, Klamath Mountains, Cascade Ranges, and Modoc Plateau provinces (see Figures 5 and 6). Within these provinces mapped areas of Ice Age glaciers are located near the Salmon Mountains, Medicine Lake Volcano, Mount Shasta, Warner Mountains, Castle Crags, Trinity Alps, Lassen Volcanic National Park, Coast Ranges, Sierra Nevada, Sweetwater Range, White-Inyo Mountains, and San Bernardino Mountains (Guyton, 1998). Table 4 shows the USGS unit name and a brief description of each till. The areas displayed in Figure 6 have been mapped by the USGS as Quaternary glacial deposits (Qg) from the Pleistocene age made up of glacial till and moraines. These deposits are located at high elevations mostly in the Sierra Nevada and Klamath Mountains.

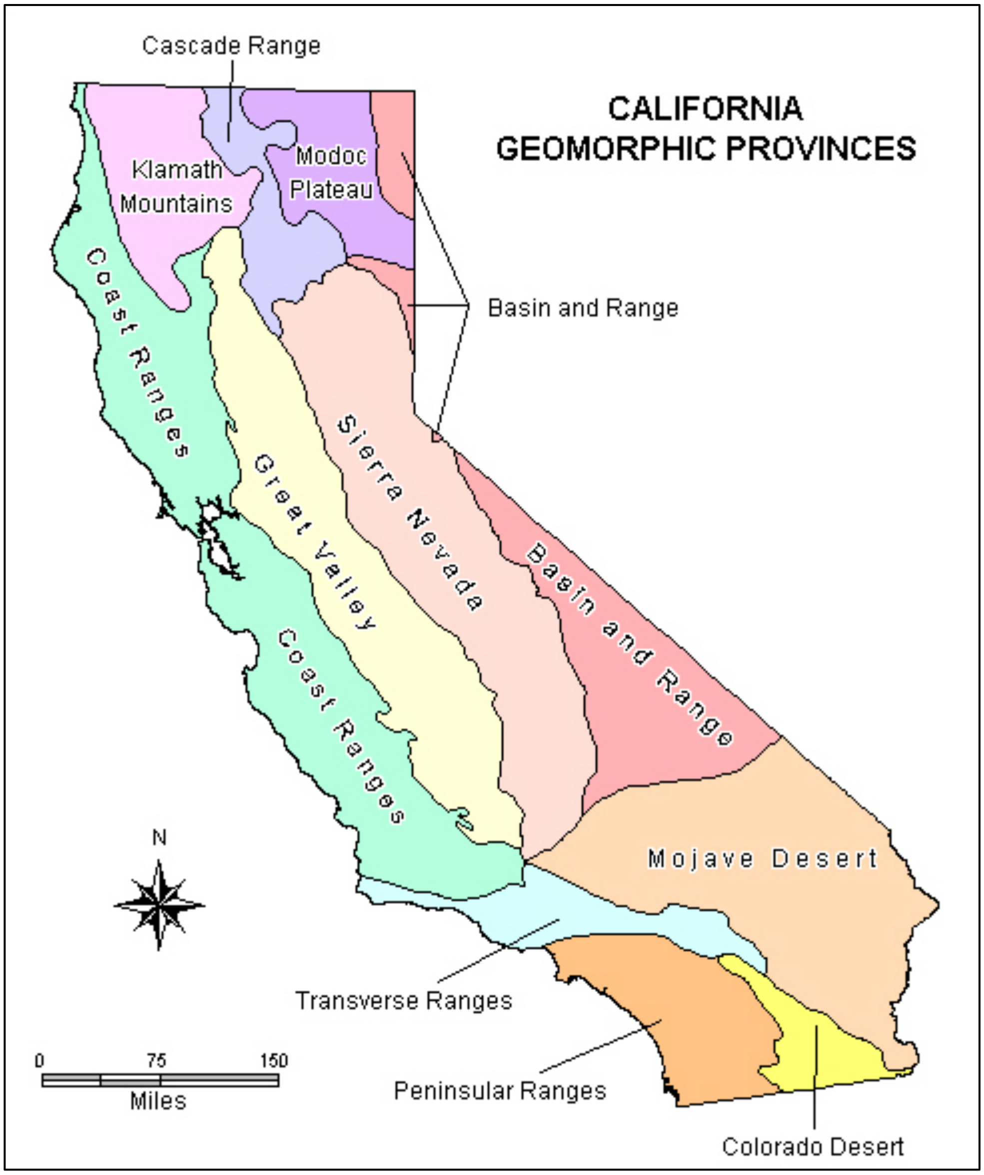

Figure 5. California Geomorphic Provinces (California Geological Survey, 2002)

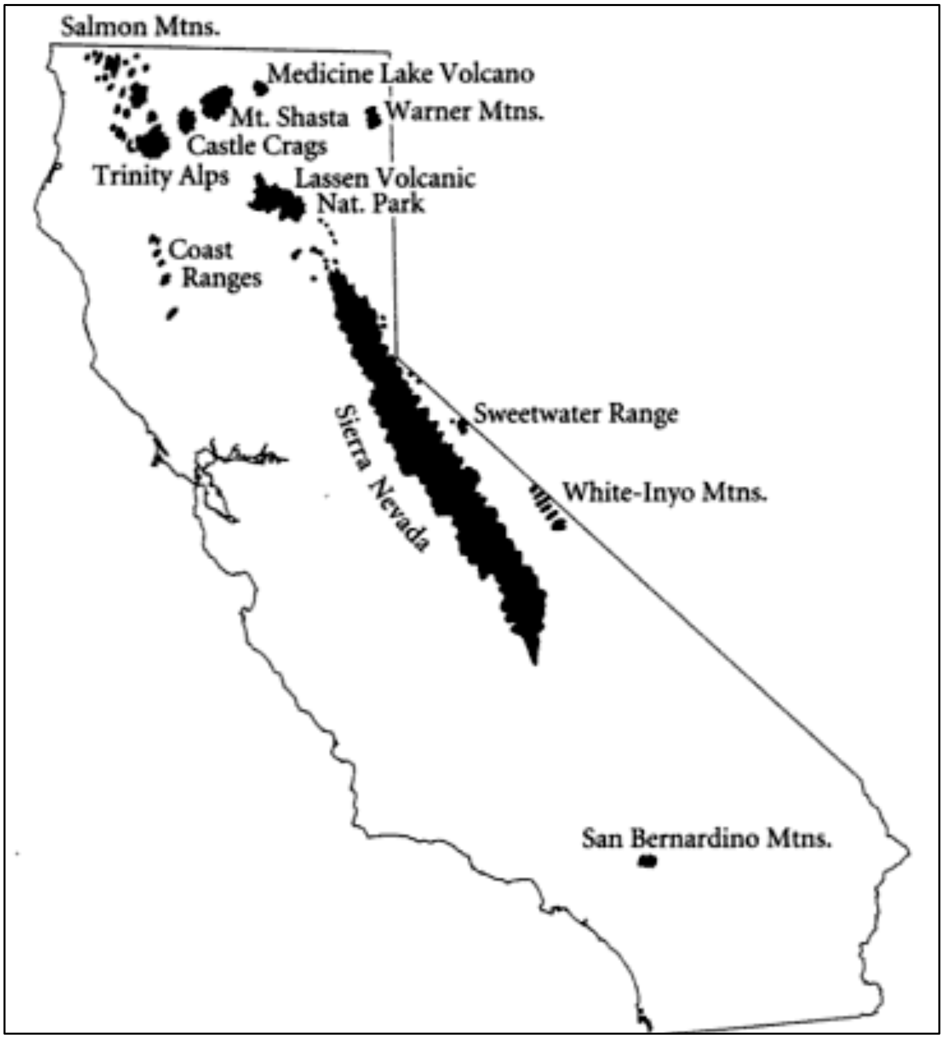

Figure 6. Mapped Areas of Ice Age Glaciers. Reprinted from *Glaciers of California: Modern glaciers, ice age glaciers, the origin of Yosemite Valley, and a glacier tour of the Sierra Nevada* (p. 4), by B. Guyton, 1999, London, England: University of California Press. Copyright 1999 by the Regents of the University of California. Reprinted with permission.

Table 4. California USGS Mapped Glacial Tills

USGS Unit Name	**Description**
Aeolian Buttes Till	From the work of Putnam, (as cited in USGS, n.d.), name abandoned, synonym of Sherwin Till, see Sherwin Till. Crops out on crest of Aeolian Buttes, a low craggy ridge between U.S. Highway 395 and Mono Craters, central CA; also exposed in Mono Craters tunnel, Great Basin province.
Casa Diablo Till	From the work of Curry (as cited in USGS, n.d.), exposures in roadcut, east-central CA, Mono Lake, Sierra Nevada province.
Deadman Pass Till	From the work of Curry (as cited in USGS, n.d.), exposed in Mammoth Lakes area, Devils Postpile quadrangle in Mono and Madera Cos., central CA, Great Basin province. Till is present in vicinity of Deadman Pass .
Donner Lake Till	From the work of Birkeland (as cited in USGS, n.d.), ground moraine exposed in east roadcut of Highway 89 just south of overpass over Highway 40 Freeway, north-central CA, Sierra Nevada province.
Frog Lake Till	From the work of Birkeland (as cited in USGS, n.d.), frog Lake, a cirque lake about 3.5 mi north of Donner Pass, north-central CA, Sierra Nevada province. All deposits are within five-eighths mi of cirque wall and between 7,400 and 7,900 ft in elevation.
Hilgard Till	From the work of Birman (as cited in USGS, n.d.), 1.5 mi downstream from Rock Creek Lake, Inyo Co., central CA. Area of best development is in Rock Creek and upper Mono Creek near 9,000-ft elevation (main valleys). Mount Hilgard is near Sierra Crest, Fresno Co., CA, San Joaquin Basin (Great Valley) province.
Hobart Till	From the work of Birkeland (as cited in USGS, n.d.), ground moraine exposed in Highway 40 Freeway roadcut north end of Truckee, just west of Trout Creek overpass, in south-central part. Named from outcrops in roadcuts along Highway 89 west of Hobart Mills and Highway 40 Freeway north of Truckee, north-central CA, Sierra Nevada province.
Mathes Till	From the work of Curry (as cited in USGS, n.d.), specific location not given, Great Basin (Basin and Range) province (USGS Bulletin 1350)
McGee Till	From the work of Blackwelder (as cited in USGS, n.d.), best exposed on high ridge west of McGee Peak, Mount Morrison quadrangle, Sierra Nevada, central CA, Great Basin (Basin and Range) province.
Mono Basin Till	From the work of Sharp and Birman (as cited in USGS, n.d.), features of the glaciation are visible from U.S. Highway 395 and are shown on US Geological Survey Mono Craters topographic quadrangle of 1953, Sierra Nevada province.
Recess Peak Till	From the work of Wahrhaftig (as cited in USGS, n.d.), upper part of First Recess, near northern base of Recess Peak, Fresno Co., central CA, San Joaquin Basin (Great Valley) province.
Sherwin Till Sherwin Drift	From USGS Bulletin 1200 (as cited in USGS, n.d.), specific location not given, Sierra Nevada province.
Tahoe Till Tahoe Drift	From the work of Blackwelder (as cited in USGS, n.d.), named from Lake Tahoe on eastern slope of the Sierra Nevada, north-central CA, Great Basin (Basin and Range) province.
Tenaya Till	From USGS Bulletin 1350 (as cited in USGS, n.d.), specific location not given, Sierra Nevada province.

Engineering Classification of Glaciated Valley Till

Engineering classification and properties of till are dependent on the type of landsystem (Trenter, 1999). As mentioned previously, the landsystem that can be identified with tills found in California is the Glaciated Valley landsystem. The purpose of this section is to summarize known research concerning the classification of till from the Glaciated Valley landsystem.

According to Trenter (1999), engineering classification of glacial till is broken up into five parts: (1) till fabric, (2) plasticity and particle size, (3) weathering, (4) undrained shear strength, and (5) the correlation between undrained shear strength and SPT *N* value. It was also recommended by Terzaghi, Peck, and Mesri (1996) that the data required to identify a till are color, grain properties, natural void ratio, natural water content, natural unit weight, maximum void ratio, minimum void ratio, and mechanical analysis. This section will cover till fabric, plasticity and particle size, weathering, undrained shear strength, and the correlation between undrained shear strength and SPT *N* value with respect to Glaciated Valley tills.

Till Fabric

The main depositional processes that produce tills are lodgement, melt-out, gravity flow, and deformation, which can be classified as four distinct till types (Trenter, 1999). Each till type can be characterized differently according to the landsystem. Three till types are identified with the Glaciated Valley landsystem: lodgement, melt-out, and flow. See Table 5 for their characteristics (the characteristics of deformation till are also included).

Lodgement, melt-out, and flow tills are associated with two types of till fabric, which are depositional and post-depositional (Trenter, 1999). In this case depositional and post-depositional relate to what was historically described as primary fabric and secondary fabric, respectively. Trenter (1999) argues that attaching primary and secondary to the fabric type could take away from the importance of the engineering behavior of secondary fabric, which could be more characteristic of the soil's engineering behavior.

Table 5. Depositional Characteristics and Relevant Geotechnical Properties of the Four Till Types. Reprinted from *Engineering in glacial tills* (pp. 35-36), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Criterion	**Lodgement Till**	**Melt-out till**	**Flow Till**	**Deformation Till**
Deposition	Deposited by plastering of glacial debris from the sliding base of a moving glacier, by pressure melting, and/or other mechanical processes.	Deposited by a slow release of glacial debris from ice neither sliding nor deforming internally.	Deposition accomplished by gravitational slope processes and may occur supraglacially, subglacially, or at the ice margin.	Comprises rock or unconsolidated sediment detached by the glacier from its source; primary sedimentary structures distorted or destroyed and some foreign material admixed.
Position and Sequence	Lodged over older glacial sediments or on bedrock.	Usually deposited during glacial retreat.	Most commonly the uppermost glacigenic deposit.	Formed and deposited subglacially, often where the glacier moves upslope.
Basal Contact	Formed and deposited at glacier base. Contact with the substratum (bedrock or unconsolidated sediments) generally erosional or sharp. Glacial erosion marks and clast alignment have same orientation.		Variable basal contact but seldom conformable over long distances. Tills may fill shallow channels or depressions.	Variable basal contact.
Landforms	Mainly ground moraines, flutes, and other subglacial landforms.	Those ice-marginal landforms where glacier ice stagnated.	Associated with most ice-marginal landforms.	Land forms rarely diagnostic.

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Criterion	**Lodgement Till**	**Melt-out till**	**Flow Till**	**Deformation Till**
Thickness	Typically one to a few meters thick; relative lateral inconsistency.	Single units usually a few centimeters to a few meters thick. Units may stack to much greater accumulated thickness.	Very variable. Individual flows usually a few tens of centimeters to meters thick. Units may stack to accumulated thickness of many meters.	Varies up to many meters depending upon nature of glacier bed.
Structure	Usually massive but may contain various consistently oriented macro- and micro-structures. Sub horizontal jointing common and vertical and transverse joints may also be present. Orientation of deformation structures related to stress applied by moving glacier and may be laterally consistent.	Either massive, or with faint structures partially preserved from debris stratification in basal debris-rich ice. Loss of volume with melting leads to draping of sorted sediments over large clasts.	Either massive or displaying various flow structures depending on type of flow and water content.	Primary structure may be preserved but usually deformed, especially in upper part of the sequence, which may blend into other massive tills.
Grain Size Composition (MIT Classification)	Abrasion in traction zone during lodgement produces silt-size particles typical of lodgement tills. Most have relatively consistent grain-size composition except for the basal part, which may contain boulders of local glacier bed.	Winnowing of silt and clay-size particles occurs during melt-out. Some particle size variability inherited from debris bands in ice. Supraglacial melt-out tills of valley glaciers contain characteristic coarse-grained debris.	Usually diamicton (Def: 6) with polymodal particle size distribution. Some particle size redistribution and sorting may occur during flow. Inverse or normal grading may develop.	Deformation tills derived from weak rocks contain clasts separated by minor amounts of finer matrix. Clast size reflects bedding thickness of original material.

Table 5. Depositional Characteristics and Relevant Geotechnical Properties of the Four Till Types. Reprinted from *Engineering in glacial tills* (pp. 35-36), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Criterion	**Lodgement Till**	**Melt-out till**	**Flow Till**	**Deformation Till**
Lithology of Clasts and Matrix	Lithological composition often more consistent than other tills. Composition of matrix particularly uniform. Materials of local derivation increase in abundance towards basal contact.	Supraglacial melt-out till more variable in composition with increased possibility of exotic material.	Lithological composition generally same as source material. May include incorporated glacier bed or exotic materials depending on debris source, transport, and deposition.	Deformation tills generally have same lithological composition as underlying sediments. Occasional erratics present particularly in upper part of sequence.
Clast Shapes and Their Surface Marks	Subangular to subrounded clasts. Bullet-shaped, faceted, crushed, sheared, and streaked-out clasts more common in lodgement than other tills. Lodged clasts striated parallel to direction of the lodging movement.	Variable degree of roundness but angular clasts occur where supraglacial melt-out debris is englacially or supraglacially derived.	If present, soft sediments clasts may be rounded or deformed by shear. More resistant rock clasts will retain their original shape.	Clast shape and surface marks generally inherited from original material and not diagnostic. Clasts generally transported passively and not significantly modified.
Fabric	Strong macro fabric with clast long axes parallel to local direction of movement. Transverse orientation possible, associated with folding and shearing.	Fabric inherited from glacier transport. Melt-out process may weaken fabric, particularly micro-fabric.	Fabric may be random or strongly developed and parallel or transverse to flow direction. Fabric may vary laterally over short distances.	Preferred orientation rare and generally reflects shearing deformation.
Consolidation Permeability Density	Over-consolidated if adequately drained. Bulk density, penetration resistance, and seismic velocity usually higher, whilst permeability low, relative to other till types.	Melt-out tills less over-consolidated than those formed subglacially. Bulk density and penetration resistance lower and more variable than lodgement till. Permeability more variable.	Usually normally consolidated and relatively permeable. Density lower than in lodgement tills.	Variably consolidated. Low densities reflect dilatancy due to continuous glacial shear stress.

With respect to the Glaciated Valley, the depositional fabrics associated with melt-out and flow tills according to Trenter (1999) are:

- Particle Size (MIT classification): Matrix to clast supported, fine- to coarse-grained
- Clasts: Poorly orientated, gravel to boulder size

Likewise, the depositional fabrics associated with flow tills according to Trenter (1999) are:

- Particle size (MIT classification): As lowland flow tills, but coarser
- Sedimentary slump structures

Lastly, the depositional fabrics associated with lodgement tills according to Trenter (1999) are:

- Particle size (MIT classification): Matrix to clast supported, fine- to coarse-grained
- Clasts: Highly orientated, gravel to boulder size, bulleted and streaked-out in direction of ice flow
- Discontinuities: Sub-horizontal shear induced joints and fissures

In general, Glaciated Valley till fines has low clay content and coarse-grained materials range from sand to boulders.

Trenter (1999) explains post-depositional fabric and stress relief mechanisms with respect to the Glaciated Valley landsystem. Stress relief would alone affect lodgement till in Glaciated Valleys by post-depositional groundwater changes and freeze-thaw stress relief mechanisms (Trenter, 1999). Essentially, Trenter explains that advancing ice created fissures or joints sub-horizontally and stress relief occurred during glacial retreat. Trenter (1999) goes on to state that this would only be found in matrix-supported Glaciated Valley tills.

The work of McGown and Derbyshire (as cited in Trenter, 1999) proposed a genetic classification method for tills specifically for geotechnical purposes, see Table 6. With respect to genetics in classifying glacial soils, Bennett, Waller, Glasser, Hambrey, and Huddart (1999) states that clast fabric can be used as a genetic fingerprint to distinguish glacigenic diamictons of unknown origin. McGown and Derbyshire's method focuses on the genetic classification and the dominant soil fraction and characterizes the till by relative geotechnical parameters.

Table 6. Characteristics and Geotechnical Properties of Glacial Tills. Reprinted from *Engineering in glacial tills* (p. 69), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

				Relative Scales (1 low to 9 high)			
Till	**DSF[1]**	**Fabric Features**	**OCR**	**Density**	**Compressibility**	**Permeability**	**Anisotropy**
Lodgement	G	Macro: Interlaying of glaciofluvials, joints, fissures, contortions. Consistent preferred clast orientation. Meso: Fissuring. Contortion. Moderate to very high consistency of preferred orientation clasts. Micro: Moderate to high degree of parallelism of fines in sympathy with clast surfaces.	2-5	4-7	1	5-6	7
	W			5-8	2	2-3	
	Mg			6-8	2	4-5	
	Mc			6-8	3	2	
Melt-Out	G	Macro: Occasional interlaying with glaciofluvials. Clast preferred orientation often retained from englacial state. Meso: Moderate to high preservation of preferred clast orientation from englacial state, especially in subglacial type. Micro: Open to moderately closed arrangements of fines with many englacial arrangements retained, especially in subglacial type.	1-2	2-4	2-4	7-9	3-5
	W			2-6	3-5	4-5	
	Mg			2-6	3-6	5-8	
	Mc			2-7	4-7	3-4	
Flow	G	Macro: Interlaying with glaciofluvials common. Segregation, contortions, layering and fissuring in upper section and nose of flow. Meso: Aligned low angle orientation of clasts conforming to flow direction rather than ice direction. Micro: Rather compact parallel arrangement of fines related to flow rather than direction of ice movement.	1-2	3	2	7	7
	W			4	2-4	4	
	Mg			5	2-4	6	
	Mc			5	2-5	3	
Deformation	G	Total Fabric: Deformed bedrock structures related to ice movement direction.	1	5	3	5-8	No value given
	W						
	Mg						
	Mc						

---

[1] DSF=Dominant Soil Fraction, G=Granular or clastic soil, W=Well graded (poorly-sorted), Mg=Granular matrix, Mc= Cohesive matrix

Trenter (1999) rationalized that the most important identifying features of tills are their particle size distribution and fabric. From Table 6, the dominant soil fraction (DSF) can be identified in different proportions according to the type of till, revealing the importance of particle size distribution in this classification method. This method also puts emphasis on identifying the type of till and its fabric features.

Fabric was defined by Derbyshire, McGowan, and Radwan (1976) as the summation of all the directional properties of a till, which includes clasts, layers, lenses, fissures, cracks, and joints. Referring to Table 6, fabric features are divided into three main groups of macro, meso, and micro. Macro fabric features are defined as the overall clast orientation. Meso fabric features are defined as the consistency and preservation of the clast. Lastly, micro fabric features are defined as the arrangement of fines.

The McGown and Derbyshire approach has been referenced in many reports and has proved to be a good method to obtain engineering information for glacial tills. Trenter (1999) states that the use of the McGown and Derbyshire classification (Table 6) allows for relative engineering information concerning tills. Even though this method of interpretation uses relative scales, it is very useful in understanding some engineering properties of glacial soils. Essentially, Table 6 suggests that the over consolidation ratio, density, compressibility, permeability, and anisotropy of glacial tills directly relate to the glacial till's type and grain size distribution.

Plasticity and Particle Size

Plasticity and particle size of Glaciated Valley tills in California are subject to collection methods. However, correlations can be determined from Glaciated Valley characteristics in other parts of the world. As mentioned previously, a wide range of particle sizes may be expected with Glaciated Valley tills, with generally little clay content (Trenter, 1999). Furthermore, fine soils that are found in Glaciated Valley tills may be partially made up of rock flour (Def: 34) that ranges in particle size from clay to silt. This can alter the overall plasticity of fines content because rock flour has little to no plasticity.

Rock flour is non-plastic or very slightly plastic because it is made up of very fine grains of the local bedrock created from the grinding action of lodgement till and glaciers on bedrock (Trenter, 1999). Rock flour is essentially a type of silt that has a specific origin from glacial deposition. The main difference is the particle size. Rock flour originates from the local bedrock and its particle size can be in the clay range.

Glaciated Valley tills in the UK show similar characteristics based on plasticity. Clay-matrix-dominant till water content may vary; however, on a Casagrande plot the values tend to cluster in a specific area. The area where they cluster is known as the T-line, Equation 1, which is parallel and above the A-line (see Figure 7 below).

$$PI = 0.73(LL - 11) \tag{1}$$

Where PI is the plasticity index and LL is the liquid limit. Trenter (1999) suggests that the plasticity of Glaciated Valley lodgement till in the UK is low to high (w_L = 20-50%) and the liquid limit increases with decreasing grain size.

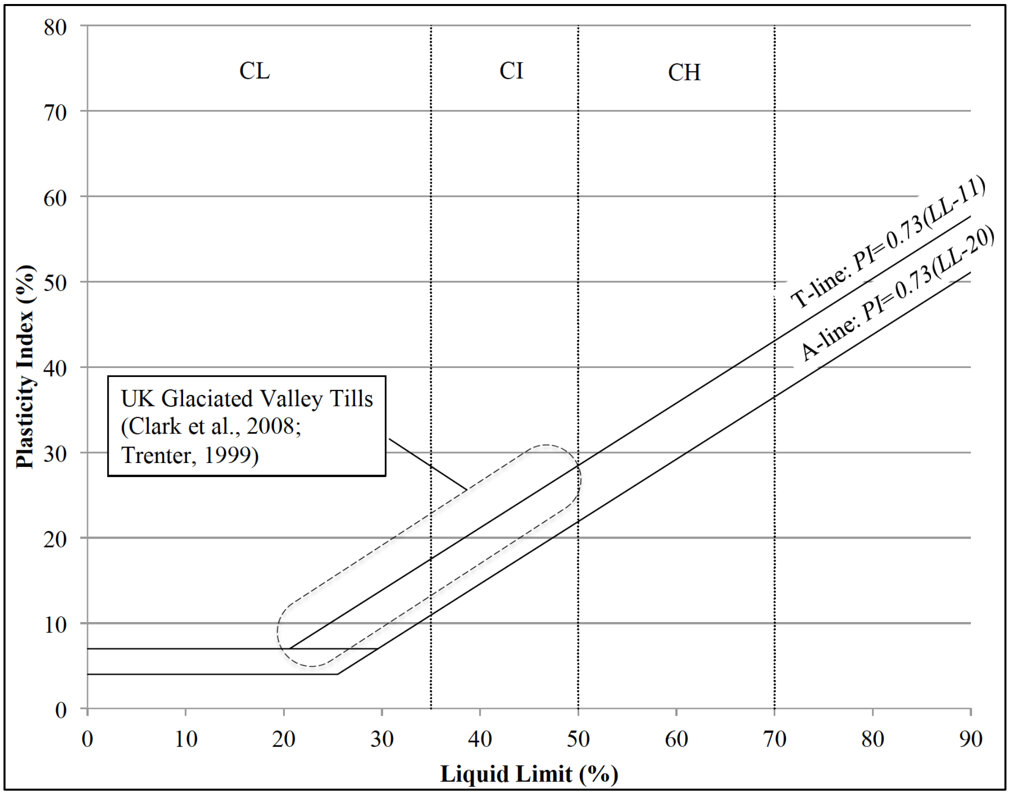


Figure 7. Idealized Plasticity Characteristics of Glaciated Valley Tills

Plasticity tests on glacial tills in other parts of Europe have also yielded similar characteristics as those previously mentioned. According to Boulton (as cited in Clarke, et al., 2008), UK tills that are clay-matrix-dominant tend to cluster about the T-line. Bell (2001) discovered similar conclusions in studying the geotechnical properties of till deposits along the coastal areas of Eastern England. In general, it is common practice and a good assumption that in the UK the T-line concept is valid.

J. Constantinescu and D. Constantinescu (2011) also completed research concerning the T-line distribution of till in the Midwest United States. Their results yielded the same distribution of tills along the T-line. The results of mineralogical research completed by J. Constantinescu and D. Constantinescu on the T-line concept revealed factors affecting the plasticity of tills. Essentially, they concluded that all fine glacial materials can be found along the T-line, but a single factor cannot explain this phenomenon, rather a synergetic association of factors. They suggest that these factors include the presence of fine powders (rock flour) and relatively inert clay minerals (kaolinite), the ratio of closed intergranular pores versus open intergranular pores, and grain-size distribution. These factors, J. Constantinescu and D. Constantinescu remarks, are caused by the subglacial mechanism of crushing and grinding. Clarke et al. (2008), concerning the T-line concept, also concluded that glacial till composition across Europe was similar due to successive periods of glaciation that widely distributed the source material.

Generally, there has been a significant amount of research completed proving the T-line concept for soils of glacial origin in Europe. As far as California glacial tills are concerned, no known research has been completed to correlate the distribution of tills along the T-line. This phenomenon will be evaluated with California glacial tills in this work.

Weathering

Weathering should be mentioned, especially with Glaciated Valley tills, due to the propensity of high fluctuations in groundwater. According to Eyles and Sladen (as cited in Trenter, 1999) weathering is caused by oxidation followed by leaching of carbonates. Color change, rotten boulders, and gleying (Def: 22) should be evident in weathered zones. As a result, Eyles and Sladen determined that clay and moisture content increase with the degree of weathering and Atterberg Limits are highly erratic in a single weathered zone. It was also determined that shear strength parameters are highly erratic in weathered zones.

In some soils, such as glacial tills, weathered zones can be classified as a material in-between rock and soil. O'Neil and Reese presented cohesionless Intermediate Geomaterials (IGMs) in AASHTO Section 10.8.2.2.3 to describe granular tills with $N1_{60}$ values greater than 50 blows/ft. Of all the research that has been completed, little conclusive engineering practice can be determined in these materials. Johnston and Novello (as cited in Brooks, 2008) defined an IGM as residing at the center of the continuum between soil and rock. Brooks (2008) goes on to suggest that IGMs are either soil that has been strengthened or rock that has been weakened. IGMs are essentially an intermediary in the geological cycle, therefore having no well-defined soil or rock description. Therefore typical engineering practice in IGMs would require classifying tills as either soil or rock to gain useful data.

Some indicators of IGMs in a given soil profile are cementation or weathering. Cementation is the process of soil strengthening whereas weathering is the process of rock weakening (Brooks, 2008). Cementation in tills can be formed by diagenesis, which is a physical, chemical, or biological change in the sediment causing bonding to form (Bates & Jackson, 1984). Bates and Jackson also suggest that weathering is strength reduction in rock by mechanical or chemical actions. Evidence of mechanical weathering are joints and fissures, whereas evidence of chemical weathering are dissolution, hydrolysis, oxidation, and carbonation (Brooks, 2008).

Clay minerals are formed in the chemical weathering process of rock decomposition (Plummer et al., 2007). Plummer states that clay minerals are generally hydrous aluminum silicate. Therefore, this process can be associated with rock that is made up of silicate minerals, such as igneous rocks. Igneous rock, such as granite, is abundant in the Sierra Nevada ranges (Brocklehurst, 2002). This suggests the possibility of large amounts of clay layers in Glaciated Valley tills in the Sierra Nevada.

Undrained Shear Strength

With respect to saturated soils, shearing resistance is realized at constant volume; therefore, water content does not change (Terzaghi et al., 1996). Furthermore, Trenter (1999) deduces that the undrained shear strength is an index rather than a geotechnical property because it is not a unique feature of a given soil. This index is also highly dependent on the sampling method and testing. As a result, caution should be taken in the use of this soil index due to its limitations.

Terzaghi et al. (1996) states that the most extensive experience concerning the mobilization of undrained shear strength is with soft clays and silts and with loose sands. Furthermore, Trenter (1999) states that the design purpose must be clear in order to use an undrained shear strength value. For example, where unloading causes stress relief that may lead to less water content, strength prior to construction may be much greater (Trenter, 1999). Essentially, if there are changes in the natural water content due to construction the undrained shear strength may differ prior to construction.

Correlation Between Undrained Shear Strength and SPT *N* Value

Recovering samples in glacial till can be difficult. Since Standard Penetration Test (SPT) *N* values are a standard method used in most field investigations, reasonable correlations between it and undrained shear strength may be appropriate. Stroud and Butler (as cited in Trenter, 1999) examined the use of correlations between undrained shear strength and SPT *N* values that resulted in the following equation:

$$c_u = f_1 \, x \, N \text{ (kN/m}^2\text{)} \tag{2}$$

Where c_u is the undrained shear strength in kN/m^2, N is the uncorrected SPT blowcount, and f_1 is a factor depending on till plasticity. Trenter (1999) reported low plasticity tills tested at twelve sites in the UK (where PI≤25) that resulted in an average f_1 value of 5.2. However, Trenter also included data from other test sites in the UK that resulted in great variability in the f_1 value.

Great caution should be taken concerning this method of correlating undrained shear strength with SPT *N* values. Trenter (1999) suggests that the best use of this approach is site-specific where only SPT *N* values are available in some boreholes and there is good strength data obtained elsewhere. Undrained triaxial data to correlate with SPT *N* values is essential in using this correlation for design purposes. Furthermore, this SPT method defined in Equation 2 can only be used in tills that are clast-dominant.

Engineering Properties of Glaciated Valley Till

According to Trenter (1999), engineering properties of glacial till consist of the drained peak shear strength, residual shear strength, coefficient of permeability, coefficient of consolidation, compressibility, and deformation modulus. In this section some of these engineering properties will be discussed along with depositional processes associated with the Glaciated Valley landsystem.

The engineering properties of till can differ greatly according to the particle distribution, i.e. whether the till is matrix- or clast-dominant. Furthermore, the engineering properties of matrix-dominant till are almost completely contributed by the clay and silt fraction (Weltman & Healy, 1978). As seen previously in Table 6, tills can be differentiated by four texture categories of granular, well-graded (poorly sorted), granular matrix, or cohesive matrix. An increase in granular content past 40% results in an increase in strength (Trenter, 1999). Therefore, there is a noted increase in strength in clast-dominant tills and granular matrix tills.

Drained Peak Shear Strength

Glaciated Valley tills are typically coarse-grained in the UK and can be correlated to rock fill according to particle size distribution and maximum particle size (Trenter, 1999). Charles and Watts (as cited in Trenter, 1999) proposed the following relationship between shear strength, τ, and normal effective stress, σ', for rock fills:

$$\tau = A(\sigma')^b \tag{3}$$

Where A and b are constants. Table 7 shows the results of 225-mm diameter triaxial tests completed by Charles and Watts (as cited in Trenter, 1999) on rockfill. Using this correlation on a site-specific basis may be appropriate to Glaciated Valley tills in California that are classified as coarse granular tills with little to no plasticity.

Table 7. Results of Large Triaxial Tests on Rockfill. Reprinted from *Engineering in glacial tills* (p. 87), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Rockfill Type	**Relative Density**	***A***	***b***
Sandy Gravel	0.95	4.4	0.81
Weak Rockfill	0.95	4.2	0.75
Weak Rockfill	0.70	1.4	0.90

Referring to Equation 3, this relationship is a power function where the constants *A* and *b* are determined by a regression line fit to a good spread of data. The test results, as presented in Table 7, may not be indicative of all Glaciated Valley tills. However, the relationship may be appropriate on a site-specific basis where there is a large spread of data results from direct shear tests. This relationship will be evaluated with California glacial tills in this work.

Coefficient of Consolidation

Terzaghi et al. (1996) presented the coefficient of consolidation, c_v, as:

$$c_v = \frac{k_v}{\gamma_w m_v} \tag{4}$$

Where k_v is the coefficient of permeability, γ_w is the unit weight of water, and m_v is the coefficient of volume compressibility. The coefficient of consolidation is highly dependent on the testing method and is one of the most difficult properties to measure in tills (Trenter, 1999). Furthermore, consolidation characteristics are principally determined by clay content (Bell, 2001). Since Glaciated Valley tills are characteristic of low clay content, consolidation may be governed by clasts of coarse material and show great variability.

Compressibility

Similar to consolidation previously discussed, the compressibility characteristics of tills are determined by their clay content (Bell, 2001). Again, Bernell (as cited in Trenter, 1999) presented information concerning the same remolded tests on Swedish glacial moraines previously discussed. For low compressibility tills of low clay content, the compression index, $C_{c,}$ was suggested by Bernell as:

$$C_c = 0.0044 f_s + 0.003 \qquad (5)$$

Where f_s is the percentage of material finer than 6μm. From Bernell's research it was determined that tills with clay content less than 2.5% indicated $C_c = 0.01$.

Trenter (1999) lists various testing that was completed by others concerning the compressibility of tills. Several compressibility equations were determined in areas known for till in Canada, the United States, and the UK. Correlations between the compressibility index and Atterberg Limits was derived from the listed research and are presented in Equations 6 to 9 below. Equation 6 below was proposed by Singh, Tatuiussian, and Flagg (as cited in Trenter, 1999) after testing on Milwaukee area soils.

$$C_c = 0.005\ PI\ G_s \qquad (6)$$

Where G_s is the particle specific gravity assumed to be a typical value of 2.67, Equation 7 becomes:

$$C_c = 0.013\ PI \qquad (7)$$

Gregory and Bell (as cited in Trenter, 1999) proposed the following from oedometer tests in Belfast tills:

$$C_c = 0.004\ (LL - 5) \qquad (8)$$

Lastly, Sauer, Egeland, and Christiansen (as cited in Trenter, 1999) presented the following equation from tests on six different tills in Saskatchewan, Canada:

$$C_c = 0.005\ LL \tag{9}$$

Bardet (1997) also gives typical values and equations for the compressibility index of clays. Terzaghi and Peck (as cited in Bardet, 1997) introduced the following correlation, which is still widely used for some clays:

$$C_c = 0.009\ (LL - 10) \tag{10}$$

Furthermore, Wroth and Wood (as cited in Bardet, 1997) showed:

$$C_c = G_s \frac{PI}{200} \tag{11}$$

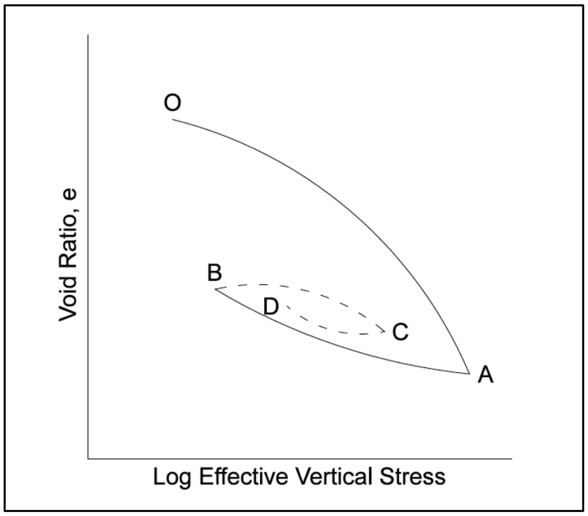
Where *PI* is the plasticity index of the soil. Assuming a typical particle specific gravity, G_s, of 2.7 Equation 13 becomes:

$$C_c = \frac{PI}{74} \tag{12}$$

When you take into consideration tills on a site-to-site basis, the fact that there is such variability from one till to another should be a warning. Considering Equations 5 to 10 there is great variability from one equation to another, indicating that there is no viable option to consider for all Glaciated Valley clay tills because of the varying constants. Trenter suggests that the above reported Equations 5 to 9 should be used on a site-specific basis. Equations 10 to 12 in tills may not be reliable for this work since they are based mostly on clays of non-till origin.

Other Factors

The effects of depositional processes on Glaciated Valley tills include ice and water movement (Trenter, 1999). In Glaciated Valley tills there is a possibility of high consolidation due to these depositional processes. However, one must be careful in assuming the mode at which overconsolidation occurred. Bell (2001) inferred that the assumptions presented for the overconsolidation of tills might not be entirely accurate. Trenter depicts the process of depositional and post-depositional consolidation in Figure 8 where line OA represents consolidation under the weight of ice, line AB represents swelling as ice wastes, line BC represents consolidation due to the lowering of groundwater, and line CD represents swelling due to the rise of groundwater.



OA: consolidation under the weight of ice.

AB: swelling as ice wastes

BC: consolidation due to the lowering of groundwater

CD: swelling due to the rise of groundwater

Figure 8. Graphic Representation of Depositional and Post-Depositional Processes for Glaciated Valley Tills. Adapted from *Engineering in glacial tills* (p. 89), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Adapted with permission.

The tendency is to assume that overconsolidation was attributed to overburden from thick ice layers over time. However, Boulton and Paul (as cited in Bell, 2001) suggest that pore water pressures can develop if there is no drainage. This absence of drainage is a common feature of some tills that are dense with little to no fracturing. With no drainage, the gathered pore water pressure counters the overburden pressure due to the overlying ice, resulting in less overconsolidation than originally assumed (Bell, 2001). Because of this, testing a sample in these conditions would result in misleading consolidation test results. Since consolidation tests are completed under free drainage conditions, estimates of consolidation would be much greater due to pore water dissipation.

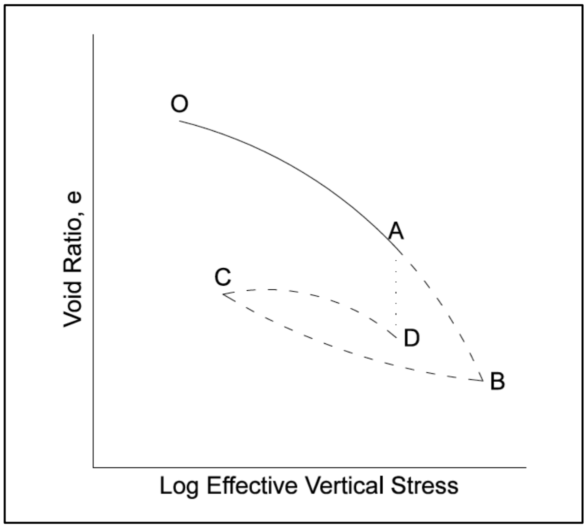
Trenter (1999) discusses the depositional factors that affect Glaciated Valley tills as sub-ice temperature, inter-ice water, ice thickness, and sub-ice drainage. Trenter also goes on to explain post-depositional factors for Glaciated Valley tills in terms of groundwater and freeze-thaw. Explanations of these depositional and post-depositional processes are summarized in Tables 8 and 9, respectively.

Table 8. Depositional Factors on Glaciated Valley Tills. Adapted from *Engineering in glacial tills* (pp. 89-90), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Adapted with permission.

Depositional Factor	**Definition**
Sub-Ice Temperature	Frozen till can shear and deform beneath a glacier, but consolidation will be mainly due to horizontal drainage. When the frozen till begins to thaw drainage will develop resulting in consolidation of thawed till. Additionally, a frost table within the layer will migrate downwards.
Inter-ice Water	Vertical effective stresses in underlying tills would be affected by free water in cracks and fissures.
Ice Thickness	Varies according to whether the glacier was waxing or wasting. The bulk of till consolidation occurs during free-drainage of pore water.
Sub-ice Drainage	Occurs during the down-melting phase and usually during warmer periods when ice advance is temporarily interrupted. Drainage may be one- or two-way depending on the permeability of the underlying bedrock.

Table 9. Post-Depositional Factors on Glaciated Valley Tills. Adapted from *Engineering in glacial tills* (p. 91), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Adapted with permission.

Post-Depositional Factor	**Definition**
Groundwater	A rise in the groundwater table during the end of the Pleistocene, in practice, concerning Glaciated Valley tills is unlikely.
Freeze-thaw	See Figure 9 below.



OA: consolidation during deposition.

AB: consolidation due to suction from initial freeze.

BC: swelling as pore pressures are generated.

CD: consolidation due to pore pressure dissipation.

DA: residual compaction.

Figure 9. Freeze-Thaw Process and Influence on Soil Consolidation. Adapted from *Engineering in glacial tills* (p. 91), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Adapted with permission.

Taber Consultants Glacial Till Samples

Taber Consultants provided a foundation report and samples of glacial till for use in this research. The samples were collected at a site mapped by the USGS as glacial deposits in California on September 7 and 8, 2011. The subject site was described as located in the bottom of the downstream portion of an alpine glacial valley within the Sierra Nevada geomorphic province, near the border of the Basin and Range Province to the east (Taber Consultants, 2012). It was also noted by Taber Consultants that gentle terrain between high ridges is typical of alpine glacial valleys and intersecting vertical strike-slip and normal faults have helped define the network of bisecting shallow streams and valleys cut into the glacial and volcanic debris from other nearby rockforms.

The following is a list of other conclusions by Taber Consultants (2012) concerning the geology of the subject site where the samples were gathered:

- Upstream of the subject site, Little Truckee River incises through glacial moraines or volcanic flows.
- Consisting of Quaternary Alluvium over Quaternary Glacial Deposits and/or Miocene-Pliocene Volcanic Rocks.
- Near the subject site, Quaternary Alluvium appears to overlay both Quaternary Glacial Deposits and Miocene-Pliocene Volcanic Rocks with Quaternary Glacial Deposits to the south of the creek and Miocene-Pliocene Volcanic Rocks to the north of the channel
- Materials found in borings were Quaternary Alluvium described as unconsolidated gravel, sand, and silt. However, large quantities of cobbles and boulders were encountered.
- The alluvium in the subject site is likely closely derived from eroding glacial deposits.
- Undivided glacial till, moraines, and outwash (Def: 32) deposits are mapped south of the subject site and likely underlie it.
- Figures 10 and 11 show the location of the subject site.

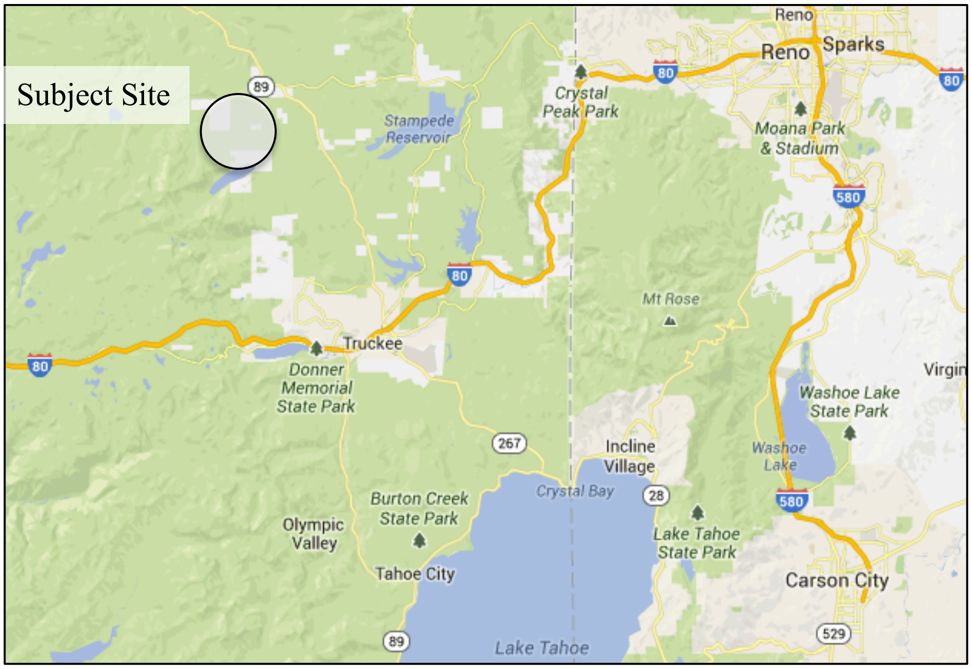


Figure 10. Location of Taber Consultants Glacial Till Samples (Google Maps, 2013)

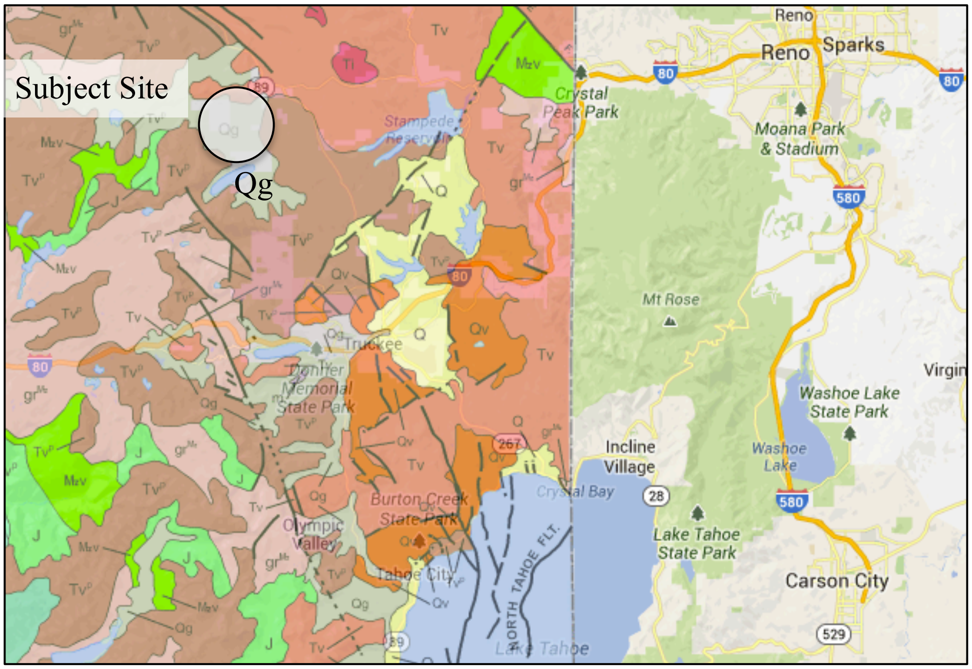


Figure 11. Location of Taber Consultants Glacial Till Samples with USGS Geologic Map (California Geological Survey, 2010 and Google Maps, 2013)

Figure 10 shows the location of the site relative to Lake Tahoe and Reno, Nevada. Figure 11 shows the location of the site within Quaternary glacial deposits, designated Qg, as mapped by the USGS. Qg includes the following glacial deposits: glacial drift (Def: 11), till (Def: 6), moraine (Def: 31), stratified glacial sediment (Def: 38), glacial outwash sediment (Def: 13), sub/supra glacial sediment (Def: 40), glaciolacustrine sediment (Def: 19), and glacial marine sediment (Def: 12). With this information it can be concluded that the samples were gathered from an area of past glaciation.

Four test borings were completed and a Taber Consultants Geologist recovered soil samples. Soil samples were recovered by means of a 1.4-inch inside diameter standard penetration split-spoon sampler as well as 2.4-inch and 2.5-inch inside diameter split-spoon samplers per ASTM D1586 (Taber Consultants, 2012). Soils encountered were interpreted by Taber Consultants as glacial outwash, till, and/or moraine along with lake or streambed, terrace, and/or ash deposits. Soils described by Taber Consultants from borings B-3 and B-4 are depicted in Figure 12 below.

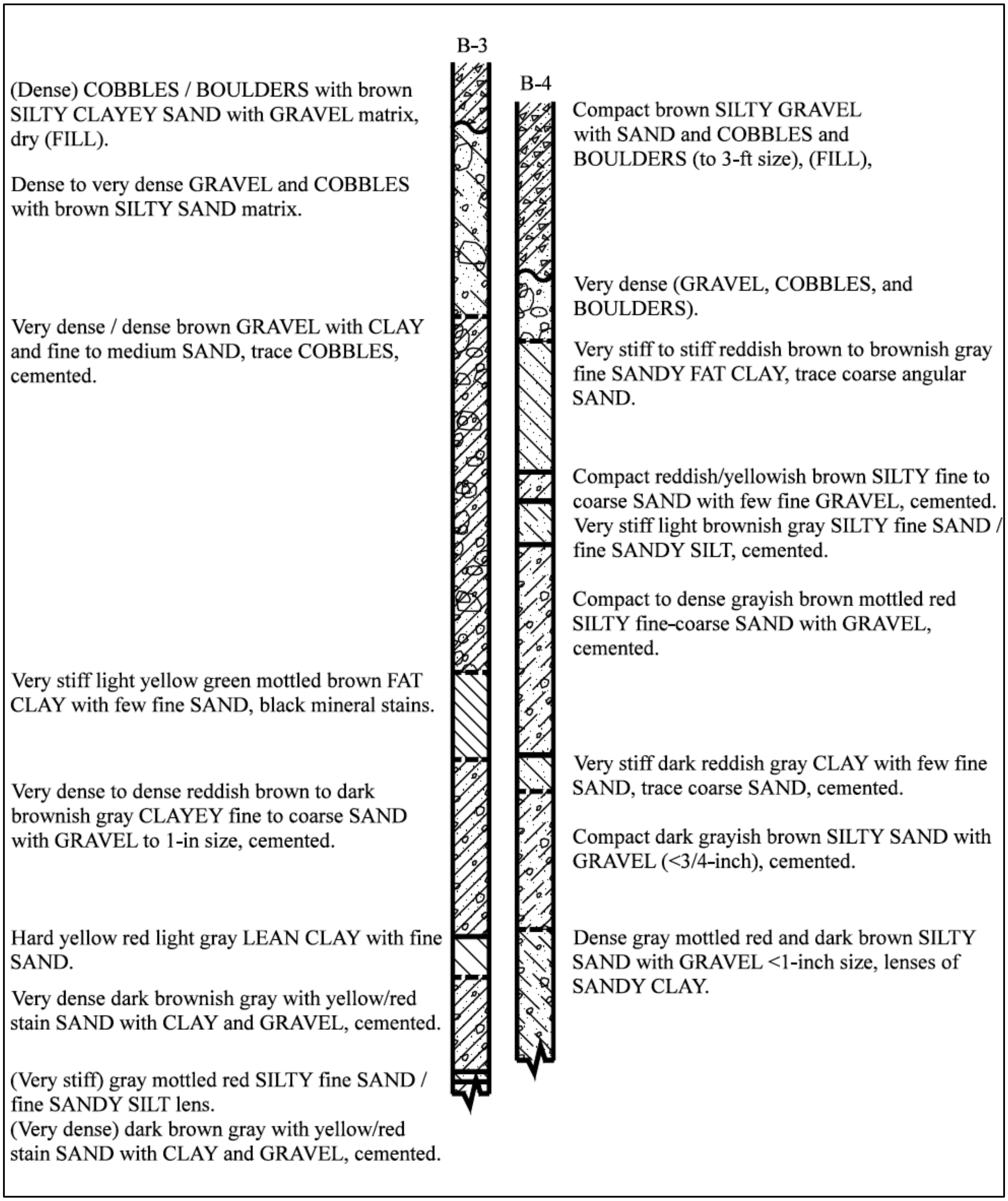


Figure 12. Soil Profile and Description of Borings B-3 and B-4. Adapted from *Taber Consultants foundation investigation: Old Fibreboard Road bridge at Little Truckee River* (Log of Test Borings), by Taber Consultants, 2012, West Sacramento, CA: Author. Copyright 2012 by Taber Consultants. Adapted with permission.

Figure 12 is not to scale and the maximum depth penetrated by borings B-3 and B-4 was 71±ft. Taber Consultants (2012) also provided a general description of the soils encountered below road fill (located up to 10±ft below ground surface) in the borings as:

- Sand and gravel with boulders and cobbles and some silt or clay.
- Sandy lean to fat clay.
- Silty sands and sandy silts.
- Cobbles and boulders generally encountered from ground surface to 20±ft below ground surface with occasional cobbles or boulders below 20±ft.
- Boulders up to 5 feet in diameter.
- Soils were variably cemented in the more granular zones
- Granular materials are generally compact to dense with higher blow counts (SPT *N* value) in soils with higher cobble/boulder fractions due to sampler refusal.

The Taber Consultants Foundation Report along with test results and figures are located in Appendix B.

Additional soil tests were completed on the above Taber Consultant samples at the San José State University (SJSU) Soils Lab. One intact California Modified (CalMod) sample was obtained along with several bag samples. The CalMod sample was labeled B-1-3 and the bag samples were labeled B-4-8A, B-4-8B, B-4-9, B-4-11, B-4-13, and B-4-14. Direct shear, Atterberg, consolidation, and gradation tests were completed on these samples.

Method

The glacial till samples used for this research were collected from an area of past glacial movement. USGS mapping confirmed the samples were located in an area of glacial deposits and further site reconnaissance by a geologist confirmed surficial glacial evidence. From Taber Consultants (2012) the lithology where the till samples was obtained agrees with the overall coarse nature of Glaciated Valley tills; however, noticeably large layers of clay were revealed.

Plasticity and Particle Size

Taber Consultants Atterberg test results of clay samples were similar to research by Trenter (1999) and Finno (2003b). Figure 13 presents Atterberg test results compared to other research on glacial soils. Samples B-3-6, B-3-9, B-3-12, B-4-7, and B-4-15 were tested at the Taber Consultants Soils Lab for Atterberg Limits. Samples B-1-3, B-4-8A, B-4-8B, B-4-9, B-4-11, B-4-13, and B-4-14 were tested at the SJSU Soils Lab for Atterberg Limits. Upon extraction of sample B-1-3, it fell apart. It was determined later that it had no plasticity and Atterberg tests were not completed. Sample B-4-8A was very sticky when handling; however, it too tested as silt from Atterberg tests. The remaining samples (B-4-8B, B-4-9, B-4-11, B-4-13, and B-4-14) were too small individually to acquire good test data, so they were combined and the results from Atterberg tests classify the samples as silt. Referring to the Log of Test Borings Figure in Appendix B, page 91 the combined samples originate from similar layers of silty sand with gravel.

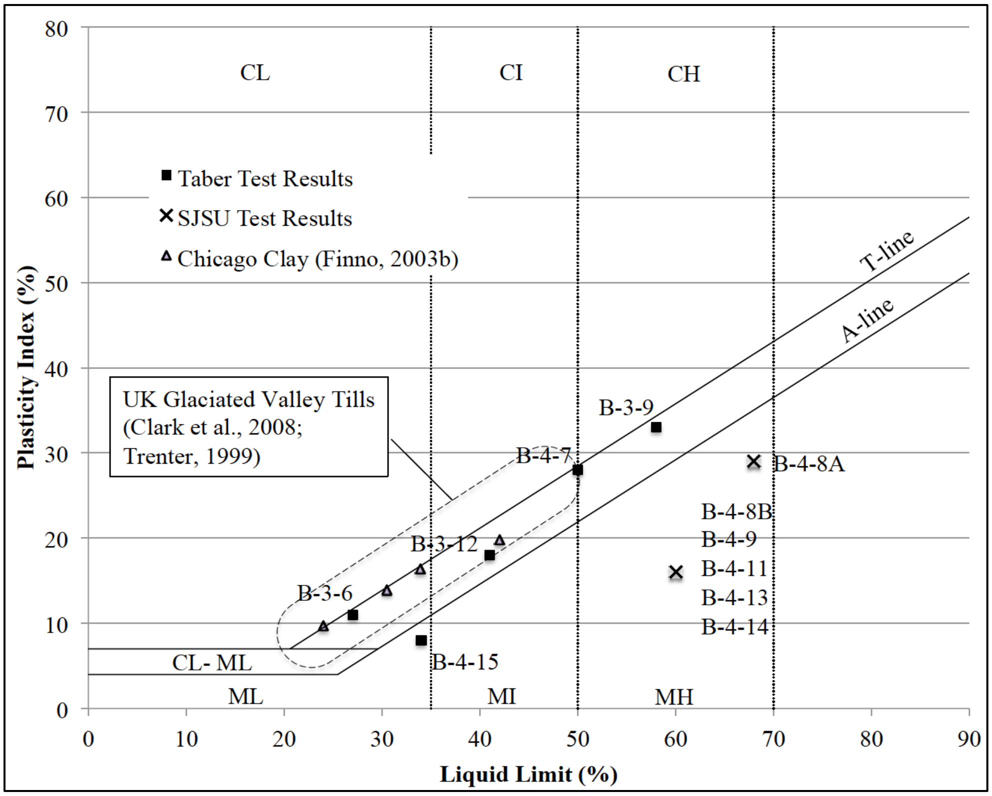


Figure 13. Atterberg Test Results

Samples classified as clay by Taber Consultants show that the composition is similar, because they lie near the T-line on a Casagrande plasticity chart. Bell (2001) stated that the T-line indicates the unsorted nature of tills and that most of the clay material is larger than the clay size. Essentially large amounts of rock flour, indicative of Glaciated Valley tills, would be a main factor in the T-line phenomenon. Results of clay samples such as these may be useful as an indicator of glacial tills across a given site. However, there is no indicator for samples that test as silt. Because rock flour is a common feature of fines in Glaciated Valley tills, more research into the sedimentology of tills at a given site may be necessary as an indicator where there is little or no clay deposits.

Knowing that glacially derived clays lay on or near the T-line does not indicate a specific engineering property of the soil; however, some engineering properties of Glaciated Valley clay tills can be determined from Atterberg Limits. According to Terzaghi et al. (1996) expansive soils store significant amounts of elastic energy and adsorbed and double-layer water. Relating to Atterberg Limits, this would result in large plastic and liquid limits. Based on research completed by Trenter (1999) in Glaciated Valley tills in the UK, expansive potential would be minimal since clays plot on the T-line at a lower plasticity index and liquid limit.

The glacial soils in the Sierra Nevada, as evidenced from Atterberg results in this research, do not fit into the low plastic and liquid limit Glaciated Valley tills presented by Trenter (1999). Two of the clay samples tested are in the high plastic range, possibly having some expansive qualities. Also, two of the silt samples tested show potential for compressibility. Geologically speaking, there is high clay content in Sierra Nevada tills since the local rock is predominantly granite. This would not necessarily explain the expansive nature of these tills, but the presence of volcanic rock may be a good indicator.

A large portion of the Sierra Nevada is made up of volcanic rocks. Specifically, surrounding the subject site are formations of volcanic, metavolcanic, and plutonic rock. Research in the Sierra Nevada on clay neoformation suggests the possibility of large amounts of clay deposits because of the presence of the local rockform (Eberl, 1984).

Bell (2001) suggests that the Atterberg Limits influence consolidation and strength. Even though Atterberg tests are primarily for classification purposes, general correlations can be made with some engineering properties. One such generalization can be determined from the liquidity index. According to Terzaghi et al. (1996) the Liquidity Index, *LI*, is defined as:

$$LI = \frac{w_n - PL}{PI} \tag{13}$$

Where w_n = the natural moisture content, *PL* = the plastic limit, and *PI* = the plasticity index. Terzaghi et al. (1996) suggests that typical results of positive *LI*s near 0 have a higher compressive strength, 1 tsf < q_u < 5 tsf, than larger *LI*s. Aryani (2006) also states that *LI* > 1 suggests sensitive soft clay and *LI* < 0 suggests stiff overconsolidated clays. This is due to the natural water content of the sample where the natural water content approaches the plastic limit. Likewise, research completed by Bell (2001) suggests that the strength of tills can dramatically drop from relatively small increases in moisture content. Tests completed by Bell (2001) show a 70% reduction in strength with a 2% increase in moisture content. From a testing perspective, this suggests that care should be taken in sealing samples so as to not alter the natural moisture content.

Another method using the Atterberg Limits to generalize engineering properties is the consistency index. To determine the consistency of cohesive soils, Anon (as cited in Bell, 2001) suggested the Consistency Index (CI) as:

$$CI = \frac{LL - w_n}{PI} \tag{14}$$

Where *CI* > 1 is very stiff soil, 0.75 < *CI* < 1 is stiff soil, and 0.5 < *CI* < 0.75 is firm soil. Using the data collected for this research the liquidity index and consistency index was compared to blow count consistency and unconfined compressive strength in the following table.

Table 10. Liquidity Index and Consistency Index Compared to c_u, Generalized Properties, and SPT N Consistency

Sample #	**Soil Description**	***LI***	***CI***	**Generalized Properties Determined from *LI***	**Unconfined Compressive Strength, q_u (tsf)**	**SPT N Value Consistency**
				Generalized Properties Determined from *CI*		
B-3-6	CL	-0.82	1.8	Stiff Overconsolidated	Not Tested	Hard to Very Hard
				Very Stiff		
B-3-9	CH	0.27	0.72	High Compressive Strength	Not Tested	Very Stiff
				Firm (or stiff)		
B-3-12	CL	0.27	0.72	High Compressive Strength	8.4	Hard
				Firm (or stiff)		
B-4-7	CI / CH	0.42	0.57	High Compressive Strength	Not Tested	Stiff to Very Stiff
				Firm (or stiff)		

Referring to Table 10, using the generalized properties according to the *LI* would be appropriate for preliminary assessments of unconfined compressive strength and consistency. For example, the high compressive strength generalized for sample B-3-12 tested high for unconfined compressive strength.

Using the Atterberg Limits to define consistency and identify a generalized unconfined compressive strength would be useful in design. In a sampling interval where SPT *N* values are abnormally high due to cobbles and boulders, the consistency index would allow for consistency determinations. With a consistency determination, a range of SPT *N* values could be assigned for engineering design. Likewise, this method would be relevant where only disturbed samples could be collected because no intact tube samples were extracted. The liquidity index would allow for generalized unconfined compressive strength determinations from Atterberg results.

Samples B-1-3, B-4-8A, B-4-8B, B-4-9, B-4-11, B-4-13, and B-4-14 were tested at the San José State University Soils Lab for grain size distribution. Grain Size Distribution curves (USC system) are presented in Figure 14 below along with grain size percentages in Table 11. Further results of grain size distribution and percentages as tested by Taber Consultants are located in Appendix B.

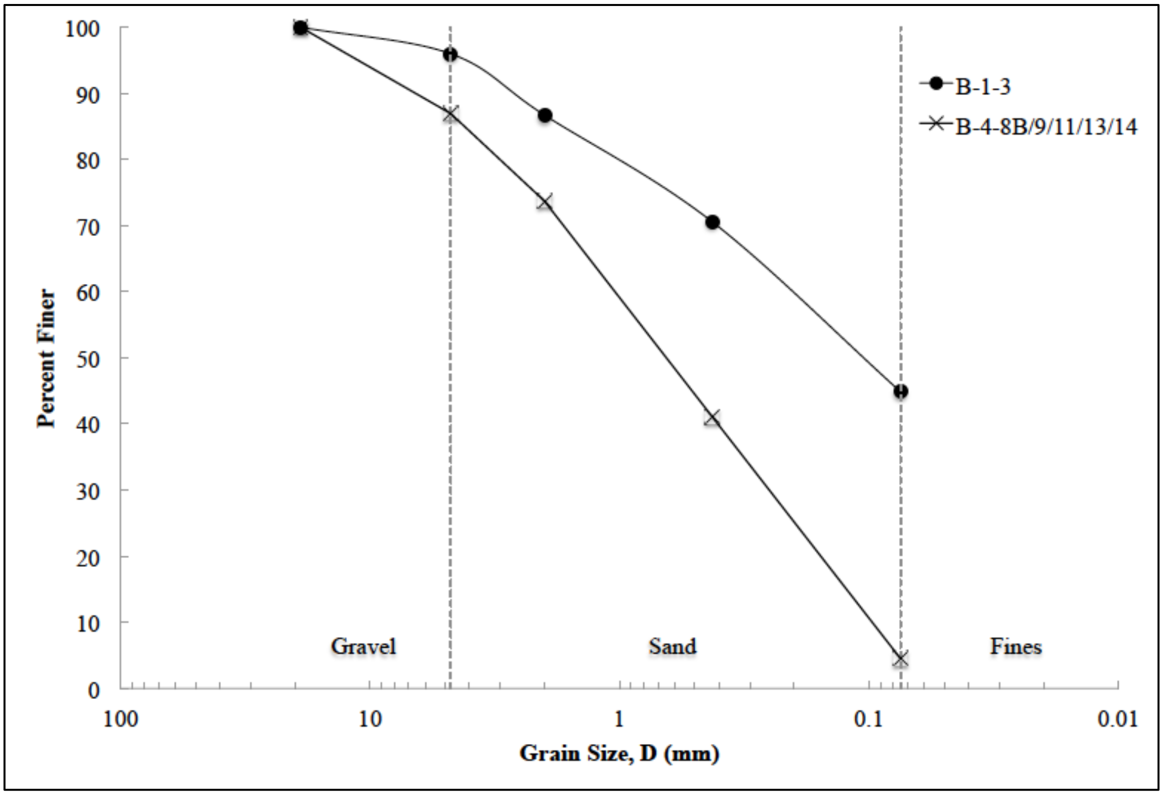


Figure 14. Grain Size Distribution Curves from Sieve Analysis

Table 11. Grain Size Distribution Percentages from Sieve Analysis

Sample #	% Gravel	% Sand	% Fines	Fines Classification
B-4-8B/9/11/13/14	13	82	5	Silt
B-1-3	4	51	45	Silt

A wide grain size distribution is evident from the sieve analysis in sample B-4-8B/9/11/13/14. Also, a review of the Log of Test Borings and Grain Size Distribution

Curves (Appendix B) for the site would suggest a similar conclusion. For this particular site there are significant amounts of fines. Most of the fines encountered were generally silt, similar to sample B-1-3; however, notably large layers of clay cannot be ignored, as seen in Figure 12 and the Log of Test Borings Figure in Appendix B, page 91.

Merely taking into consideration the results from gradation tests is not an indicator of the nature of the materials on the entire site. After combining the lab results with the Log of Test Borings provided by Taber Consultants, the particle sizes range from boulder to clay. This is important to recognize due to the overall engineering characteristics and construction conditions of the site. Soil sample sizes are very small in comparison, even if larger diameter samples are taken.

However, a wide grain size distribution does not significantly affect the engineering characteristics of tills. Clarke et al. (2008) spoke on the difficulties of obtaining quality samples and how even though there are a wide variety of particle sizes, the matrix dominates the behavior of the till. Nevertheless, construction conditions are significantly affected by the outcome of particle distribution since the presence of boulders would call for different construction equipment.

Weathering

Weathering has attributed to the depositional nature of the glacial tills studied on this subject site. Weak rock, strong soil, and clay have been created as evidenced in the soil cross-sections. Weathering in the soil cross-section at the subject site can be seen on Figure 12 and the Log of Test Borings Figure in Appendix B, page 91. Cementation, mineral staining, oxidation, and large layers of clayey material were noted in these figures.

Referring to the Log of Test Borings Figure in Appendix B, page 91, some areas of cementation correlate with larger SPT *N* values in borings B-3 and B-4. This may indicate strengthening of soil from the cementation weathering process. Also, mineral staining is located below a very dense layer of consistent SPT refusals. This could be an indicator of rock decomposition from the above layer of gravel, clay, sand, and cobbles. Areas of red and reddish brown colored or stained sands and gravels are evident in both borings B-3 and B-4, which could attribute to weathering by oxidation.

As mentioned previously in the discussion on plasticity and particle size, the Sierra Nevada is a good location for large deposits of clay derived from weathering. From review of CGS geologic mapping data, the subject site is surrounded by volcanic, plutonic, and metavolcanic rock (California Geologic Survey, 2010). The Log of Test Borings Figure in Appendix B, page 91 illustrates large layers of clay material. Since these clays are intermingled with various indications of weathering, it can be deduced that they were derived from rock decomposition of the local rock form. Therefore, high plastic and liquid limit clays may be present in the Sierra Nevada.

Correlation Between Undrained Shear Strength and SPT *N* Value

SPT sampling is the most common sampling method in glacial tills. Glaciated Valley tills have a complex soil lithology that contains very dense materials, such as cobbles, that may have less dense or cohesive matrix materials. With this method of sampling in glacial tills, samples may be obtained in the matrix material for conservative estimates of overall strength and estimates of compressibility in areas of little sample recovery. Taber Consultants completed the SPT tests and unconfined compressive strength tests used for this research at the aforementioned site in the Sierra Nevada.

The results of SPT tests correlated to undrained shear strength are variable in glacially derived soils. In general, SPT *N* values increase; however, there are outliers in data that must be taken into consideration. The results of which are due to the deposition of glacial soils that tend to have cobbles and boulders present in a given soil profile. As a result, much of the SPT *N* values recorded throughout large portions of borings B-3 and B-4 are unreliable because of the presence of dense coarse material. Because of this, there are abnormally high SPT *N* values and little sample recovery for lab testing in these very dense layers. The till samples that were tested by Taber Consultants for unconfined compressive strength (q_u) are depicted in Figures 15 to 20 with respect to undrained shear strength ($c_u = q_u/2$), SPT *N* values, depth, and soil description.

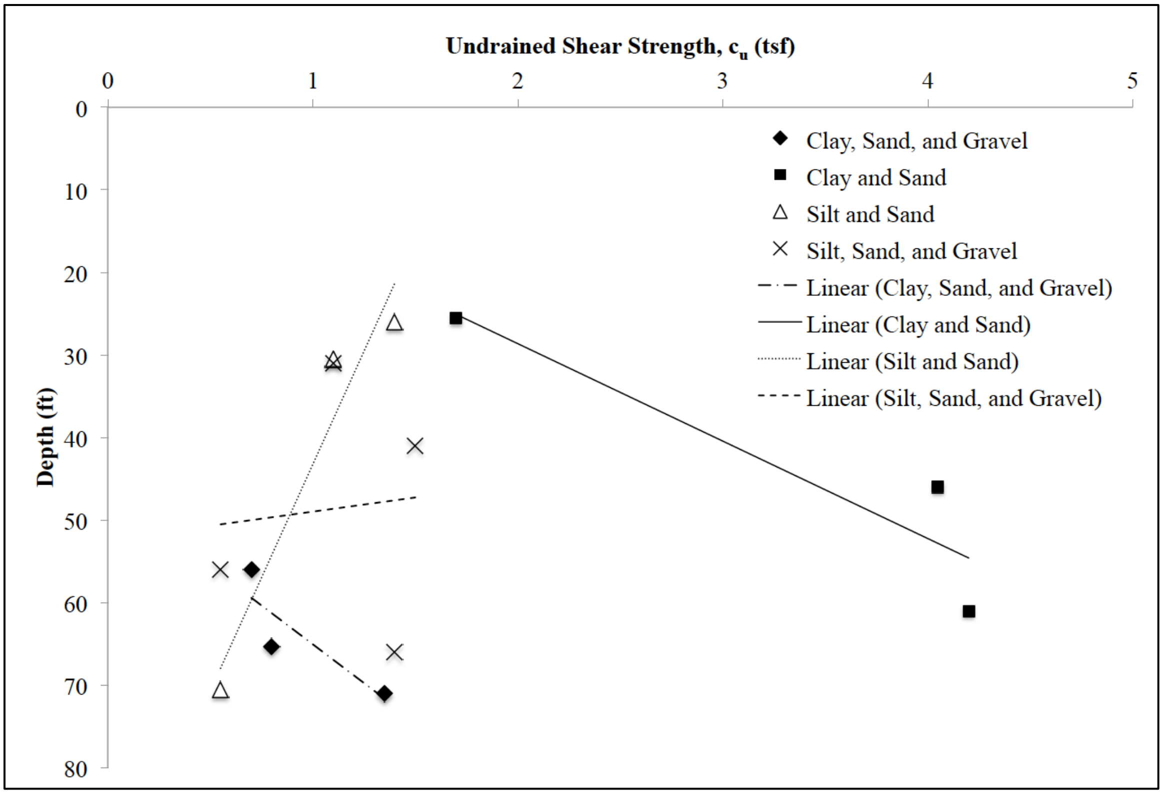


Figure 15. Results of Undrained Shear Strength Versus Depth According to Soil Description

Considering Figure 15, there is little to no correlations in the overall data that would suggest an increase in shear strength with depth. When considering the samples separately by soil description the Silt, Sand, and Gravel samples show little to no correlation. Also, the undrained shear strength of the Silt and Sand samples decreases with depth. This would indicate that the results of unconfined compressive strength for granular samples are independent of depth. However, the undrained shear strength of the Clay, Sand, and Gravel and Clay and Sand samples generally increases with depth.

The increase in undrained shear strength in the Clay, Sand, and Gravel and Clay and Sand samples could be attributed to the clay binder, since this is a common feature with regard to these samples. In the case of the other samples, the decrease in unconfined compressive strength is most likely attributed to the lack of cohesive binding between the coarser materials. Correlations with depth may not be attainable on cohesionless samples with respect to undrained shear strength since there is no binding material. The unconfined compressive strength of cohesionless samples may be an underestimation of strength because confining pressures are not taken into consideration. In an attempt to find other correlations Figure 16 below depicts sample depth with respect to the SPT *N* value.

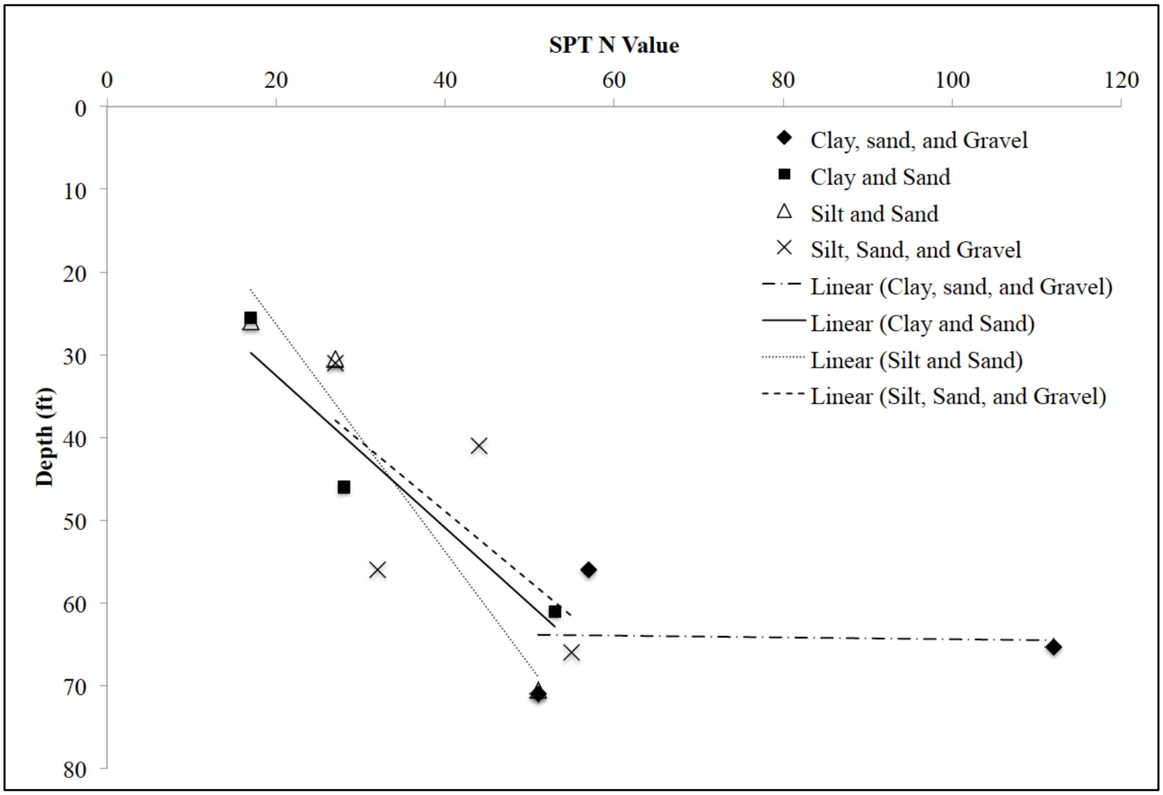


Figure 16. Results of SPT N Value Versus Depth According to Soil Description

Referring to Figure 16, the SPT *N* value generally increases with depth. However, considering the samples by classification separately show a disruption in the perceived increase in SPT *N* values. SPT *N* values from the Clay, Sand, and Gravel samples decrease dramatically with depth from 65-ft to 70-ft. The large SPT *N* value in the Clay, Sand, and Gravel samples, where SPT $N = 112$, is due to driving refusal in very dense material. SPT *N* values that result due to driving refusal should not be taken into consideration. They may not be an accurate assessment of matrix material and it could be an indicator of soil strengthening due to weathering.

Considering the Silt, Sand, and Gravel samples, the SPT *N* value decreases with depth from 41-ft to 56-ft. The Clay, Sand, and Gravel and Silt, Sand, and Gravel samples show the most variability in SPT *N* values with depth. This is due to the presence of gravel. SPT *N* values can be erratic with depth because of the changing gradation of gravel penetration with the sampler. Essentially, SPT *N* values would increase due to the amount of gravel entering the sampler.

Lack of correlations concerning depth and the SPT *N* value can be contributed to differing soil layers noted in the soil cross-section. Since Glaciated Valley tills show great variability in a given cross-section due to depositional processes, engineering properties may change dramatically from one layer to the next. Considering all of the SPT *N* Value versus depth data for borings B-3 and B-4 in Figure 17 below confirms the differing engineering properties that can be attributed to each layer. Note there are several points of refusal during SPTs.

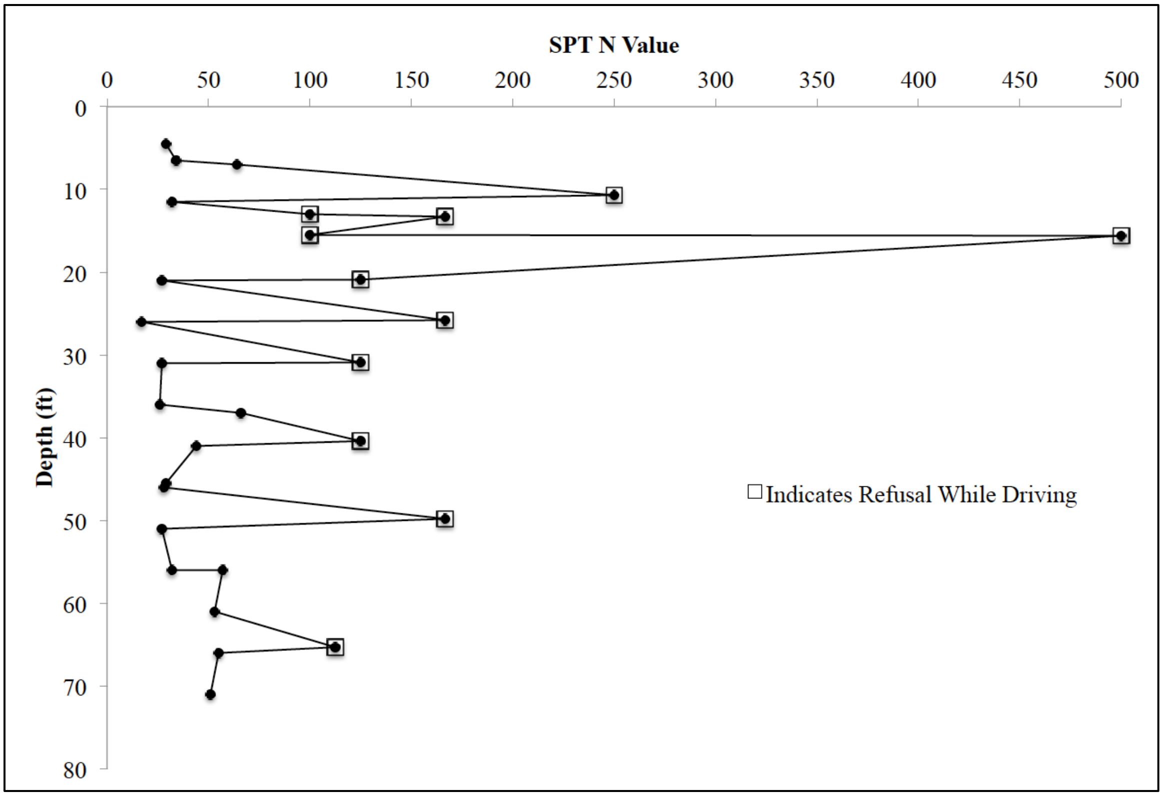


Figure 17. Results of SPT N Value Versus Depth Where All Data is Considered

A typical cross-section of Glaciated Valley tills are made up of clay and silt till with layers of cobbles and boulders and large detached bedrock blocks near rockhead (Trenter, 1999). Considering these depositional characteristics of Glaciated Valley tills, the depths at which refusal was realized in Figure 17 is explained by the presence of dense granular material. These zones can also be attributed to soil strengthening by weathering.

In this case Stroud and Butler's approach to relating the SPT *N* value with undrained shear strength may not be possible, since their approach is for tills at a plasticity index, PI ≤ 25. The data collected for this research only had one result for the plasticity index to correspond with undrained shear strength, indicating a need for more plasticity data. Furthermore, Stroud and Butler's approach used data collected at corresponding depths, the results of which were from triaxial testing. The data collected for this research was minimal, where only two boreholes were completed, and no triaxial testing was implemented. At most only two data points could have corresponding depths, resulting in a poor spread of data.

For research purposes, multiple borings over a site are necessary to gain understanding of engineering properties. However, when a geotechnical foundation investigation is implemented the most economical approach is used. In this case data used for research was obtained from a geotechnical investigation, therefore resulting in little spread of data over the site area. So, using the suggested relationships from till research should be used with caution when using this type of data.

In this case, the best approach would be to correlate the SPT *N* Value versus depth, disregarding outlier data points, and to use unconfined compressive strengths where available with no correlations to depth. Figure 17 is a good starting point to help identify very dense layers, i.e. cobbles and boulders. Disregarding the outlier SPT *N* values from Figure 17, Figure 18 below shows a comparison of SPT *N* values with depth. In Figure 18, the SPT *N* Value is relatively linear at depths below 20-ft. The trendline through the data below 20-ft results in the following equation:

$$SPT\ N\ value = \frac{Depth}{1.2} \tag{15}$$

With depth the SPT *N* value increases by a factor of approximately 1.2. This approach allows for the "filling-in" of data where SPT *N* values are unreliable or absent.

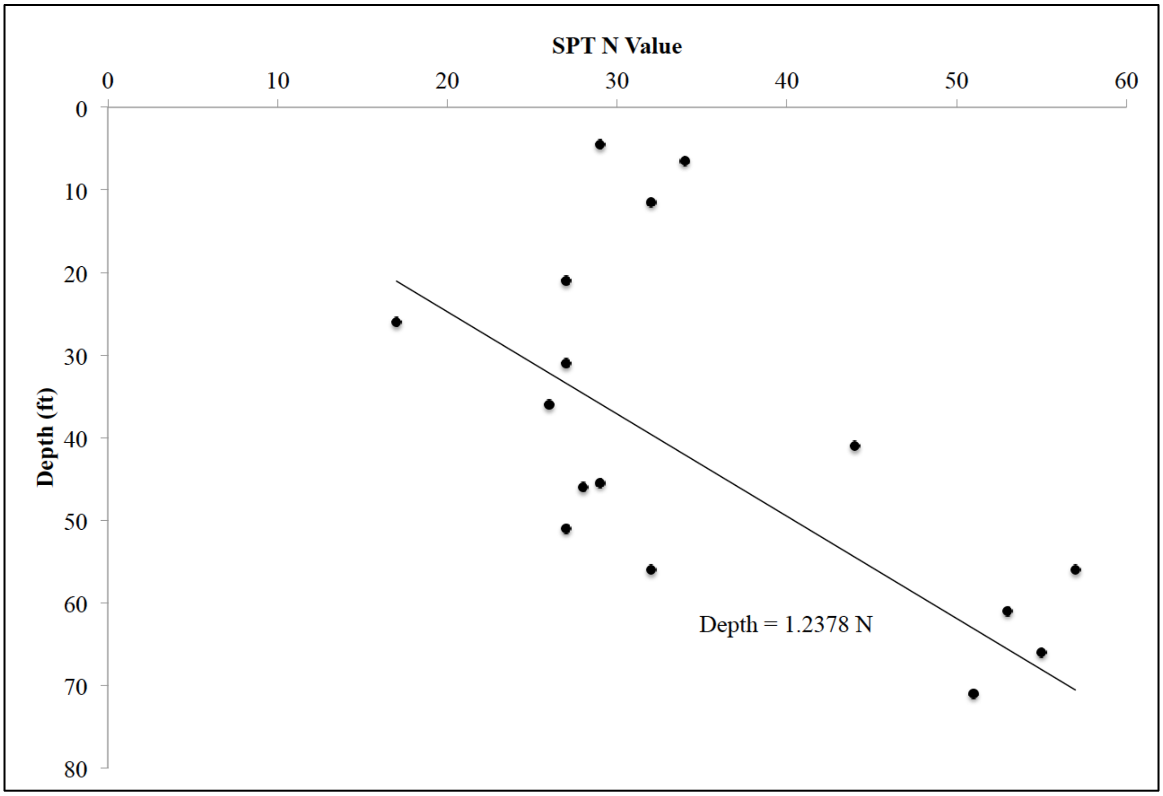


Figure 18. SPT N Value Versus Depth Excluding Outlier Data

The results of Figure 18 are a useful approach at sites where sample recovery is minimal and laboratory data is sparse. In practice, administering laboratory tests to find friction angle data at every sample depth or soil layer would not be feasible. Therefore, this approach would be practical to correlate the SPT *N* value to empirical friction angle data from other research on similar materials or to correlate with direct shear or triaxial results obtained on the same site.

Drained Peak Shear Strength

Figure 19 illustrates the shear envelope from direct shear tests completed on sample B-1-3, which was classified as silty sand with trace gravel and angular grain shape. The sample was disturbed. In fact the sample did not stay intact while extracting;

this was mainly due to the lack of plasticity of the fines. As a result, the sample was dried and tested under loose conditions at three stages of normal stress. The test reports are located in Appendix C.

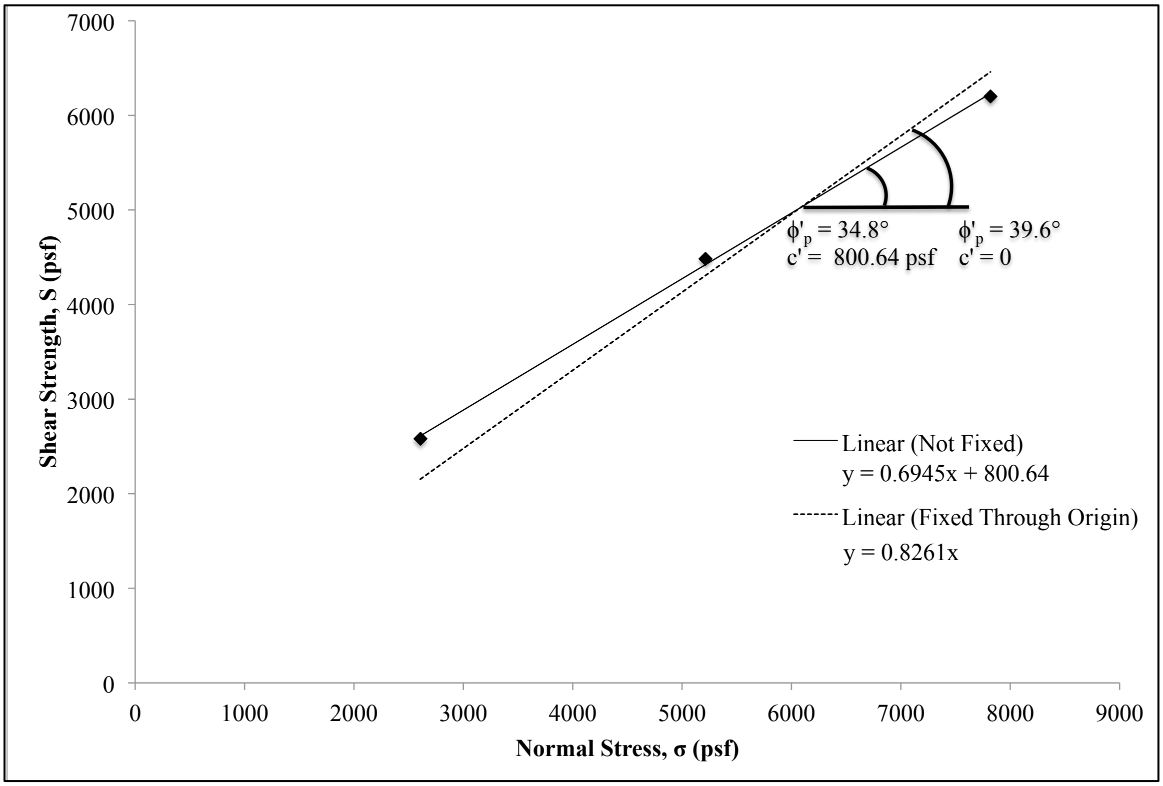


Figure 19. Shear Strength Envelope of Sample B-1-3, Silty Sand with Trace Gravel and Angular Grain Shape

Two values are estimated for the friction angle at peak shear strength. The lesser friction angle (ϕ'_p = 34.8°) assumes there is cohesion (c' = 800.64 psf) due to fine-grained materials. On the other hand, the larger friction angle value (ϕ'_p = 39.6°) assumes there is no cohesion due to fine-grained materials. Typically, the more conservative value is used in calculations; however, this assumption is due to the soil type. Since the fines were determined to be silt with no plasticity, the assumption may be valid to use the higher friction angle, in this case.

The friction angle of this material was 35° or 40°, depending on whether the regression line was forced through the origin. From an engineering perspective the more conservative approach is usually recommended, especially with soils. However, in this case the results of Atterberg tests on the fines portion showed no plasticity. Since the sample showed no plasticity, this can be interpreted as no cohesiveness to the material. In this case the larger friction angle of 40°, with the regression line forced through the origin (effective cohesion = 0), may be appropriate for design purposes. However, using the linear relationship may not be the appropriate determination. Using a power function, as proposed by Charles and Watts in weak rockfill, would be more appropriate in determining the friction angle. Figure 20 below illustrates the use of the power function trendline to obtain the shear envelope from direct shear tests completed on sample B-1-3.

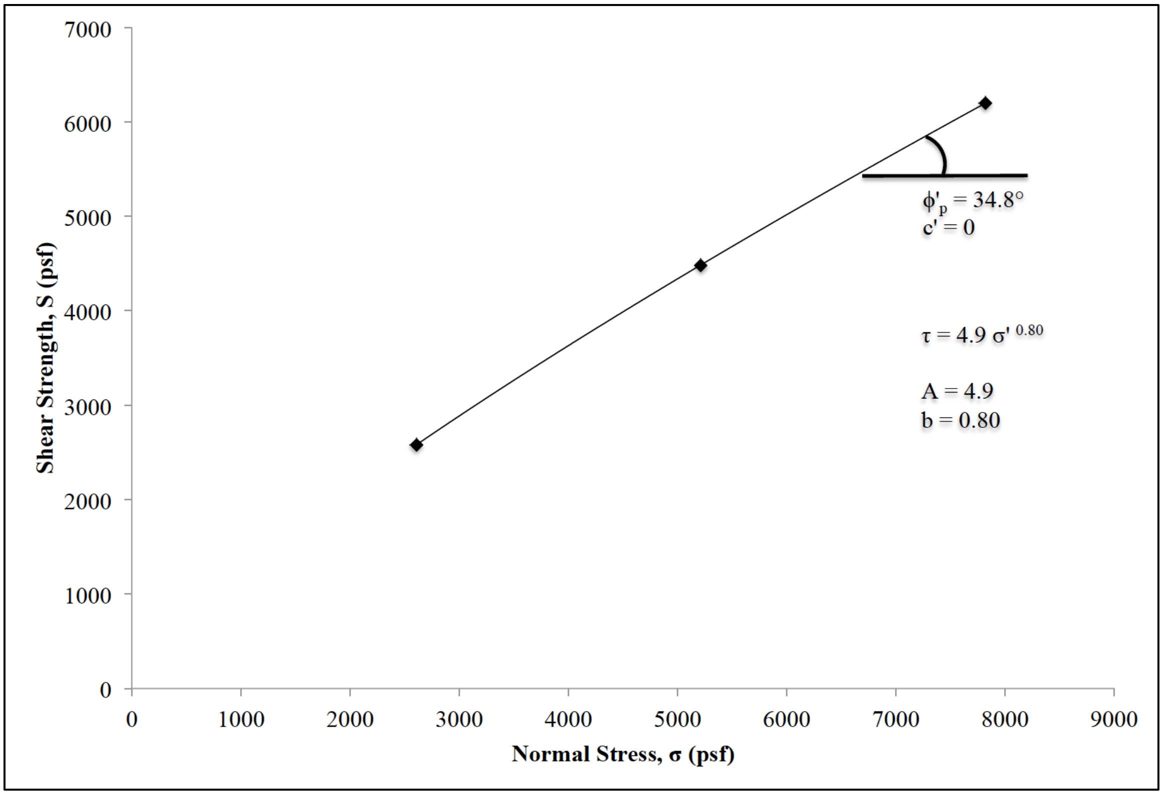


Figure 20. Shear Strength Envelope with Power Function Trendline of Sample B-1-3, Silty Sand with Trace Gravel and Angular Grain Shape

Referring to Figure 20, the result for the friction angle is the same as the linear trendline from Figure 19 that is not forced through the origin. This would be a more accurate representation of the shear envelope created during direct shear tests in non-cohesive soils. The results of the *A* and *b* values from this test are similar to those results from research completed by Charles and Watts (as cited in Trenter, 1999) on sandy gravel rockfill. The design friction angle for this sample is $\phi'_p = 35°$. Results for the friction angle at peak shear strength, ϕ'_p, can be correlated to the tested soil types presented in Table 12 and general soil types presented in Table 13.

Table 12. Friction Angle of Cohesionless Soils by Soil Type (Bardet, 1997)

Soil Type	**Grain Shape**	**Friction Angle at Peak Strength, ϕ'_p (deg)**	
		Loose	Dense
Ottawa standard sand	Well rounded	28	35
Sand from St. Peter Sandstone	Rounded	31	37
Beach sand from Plymouth, MA	Rounded	29	No value given
Silty sand from Franklin Falls dam site, NH	Subrounded	33	37
Silty sand from vicinity of John Martin dam, CO	Subangular to subrounded	36	40
Slightly silty sand, Ft. Peck dam, MT	Subangular to subrounded	34	42
Screened glacial sand, Manchester, NH	Subangular	33	43
Beach sand of hydraulic fill dam, Quabbin Project, MA	Subangular	35	46
Artificial, well-graded (poorly-sorted) mixture of gravel with sands	Subangular to subrounded	42	57
Sand from Great Salt Lake fill (dust gritty)	Angular	38	47
Well-graded (poorly sorted), compacted crushed rock	Angular	No value given	60

Table 13. Friction Angle of Cohesionless Soils by Classification (Bardet, 1997)

Classification	**Friction Angle at Peak Strength, ϕ'_p (deg)**	
	Medium Dense	Dense
Silt (nonplastic)	28-32	30-34
Uniform fine to medium sand	30-34	32-36
Well-graded (poorly-sorted) sand	34-40	38-46
Sand and gravel	36-42	40-48

The sample tested was classified as silty sand with trace gravel. Comparing the friction angle determined for sample B-1-3 to Tables 12 and 13 results in similar soil type and classification. At a friction angle of 34°- 40° Table 12 shows a range of silty sand and sand soil types and Table 13 shows a generalization of well-graded (poorly sorted) sand.

The friction angle results for this test may be higher than typical results. This is mainly due to the moisture content of the sample during testing. The direct shear results for this sample was taken under dry conditions. This could result in overestimates of the friction angle because there were no considerations to pore water pressure and particle lubrication. Essentially pore water pressure can develop during direct shear tests, decreasing the friction angle of the sample. Furthermore, particle lubrication due to the presence of water can decrease the friction angle.

Correlations to boring B-1 with samples collected in borings B-3 and B-4 may not be applicable. Boring B-1 is approximately 800-ft west of borings B-3 and B-4 with an extreme change in elevation, indicating a similar but not the same lithologic sequence. As a result, engineering properties associated with samples collected in boring B-1 should not be correlated with engineering properties in borings B-3 and B-4.

Examining the results of Atterberg and direct shear tests reveals the importance of understanding the results of multiple soils tests. As a result, over- or under-design could easily occur without closely scrutinizing the results of these tests. For example, the failure envelope equation, Equation 16 below, for a given soil can be altered according to whether the soil is cohesive or cohesionless.

$$s = c' + \sigma' \tan \phi' \tag{16}$$

Where s = shear strength, c’ = effective cohesion, σ’ = effective normal stress, and ϕ’ = friction angle. For design purposes, assuming cohesionless soil, effective cohesion is set to 0 in Equation 16 resulting in Equation 17 below.

$$s = \sigma' \tan \phi' \tag{17}$$

To show a comparison of shear strengths using the direct shear results for sample B-1-3, the following Table 14 was created.

Table 14. Example Shear Strength Analysis

Case	Effective Normal Stress, σ' (psf)	Effective Cohesion, c' (psf)	Friction Angle, ϕ'	Shear Strength, s (psf)	% Difference from Case 1
1	150	0	40	126	
2	150	800.64	35	906	719
3	150	0	35	105	-17

An arbitrary value for effective normal stress was used for the shear strength analysis in Table 14. Whether or not the cohesive strength of the soil is used results in an apparent 719% increase in shear strength from Case 1 to Case 2. This could result in possible under-design. Case 3 depicts the power function cohesion and friction angle values to use in this case, showing a 17% decrease in shear strength as compared to Case 1. The lower friction angle may seem conservative; however, this may be a more accurate assessment of the shear strength of the soil.

Coefficient of Consolidation

Consolidation tests were completed on sample B-1-3 during the consolidation stages of the direct shear tests. The sample was tested under dry conditions with no incremental loading. The results of the consolidation tests are presented below in Table 15. The coefficient of consolidation, C_v, for the silty sand with trace gravel sample ranged from 0.127 cm^2/sec to 0.186 cm^2/sec.

Table 15. Consolidation Test Results

Sample #	Normal Stress (psf)	Soil Description	Coefficient of Consolidation, C_v (cm^2/sec)
B-1-3	2606	Silty sand with trace gravel	0.186
	5212		0.127
	7819		0.186

Typical values of the coefficient of consolidation of coarse-grained soils were not found. However, these values can be compared to select silts and clays listed by Bardet (1997) below in Table 16. Even though the sample's soil description alludes to a predominantly coarse-grained material, in this case sand, the results lie within the silt range as described in Table 16. Since the percentage of silt was so high in this sample, the entire sample took on the nature of silt, according to the coefficient of consolidation.

Table 16. Values of Coefficient of Consolidation for Various Soils (Bardet, 1997)

Type of Soil	Coefficient of Consolidation, C_v (cm^2/s)
Boulder clay and residual clay	0.0001-0.002
Sandy clay	0.001-0.01
Boulder clay	0.002-0.02
Marine clay	0.02-0.2
Silt	0.01-1.0

There are three stages of consolidation, those being initial, primary, and secondary consolidation. Generally, consolidation of dry coarse-grained soils is governed by initial consolidation. Bardet (1997) suggests that initial consolidation is instantaneous and is mainly due to elastic compression and redistribution of the soil grains. He further suggests that during primary consolidation excess pore water is dissipated completely over time. In coarse-grained soils this has little effect because there is no excess pore pressure. Bardet also suggests that secondary consolidation occurs after pore pressure is dissipated. Essentially, the load on dry coarse-grained soils is immediately taken by the particles instead of being dispersed between the particles and pore pressure. However, sample B-1-3 took on the characteristics of silt during the consolidation test. This may indicate that the matrix material of till samples would take on the engineering characteristics of a matrix-dominant layer.

Considering sample B-1-3 and the methods at which it was tested, bias may have been introduced since the sample was tested dry and disturbed. Testing under dry conditions does not take into consideration the effects of pore water pressure. Pore water does not start dissipating until primary consolidation in fine-grained soils because the load is carried during initial consolidation by pore water pressure. This would in turn decrease the coefficient of consolidation.

Furthermore, testing the sample disturbed does not take into consideration the effects of in-situ bonding between particles. Since the sample fell apart while extracting from the sample tube, natural bonding between particles was disturbed. Since initial consolidation is mainly due to the particles, testing the sample out of its natural state may not be an accurate assessment of the coefficient of consolidation.

Bardet (1997) states that fine-grained soils deform different than coarse-grained soils. However, fine-grained soils show a difference in deformation depending on whether they are silt or clay. Typically, a clay soil has a much lower coefficient of consolidation due to the dissipation of pore pressure over time. On the other hand, silt acts more like coarse-grained soil due to much larger primary consolidation as compared to secondary consolidation. As a result, determining settlement of glacial soils due to consolidation is probably one of the most difficult design applications in foundation design.

Difficulties in determining settlement due to consolidation are a result of multiple soil layers from a typical soil cross-section. For example, reviewing the soil borings for this research from Figure 12 and the Log of Test Borings Figure in Appendix B, page 91 shows the erratic composition that may occur in some glacial till cross-sections. Each soil layer contributes different characteristics of consolidation. From a sampling and testing perspective, it may not be practical or economical to test every sample within a soil layer for the coefficient consolidation.

Representative samples may be used to describe the consolidation characteristics of larger stratum within a cross-section. Since the matrix material governs the engineering properties of a till, reconstituting a sample from matrix material collected over several similar soil samples within a defined soil layer may be appropriate for design. As a result, the coefficient of consolidation of matrix-dominant soils would be governed by tests on the matrix-dominant material, whether it is fine-grained or coarse-grained.

Compressibility

The compression index, C_c, is defined as the slope of the virgin consolidation line on an e-log σ' axes (Bardet, 1997). Since consolidation tests were completed during the direct shear tests, a virgin consolidation line could not be defined. Therefore, the compression index was evaluated using the results of Atterberg tests completed on various samples tested in this research and applied to Equations 7, 8, 9, 10, and 12 previously discussed. The results are presented below omitting Equation 5 presented by Bernell (as cited in Trenter, 1999) because the percent fraction of clay was not determined for the tested samples.

Table 17. Compression Index Results According to Atterberg Limits

Equation # from text	**Equation**	**Clay Type**	**Compression Index, C_c**						
			B-3-6	B-3-9	B-3-12	B-4-7	B-4-15	B-4-Combined	B-4-8A
7	*0.013 PI*	Clay Till	0.14	0.43	0.23	0.36	0.10	0.21	0.38
8	*0.004 (LL-5)*		0.09	0.21	0.14	0.18	0.12	0.22	0.25
9	*0.005 LL*		0.14	0.29	0.21	0.25	0.17	0.30	0.34
10	*0.009 (LL-10)*	Clay	0.15	0.43	0.28	0.36	0.22	0.45	0.52
12	*PI/74*		0.15	0.45	0.24	0.38	0.11	0.22	0.39
Average C_c			0.13	0.36	0.22	0.30	0.14	0.28	0.38
Atterberg Classification			CL	CH	CI	CI/CH	ML	MH	MH

Table 17 above displays compression index results according to the previously discussed equations. Equations 7, 8, and 9 were interpreted from various clay tills in the UK and equations 10 and 12 were interpreted from clays not derived from glacial deposition. On the one hand the largest compression index results are realized in non-till Equations 10 and 12. On the other hand, the lowest compression index results are realized in till Equations 7 and 8. Since the soils on the site are derived from glacial deposits, Equations 7, 8, and 9 should be considered in design using the most conservative estimate. Also, looking at the range of results makes sense as compared to the Atterberg results. In low plasticity clays and silts the compression index is much lower than the high plasticity clays and silts, with intermediate clays in-between. Typical results of the compression index of some clay and silt soils are presented below in Table 18.

Table 18. Compression Index Values for Some Silt and Clay Soils (Bardet, 1997)

Type of Soil	**Compression Index, C_c**
CL-clay, soft	0.34
CL-clay, firm	0.44
ML-sandy silt	0.16
CH-clay, soft	0.84
CH-clay with silt strata	0.52
Clay till	0.08

Results nearest to the clay till presented in Table 18 are realized in the low plasticity clay sample B-3-6 results presented in Table 17. Other results are much higher, indicating that there is a wide range of compressibility characteristics of the clay tills on this site. This may be due to the neoformation of clay from volcanic rock surrounding the glacial deposits in the subject site. Also, some of these samples have been altered from their original state of glaciation. This agrees with the geologic interpretations of the subject site, which states that alluvial sediments were derived from glacial deposits.

The compression index results of the silt samples from Table 17 indicate similarities to typical values presented in Table 18. The ML sample is very near typical results for ML-sandy silt. The other silt samples show higher compression indices, which would indicate clayey silt characteristics. Sample B-4 Combined was a combination of several samples over similar soil layers and sample B-4-8A was at a gradational contact between a clay layer and a silty sand layer.

Even though the T-line phenomenon would indicate that the clays are glacially derived, erosive processes over time may have changed the consolidated nature of the tills. Samples at lesser depths, such as sample B-4-7, may have experienced post-glacial erosion and deposition from the river incising the glacial debris. Turned into river sediments and deposited as such, these glacial soils would then take on those engineering characteristics. Therefore, considering the results from Table 17, Equations 11 and 13 may be more applicable for design purposes because they are equations derived from non-till clay research.

There are large amounts of clay and high compression indices in the subject site soil cross-section, which differs from research on Glaciated Valley Tills in other parts of the world. This may be due to volcanic rock surrounding the subject site, as previously discussed in the weathering section. As a result, a spread of compression indices at a given site in Sierra Nevada tills may be typical.

Testing Procedures

Difficulties in field-testing are typical in glacial deposits due to the presence of cobbles and boulders. Recovering samples in gravels and sands may present difficulties due to the lack of sample recovery or hard driving in very dense or cemented units. Clarke et al. (2008) and Trenter (1999) had comments concerning sample recovery in their research. Clarke stated that laboratory tests in their research were mainly on clay samples because of the difficulty in sampling the more granular component of the till. Likewise, Trenter stated that there are clear difficulties in using cable tool methods and SPTs in deep glacial successions. As a result, materials that are obtained for lab tests may be predominantly fine-grained.

Where hard driving is realized in very dense coarse-grained units, there may be small recovery of soil samples. Using split-spoon samplers may not result in full recovery of tube samples, requiring a disturbed bag sample instead. In general, Trenter

(1999) states that driven samples may experience induced strains, water content redistribution, and the creation of voids where large clasts are pushed aside by the sampler wall.

The Glaciated Valley tills sampled in this research by Taber Consultants is a good example of the difficulties in recovering samples in glacial deposits and the different sampling methods required. Taber Consultants utilized three different boring methods that consisted of auger, air rotary, and mud rotary. Also, split-spoon samplers were used during SPTs for sample recovery. Using SPT equipment is generally the most inexpensive method of soil investigation. Trenter (1999) states that the SPT is probably the widest used in-situ test for investigating glacial tills. Rock coring may be another viable option for sample collection; however, high water pressures during drilling disturb lower strength materials resulting in no-to-low sample recovery.

Since field tests in glacial tills may result in low sample recovery and disturbed samples, lab testing with reconstituted samples may be the best option. Other field tests may be used to obtain undisturbed samples; however, cost must be considered. Trenter (1999) suggests bulk and block sampling and Cone Penetration Tests (CPTs) as alternatives to the SPT.

As discussed previously, difficulties with in-situ testing in glacial soils can be interrelated to testing methods in IGMs. SPTs in glacial soils at this point are the best alternative for collecting samples for lab testing and gaining SPT *N* values to correlate with lab data. Brooks (2008) suggests the use of in-situ pressuremeter testing as an alternative to SPTs. Pressuremeter testing can be accomplished by open borehole or a special self-boring pressuremeter (Brooks, 2008).

Bulk samples at shallow depths using auger or air rotary may be suitable for dry disturbed samples. However, obtaining samples at greater depths may require wet drilling due to groundwater or hard drilling. Trenter (1999) states that bulk samples gathered in wet conditions might be unsatisfactory because the fines are often washed out. In soil layers with suitable penetration, it may be advantageous to obtain a bulk sample by means of a large diameter split-spoon sampler. Large diameter split-spoon samplers such as the CalMod have a diameter of 2.4-inch as opposed to the smaller 1.4-inch sampler.

Head (as cited in Trenter, 1999) suggests sample quantities for coarse materials by the following relationship:

$$\textit{Mass of sample} = 100 \textit{ x mass of largest particle} \tag{18}$$

With this in mind, coarse materials, such as cobbles and boulders would require a large sample mass; thus, requiring a trial pit. Using a trial pit, block sampling may be utilized for sampling in glacial soils. Trenter (1999) suggests the use of this method in matrix- and some clast-dominant tills where tube samples cannot be acquired. Trenter also suggests the use of this method at depths where excavation by a trial pit is safe and feasible.

CPTs are used as a soil-profiling device and for assessing geotechnical parameters; however, they should be accompanied by borehole control to account for anomalies (Trenter, 1999). Trenter also suggests the use of CPT tests only in clast-dominant clayey sandy gravel with occasional cobbles and matrix-dominant sandy clay with gravel. With respect to Glaciated Valley tills this method may not be feasible due to large layers of gravel, cobbles, boulders, and very dense soil units.

There are stipulations to combining similar samples for lab testing. Atterberg tests should be administered to determine the cohesive nature of fine soils before combining. Also, the soil layers must be classified as either matrix-dominant or clast-dominant. Figure 21 below depicts recommended in-situ and lab tests in matrix-dominant California Glaciated Valley tills.

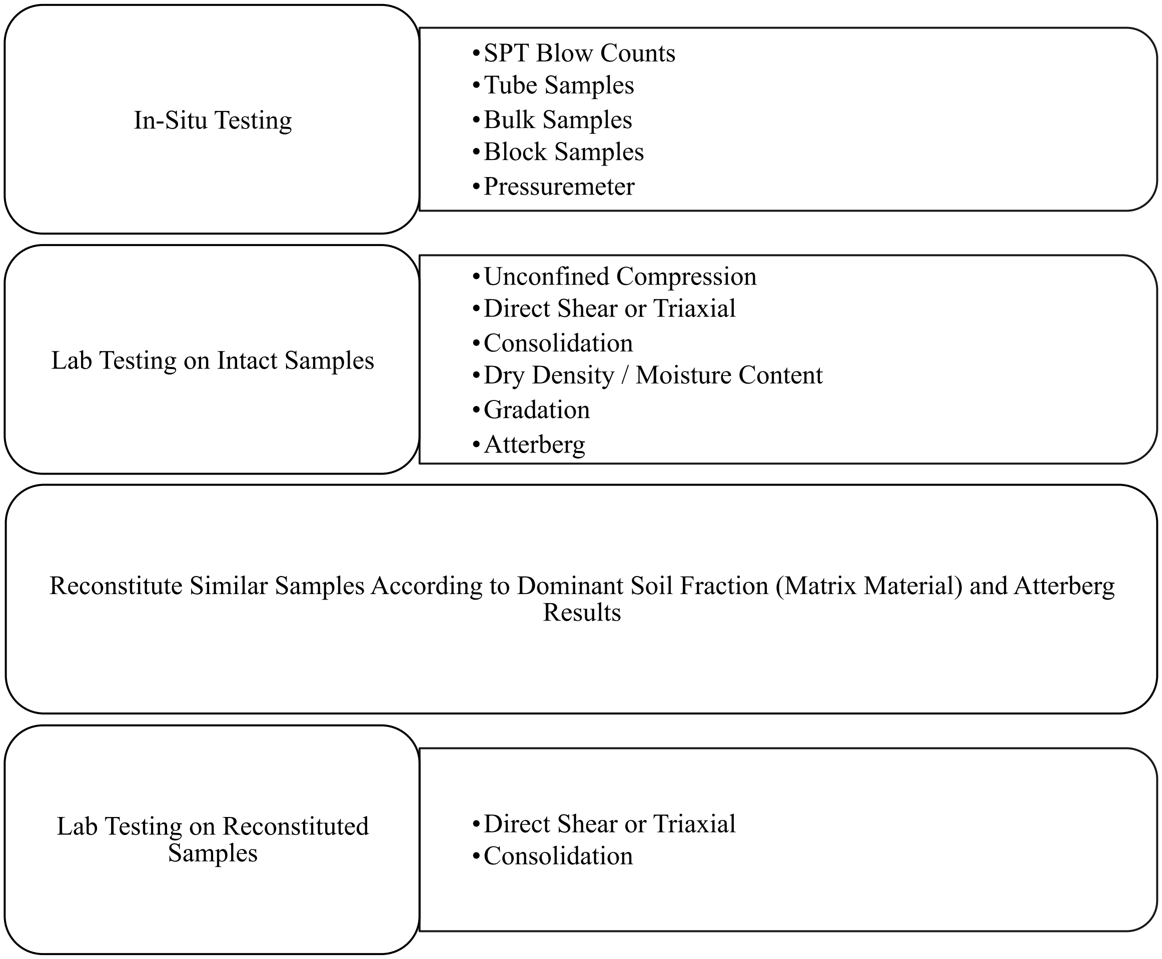


Figure 21. Recommended In-Situ and Lab Tests in Matrix-Dominant California Glaciated Valley Tills

SPT *N* values are appropriate in matrix-dominant material where penetration does not reach refusal. Where there is refusal upon cobbles, boulders, or cemented zones. SPT *N* values may not be representative of the soil layer and should not be used for design purposes. Small diameter or large diameter 1.4-inch or 2.4-inch tube samples are appropriate for fine- or coarse-grained matrix material. Additional material for bulk samples may be collected from large diameter SPT tubes or directly from drill cuttings. Block samples may be collected where there is no recovery from tube samples. Since trial pits are required for block sampling, safety and feasibility must be taken into consideration. Pressuremeter testing, when available, would be the most worthwhile option for in-situ testing as it captures the strength and compressibility of the soil most accurately in the soil's natural state.

Lab testing on intact samples includes unconfined compression, direct shear or triaxial, consolidation, dry density and moisture content, gradation, and Atterberg tests. It is important to complete as many tests as possible on intact samples of any size as they may be more representative of the in-situ soil characteristics. The most common intact sample tests include unconfined compression, dry density, and moisture content, which are completed on small diameter 1.4-inch tube samples. Direct shear and triaxial tests require large diameter 2.4-inch samples. Gradation and Atterberg tests should be completed on intact and bag samples for classification. For block samples, strength and consolidation lab tests should be administered taking into consideration sample orientation.

Once classification of the intact and bag samples are complete, reconstitution of similarly characterized samples for further tests should be completed. This procedure for lab testing is necessary for sites that may have little recovery across an identified soil layer. Also, results of intact sample lab testing from the same soil layer can be compared to these tests for confirmation.

Clast-dominant soils in Glaciated Valley tills are typically made up of gravels and boulders (Trenter, 1999). Little lab testing can be administered on such material unless rock-coring techniques are used in the field. Even then, weaker portions of the sample may be completely disturbed due to high water pressures used during rock coring. Strength testing in the lab would be appropriate for intact rock cores; however, the results would not be indicative of weaker sections lost in sample recovery. Therefore, in clast-dominant lithologies self-boring pressuremeter testing would be appropriate if available. However, Schmidt and Rumpelt (as cited in Brooks, 2008) suggest that pressuremeter testing in IGMs only be used where design is governed by serviceability.

Typically, there are errors during field-testing and lab experiments. SPT *N* values, particularly in glacial tills, can be significantly over-estimated in cobbles and boulders. During SPTs altering of the strength of the soil may develop while driving the sampler. Furthermore, rock-coring techniques can significantly alter the nature of the sample.

With respect to lab experiments, it is likely that an inexperienced lab technician can misjudge Atterberg tests. Several errors could occur during the liquid limit test, such as improper width and depth of the groove, non-uniform soil mixture, improper speed at which the handle is turned, and incorrect final closure length. Likewise, errors in the plastic limit test could come from improper technique in rolling thread and thread not crumbling at 1/8 inch in diameter.

The results of Atterberg tests completed in the SJSU Soils Lab on samples B-1-3 and B-4-8B/9/11/13/14 were silt. These results are similar to the soil units they were sampled, which were also classified as silt. Furthermore, the results are similar to other Atterberg tests that were completed by Taber Consultants in the same soil unit locations. On the other hand, sample B-4-8A had an unexpected result of silt. This could be explained by referring to the Log of Test Borings Figure in Appendix B, page 91. The depth at which sample B-4-8A was collected is at a gradational contact where clay material is above and silt material is below.

Conclusions

Four major conclusions can be identified from this research in regards to in-situ and lab testing of glacially derived soils in the Sierra Nevada. First, Sierra Nevada glacial tills may have large amounts of clay in a typical soil profile. This is due to the presence of volcanic rock within glacial debris undergoing neoformation in an area susceptible to high amounts of precipitation and groundwater. This is evident from testing completed at the subject site where large amounts of clay deposits along with evidence of weathering are in the soil profile. Furthermore, typical values of plasticity in Glaciated Valley research in other parts of the world do not support the data that was collected at the Sierra Nevada subject site. Plasticity values in the Sierra Nevada may range from low to high, affecting the compressibility characteristics of fines material which would in turn range from low to high.

Second, SPT *N* values can be correlated with depth for matrix material where blow counts and sampling are inconsistent due to refusal. These areas of refusal result in no practical design SPT *N* value and little to no sample recovery for lab tests. Correlating the SPT *N* value is useful in glacial till profiles that have some amount of cobbles and boulders or show signs of soil strengthening from weathering. Since SPT *N* values generally increase with depth, this correlation may be used to obtain friction angles, for design purposes, where none can be obtained otherwise.

Third, unconfined compression strength tests are independent of depth regarding coarse-grained material with no cohesive binder. This is due to the testing method, which utilizes no confining pressure to hold the sample together during testing. These types of test results may not be applicable in design because they may severely underestimate the compressive strength of coarse-grained materials with no cohesive binder.

Lastly, the matrix material dominates direct shear and consolidation lab test results. The samples tested were classified as silty sand with trace gravel. However, the results of the friction angle and coefficient of consolidation were related to typical values of silt rather than sand. This conclusion can be applied to large glacial till layers that show little sample recovery other than the matrix material. Since the matrix material takes on the engineering properties of the soil layer, test results for friction angles and the coefficient of consolidation may be indicative of the entire soil layer.

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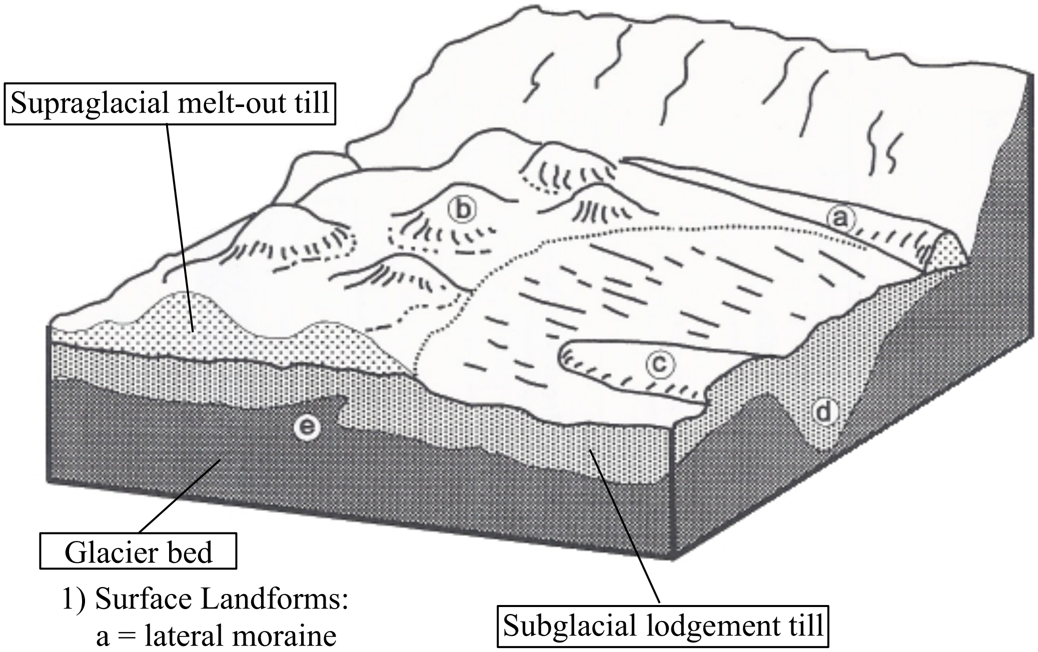
Appendix A – Definitions

Term	**Definition**
1. Basal and Ablation Till	These are also broad terms in glacial geology. Basal till is essentially the soil at the base of a glacier and ablation till is the soil carried near the surface of the glacier (Plummer, Carlson, and Mcgeary 2007).
2. Clast	An individual constituent grain, or fragment of a detrital sediment or sedimentary rock, produced by the physical disintegration of a larger rock mass (Bates and Jackson, 1984).
3. Comminution Till	Very dense till that appears to have been formed by abrasion of bedrock and the crushing of detritus dragged along underneath the ice, accompanied by a mixing process that results in the incorporation of rock powder produced by abrasion at the till-rock interface into the overlying glacial load (Evans, Phillips, Hiemstra, and Auton, 2006).
4. Crag and Tail	A streamlined hill or ridge, resulting from glaciation and consisting of a knob of resistant bedrock (the “crag”), with an elongated body (the “tail”) of more erodible bedrock, till, or both, on its leeside (Bates and Jackson, 1984).
5. Deformation Till	A rock or sediment that has been disaggregated and completely or largely homogenised by shearing in a subglacial deforming layer (Evans, Phillips, Hiemstra, and Auton, 2006).
6. Diamicton	Essentially another term for till. In general, it is described as a poorly sorted (well-graded), poorly stratified sediment. Till also has a broad definition as a sediment directly deposited by glacial movement with little to no sorting (Stephenson, Flemming, and Mickleson 1988).
7. Drumlins	Similar to lateral moraines in shape because they are formed parallel to the direction of glacial movement. They are described as till shaped into streamlined hills. However, it is uncertain how they were shaped by glaciers (Plummer et al., 2007).
8. En-Echelon Joints	Said of geologic features [such as joints] that are in an overlapping or staggered arrangement, “in step-like arrangement” (Bates and Jackson, 1984).
9. Englacial	Contained, embedded, or carried within the body of a glacier or ice sheet (Bates and Jackson, 1984).
10. Esker	A long, sinuous ridge of sediment deposited by glacial meltwater (Plummer et al., 2007).
11. Glacial Drift	A general term applied to all rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier. This category is also used for Glacial sediment (Glacial Drift, n.d.).
12. Glacial Marine Sediment	Deposits of glacially eroded, terrestrially derived sediment in the marine environment (Glacial Marine Sediment, n.d.).
13. Glacial Outwash Sediment	Stratified detritus (chiefly sand and gravel) removed or "washed out" from a glacier by meltwater streams and deposited in front of or behind the end moraine or the margin of an active glacier. This category is also used for outwash (Glacial Outwash Sediment, n.d.).

14. Glacial Polish	Shiny rock surfaces created by the grinding of rock fragments contained within a moving glacier (Harden, 1998).
15. Glacigenic Debris	Debris formed by glaciation (Trenter, 1999).
16. Glacigenic Sediments	Sediments formed by glaciation (Trenter, 1999).
17. Glaciofluvial deposits	Stream deposits associated with glacial activity. The term outwash is used in conjunction as glaciofluvial sediment deposited by streams flowing away from the glacier (Stephenson et al., 1988).
18. Glaciolacustrine Deposits	Lake deposits associated with glacial activity. These are generally well-sorted (poorly-graded) sand, silt, or clay deposits with well developed to absent stratification (Stephenson et al., 1988).
19. Glaciolacustrine Sediments	Deposits and landforms composed of suspended material brought by meltwater streams flowing into lakes bordering the glacier, such as deltas, kame deltas, and varved sediments. This category is also used for glaciolacustrine (Glaciolacustrine Sediments, n.d.).
20. Glaciotectonite	Intact thrust block that has been moved short distances and imbedded in till (Brockman, 2000).
21. Glaciotectonite	Rock or sediment that has been deformed by subglacial shearing (deformation) but retains some of the structural characteristics of the parent material (Evans, Phillips, Hiemstra, and Auton, 2006).
22. Gleying	A soil-forming process occurring under conditions of oxygen reduction. Gleying is promoted by microorganisms, the presence of organic substances, and the constant or prolonged flooding of individual horizons or the entire soil profile (Gleying, n.d.).
23. Hummocky Moraine	An area of knob and kettle topography that may have been formed along a live ice front or around masses of stagnant ice (Bates and Jackson, 1984).
24. Kettles and Kames	Associated with outwash. A kettle is formed where blocks of stagnant ice are trapped within outwash deposits. When the ice melts a depression is formed. Kames are irregular ridges formed of outwash deposits on a stagnating glacier (Plummer et al., 2007).
25. Lamina	The thinnest recognizable layer in a sediment, differing from other layers in color, composition, or particle size; commonly 0.05 to 1.00 mm thick (Bates and Jackson, 1984).
26. Landform	A specific geomorphic feature on the surface of the earth (Landform, n.d.).
27. Lee-Side Cavities	A cavity that forms on the down-ice side of uneven beds or roches moutonnées (Evans, Phillips, Hiemstra, and Auton, 2006).
28. Lee-Side Cavity-Filled Deposits	Wedge-shaped masses of massive to crudely stratified diamictons with steeply dipping lenses of water-sorted sediments. Clasts are striated and possess a strong down-valley dipping fabric. Although much of the material has been emplaced by non-glacial processes (Evans, Phillips, Hiemstra, and Auton, 2006).
29. Lodgement Till	Sediment deposited by plastering of glacial debris from a sliding glacier sole due to the combined effects of pressure melting and frictional drag (Evans, Phillips, Hiemstra, and Auton, 2006).

30. Meltwater	Water that comes from the melting of snow or ice (Meltwater, n.d.).
31. Moraines	Consist of unsorted and unlayered debris mounded either on a glacier or left behind by a glacier. There are four types of moraines, those being lateral, medial, end, and ground moraines. A lateral moraine forms along the sides of a valley glacier. A medial moraine forms where adjacent lateral moraines join where tributary glaciers come together. An end moraine is formed along the front edge of an advancing glacier. A ground moraine covers large areas and are thin layers or blankets of till deposited as an ice sheet melts (Plummer et al., 2007). Moraines show in the subsurface as lenses of till and boulders (Stephenson et al., 1988).
32. Outwash	Material deposited by meltwater that runs over, beneath, and away from the glacier (Plummer et al., 2007).
33. Roche Moutonnée	In the Sierra Nevada, granitic mounds streamlined underneath glaciers that formed asymmetrical domes that point in the direction of ice flow (Harden, 1998).
34. Rock flour	Created from the grinding of rock on rock and is composed of silt to clay-sized particles (Plummer et al., 2007).
35. Rock Rafts	Also known as bedrock rafts in the drift or megablocks. Slabs of bedrock resting on layers of drift, often buried by other drift. Some are quite extensive, covering areas of up to several hundreds of km^2. They may be deformed, or associated with deformation of the surrounding drift (Cox, 2006).
36. Rockhead	Top of bedrock (Trenter, 1999).
37. Scree	Any loose fragmental material lying in or mantling a slope; loose equivalent of talus, rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived (Bates and Jackson, 1984).
38. Slickenside	A polished and striated rock surface that results from friction along a fault plane (Bates and Jackson, 1984).
39. Stratified Glacial Sediment	Stratified glacial drift deposited by, or reworked by running water, or deposited in standing water. This category is also used for stratified drift (Stratified Glacial Sediment, n.d.).
40. Striated Rockhead	Scratches or parallel grooves on the surface of rock (Plummer et al., 2007).
41. Sub/Supra Glacial Sediment	A variety of irregularly stratified sand and gravel deposits, such as eskers, kames, etc., that were deposited by a subglacial or supra-glacial stream or pond and were left behind when the ice melted (Sub/Supra Glacial Sediment, n.d.).
42. Subglacial Melt-Out Till	Deposition of stratified sediments and diamictons beneath glaciers and ice sheets (Evans, Phillips, Hiemstra, and Auton, 2006).
43. Subglacial	Formed or accumulated in the bottom parts of a glacier; said of meltwater streams, till, moraine, etc. (Bates and Jackson, 1984).

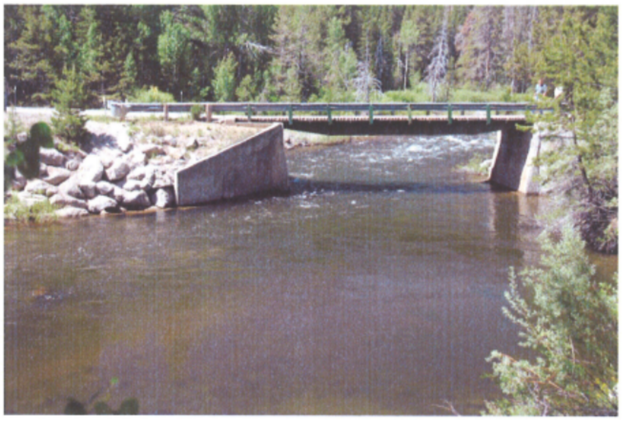
44. Subglacial Sliding Bed Deposits	Products of lodgement and melt-out: Non-deformed lenses and stringers of waterlaid sediment and slickensided fissures typical of lodgement. Deposition in a water film at the ice-bed interface and association with stratified units suggest deposition by passive melt-out (Evans, Phillips, Hiemstra, and Auton, 2006).
45. Terminal and Recessional Moraines	A terminal moraine marks the farthest advance of a glacier. A recessional moraine is created when a receding glacier is temporarily stationary (Plummer et al., 2007).



1) Surface Landforms:
   a = lateral moraine
   b = hummocky moraine
   c = drumlin
2) Sediment sequence:
   Hatched areas called out above
3) Bedrock topography:
   d = buried meltwater channel
   e = buried roche moutonnée

Figure A-1. Diagram Illustrating the Three Main Components of a Landsystem. Reprinted from *Engineering in glacial tills* (p. 28), by N. A. Trenter, 1999, London, England: Alden Press, Oxford. Copyright 1999 by CIRIA. Reprinted with permission.

Appendix B – Taber Consultants Foundation Report



The site is in the bottom of the downstream portion of an alpine glacial valley within the Sierra Nevada geomorphic province, in the "Walker Lane," near the border with the basin and range province to the east. Topography at the bridge location is relatively gentle, but steep terrain immediately to the north rises to peaks above USGS elev. 7000 feet. More gentle sloping terrain extends approximately 1.5-2 miles to the south and southwest before ascending steeply to similar elevations.

Gentle terrain is typical between high ridges within alpine glacial valleys in the Sierra. Intersecting vertical strike-slip and normal faults to the east and southeast of the site have helped define the network of bisecting shallow streams and valleys cut into the glacial and volcanic deposits. The confluence of Independence Creek and Little Truckee River is about 1.5±miles east of the site, with Independence Creek approaching from the south. Upstream of the site, Little Truckee River meanders from Webber Lake through flatter portions of the valley. The meandering portion of the river is interrupted by zones where the river incises through glacial moraines or volcanic flows.

Bedrock is not exposed in the channel or channel banks immediately upstream and downstream of the bridge. Exposed materials consist primarily of boulder, cobble, and gravel-sized rock particles in the channel. Native clayey soils were also locally observed in the channel bottom downstream of the bridge. The low channel (thalweg) elevation at the upstream edge of the existing bridge was measured at elev. 6359±, 8.2±feet below the water surface on September 7, 2011.

Per the Caltrans inspections of the bridge, scour has been a major factor for the existing bridge structure, as both abutments experienced major scour in 1997, including undermining of the Abutment-2 footing. Grouted rip-rap, or "slope-paving," placed at both abutments after 1997 has experienced under-mining of up to 1.5± vertical feet per our field measurements. We did not measure horizontal under-mining, but the 2008 Caltrans inspection measured horizontal scour under the slope-paving at Abutment-2 at 4 to 5 feet (or possibly more) and 8 feet at Abutment-1. Current rip-rap slope protection upstream and downstream of the slope-paving did not appear to be majorly scoured, and may have been placed since the 2008 inspection.

The upstream corner of Abutment-2 (right bank) is being directly attacked by flow that is following the relatively-steep thalweg, aligned directly towards it for about 700±feet upstream of the bridge. The abutment deflects the flow about 40-degrees to the left, where it flows northeast along the abutment face before making a 40 to 50-degree right turn as it follows the downstream wingwall and disperses across the rest of the channel. Scour noted on the downstream portion of Abutment-1 (left bank) is likely due to an eddy observed along the left bank.

Exploration and Testing

The subsurface exploration at the site was obtained by means of two logged and sampled solid auger/concentrix air/mud rotary test borings (B-3 and B-4) penetrating to maximum depth of 71.0±ft (elev. 6312±). Borings B-1 and B-2 were shallow roadway borings not adjacent to the bridge location; results of our roadway field investigation and laboratory testing for these two borings have been provided under separate cover.

Soil samples were recovered from the borings by means of a 1.4-inch I.D. "Standard Penetration" (per ASTM D1586) split-spoon sampler as well as 2.4-inch and 2.5-inch I.D. split-spoon samplers advanced with standard 350 ft-lb striking force (ASTM D1586) using our calibrated automatic trip hammer to provide an estimation of soils consistency. Field-recorded blow counts are presented in the "Log of Test Borings" drawing. The hammer used during our investigation has an average energy rating of 109% per an energy calibration performed on July 20, 2011.

Borings were logged and earth materials field-classified by a geologist as to consistency, color, gradation and texture on the bases of sampler penetration resistance, and examination and inspection of samples and drill cuttings. Groundwater observations were made in the borings during drilling operations. Borings were backfilled with bentonite chips (to help with groundwater conditions, see below) and bentonite-cement grout upon completion of drilling operations.

Selected portions of recovered soil samples were retained in sealed containers for laboratory testing and reference. Testing included moisture content-dry density determinations, unconfined compressive strength, gradation, Atterberg Limits, and corrosivity testing (minimum resistivity, pH, chloride, and sulfate).

Locations, elevations, and details of borings are shown in the "Log of Test Borings" drawing. Laboratory results are shown in Appendix-A. Glen G. Wade, P.G., was the field geologist for this study. Borings were completed on September 7 and 8, 2011.

Earth Materials and Foundation Conditions

The site is shown on available geologic maps (Geologic map of California: Chico sheet, CGS, 1992) as consisting of Quaternary Alluvium over Quaternary Glacial Deposits and/or Miocene-Pliocene Volcanic Rocks. In the vicinity of the subject site, the Quaternary Alluvium is confined to an area close to the channel of the creek. This alluvium appears to overlay both Quaternary Glacial Deposits and Miocene-Pliocene

Volcanic Rocks with Quaternary Glacial Deposits shown to the south of the creek and Miocene-Pliocene Volcanic Rocks to the north of the channel.

The Quaternary Alluvium is described as undivided alluvial deposits of unconsolidated gravel, sand, and silt. Locally it may include fan deposits, colluviums, and older alluvium. The materials found in our borings generally agree with this description except that large quantities of cobbles and boulders were encountered. Alluvium in this area is likely closely-derived from eroding glacial deposits.

Quaternary Glacial Deposits are described as undivided glacial till, moraine, and outwash deposits. These deposits are mapped over a large area south of the creek channel. The younger Quaternary Alluvium deposit is likely derived in part from this material that likely underlies the project site.

Miocene-Pliocene Volcanic Rocks are shown underlying the area to the north of the creek channel and also outcrop south of the Quaternary Glacial Deposits found south of the channel. These materials are described as Andesite, undivided, north of the site and Andesite flows, locally including interbedded lahars, south of the site. It is likely that these materials are found at depth below the entire site and the Quaternary Alluvium may be derived in part from these materials.

Materials encountered in the borings can be divided into two generalized units comprised of fill and native soils.

Fill and Near Surface Soil

Fill material was encountered in the upper portion of B-3 to 4±foot depth (elev. 6379±) and at the surface in B-4 to a depth of 12±feet (elev. 6368±). The fill material was semicompact/very dense cobbles and boulders with a matrix of silty and/or clayey sand with gravel. This unit also includes recent river channel deposits and material observed at the surface in the channel and along the banks. The exposed material in the channel and banks contained gravel and cobbles with sand and significant quantities of boulders up to 3-4 feet in diameter. These soils are not expected to be capable of supporting significant foundation and/or fill loads without distress, as high blow counts are due to encountered cobbles and boulders, not high relative compaction.

Native Soils

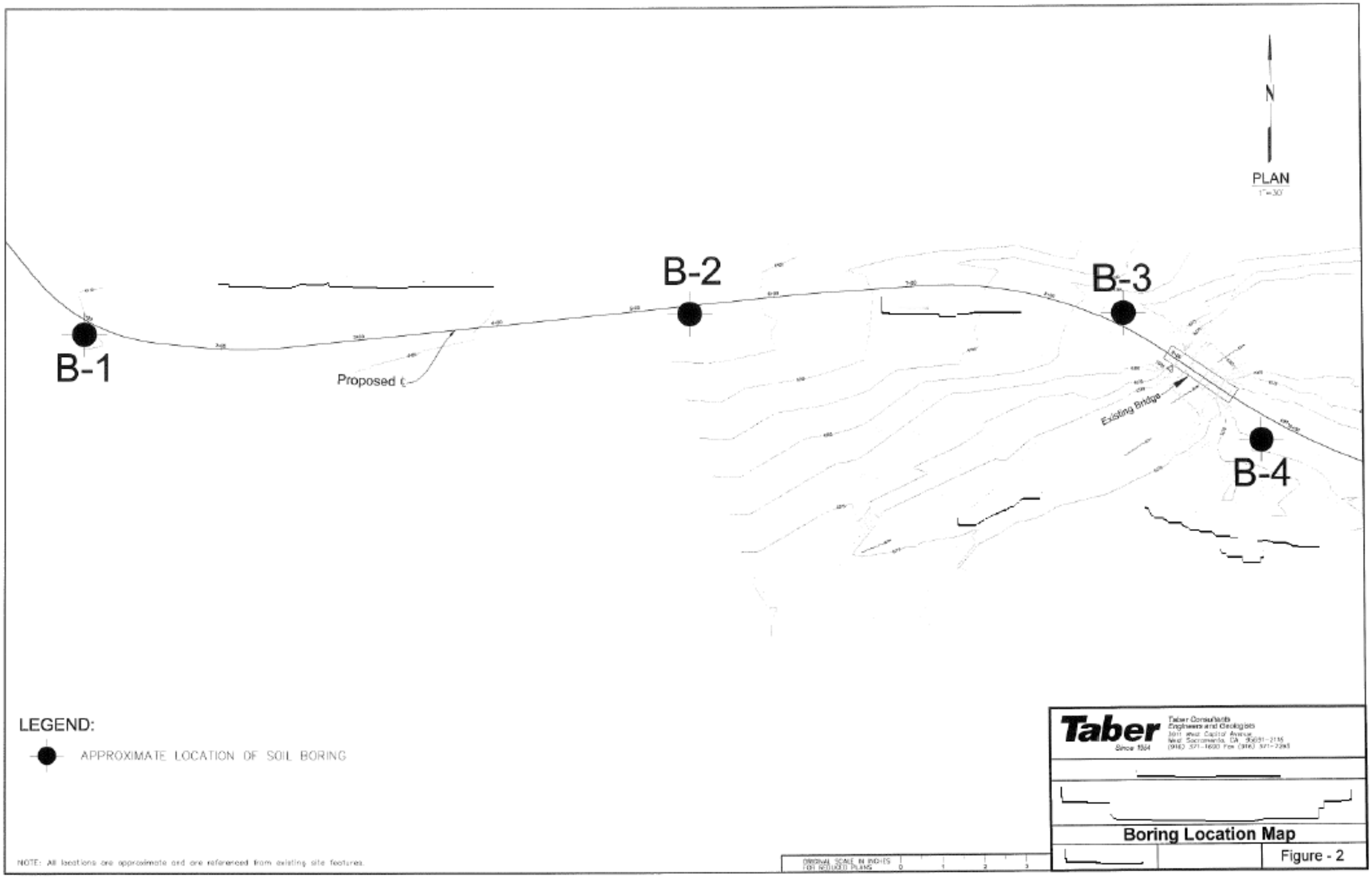
Native soils were encountered below the fill to the maximum depth explored in our test borings. These soils consist of interbedded layers of granular and fine grained soils. Native soils are interpreted as glacial outwash, till and/or moraine, along with lake or streambed, terrace, and/or ash deposits. These materials are generally described as:

- sand and gravel soils with boulders and cobbles and some silt or clay;
- sandy lean to fat clays; and
- silty sands and sandy silts.

Cobbles and boulders were generally encountered above elev. 6364; however occasional cobbles or boulders below this elevation would not be unexpected. Boulder dimensions up to 5 feet in diameter were noted either during drilling or at ground surface in the project vicinity (near the surface in B-4, at the outboard edge of the road near B-3, and in the channel).

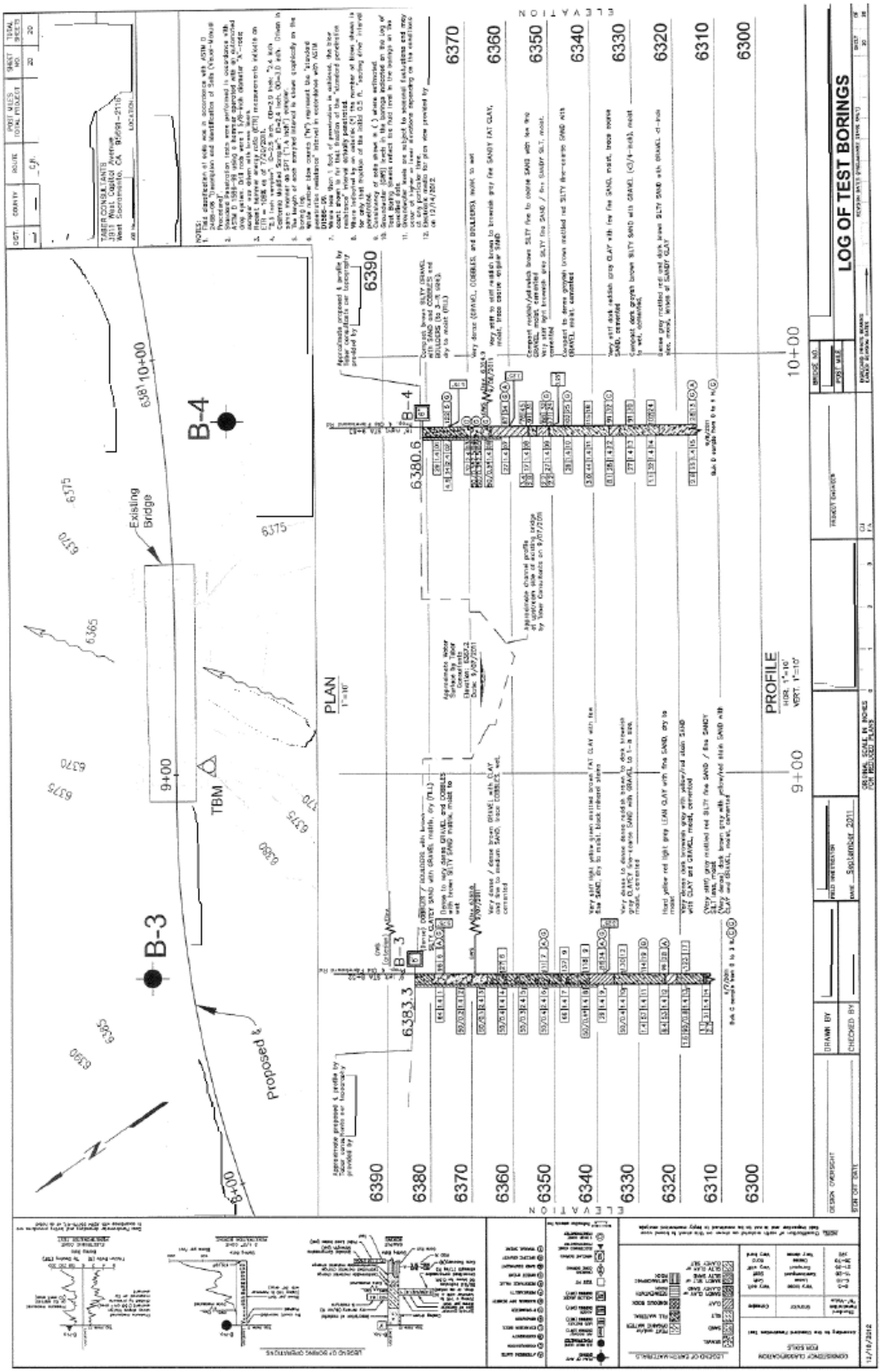
Soils encountered were variably cemented in the more granular zones. Granular materials are generally compact to dense in nature, with higher blow counts observed in the soils with higher cobble/boulder fractions due to sampler refusal on these larger rock particles.

Fine grained soils primarily consisted of layers of lean and fat clays and were generally very stiff to hard in consistency.



Boring Location Map

Figure - 2


LOG OF TEST BORINGS
PLAN
1"=10'
PROFILE
HOR. 1"=10'
VERT. 1"=10'
B-3
B-4
Existing Bridge
Proposed ℄
TBM
8+00
9+00
10+00
6383.3
6380.6
ELEVATION
6390
6380
6370
6360
6350
6340
6330
6320
6310
6300
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3911 West Capitol Avenue
West Sacramento, CA 95691-2116
NOTES:
DESIGN OVERSIGHT
DRAWN BY
CHECKED BY
FIELD INVESTIGATION
DATE September 2011
LEGEND OF BORING OPERATIONS
LEGEND OF EARTH MATERIALS
CONSISTENCY CLASSIFICATION FOR SOILS
12/18/2012

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TEST BORING LOG

Job No. 2011-0055

STATION: 8.6' right STA 3+50
SURFACE ELEVATION: 5029.4

TYPE: 6-INCH SOLID FLIGHT AUGER

BORING NO B-1

UNCONFINED COMPRESSIVE STRENGTH (tsf)	OTHER TESTS	DRY DENSITY (lbs/cu. ft.)	Moisture (%)	BLOWS/FOOT 350 ft-lb	SAMPLE SIZE (inches)	SAMPLE No.
1.8	G	121	9	29	1.4	01
						Bulk A
		92	6	50/0.3	2.4	02
		106	20 5	54	2.5	03

DEPTH IN FEET	UNIFIED SOIL CLASSIFICATION	
0.1		AC grindings (road surface)
4.0	SM	Compact, brown/dark brown SILTY fine to coarse SAND with fine-coarse gravel and occassional cobbles to 6" size (FILL)
5.5	SM	(Compact) dark brown SILTY SAND with gravel and organics (native ground surface)
8.5	SP-SM	(Very dense), light brown SAND with silt and gravel (to 2.5-inch size), moist
10.8	SM/ML	(Semicompact / stiff) SILTY fine SAND / fine SANDY SILT, wet from perched water
11.5	SP	(Compact to dense), gray medium-coarse SAND with gravel and trace silt

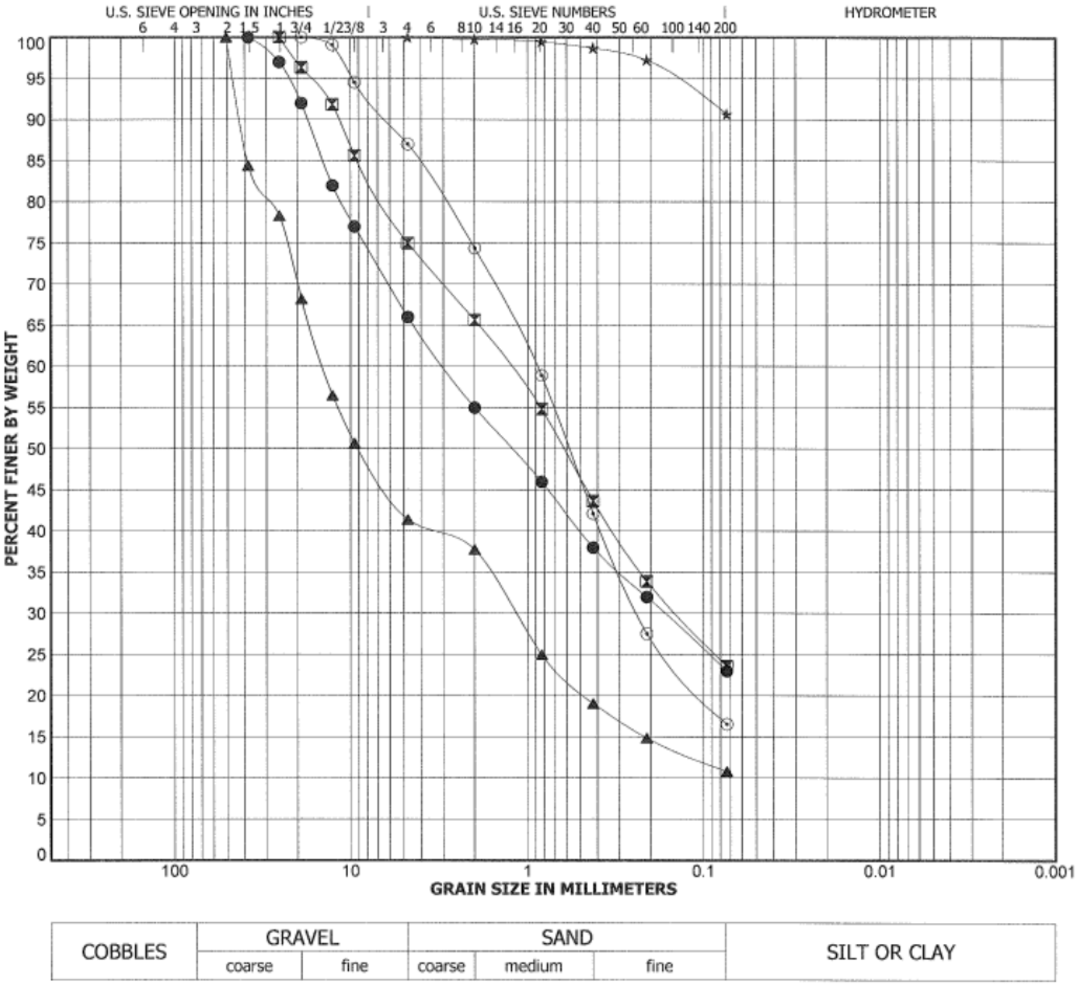
Bottom of hole at 11.5 feet.

Less than 1-inch of water after 1/2 hour.

MATERIAL SYMBOL

LOGGED BY: GGW

DATE: 09-06-2011



	Boring/Sample	Depth	Description	LL	PL	PI	Cc	Cu
●	B-3 / Bulk C	0.0						
⧗	B-3 / 01	5.0	SILTY SAND with GRAVEL(SM)	23	NP	NP		
▲	B-3 / 06	30.0		27	16	11		
★	B-3 / 09	44.0	FAT CLAY(CH)	58	25	33		
⊙	B-3 / 11	54.0						

	Boring/Sample	Depth	D100	D60	D50	D30	D10	%Gravel	%Sand	%Silt	%Clay
●	B-3 / Bulk C	0.0	38.1	2.963	1.229	0.167		34.0	42.8	23.2	
⧗	B-3 / 01	5.0	25.4	1.266	0.623	0.142		25.0	51.2	23.8	
▲	B-3 / 06	30.0	50.8	14.346	9.035	1.175		58.6	30.5	10.9	
★	B-3 / 09	44.0	4.75					0.0	9.2	90.8	
⊙	B-3 / 11	54.0	19.05	0.885	0.582	0.237		13.0	70.3	16.7	

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GRAIN SIZE DISTRIBUTION

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Project No.

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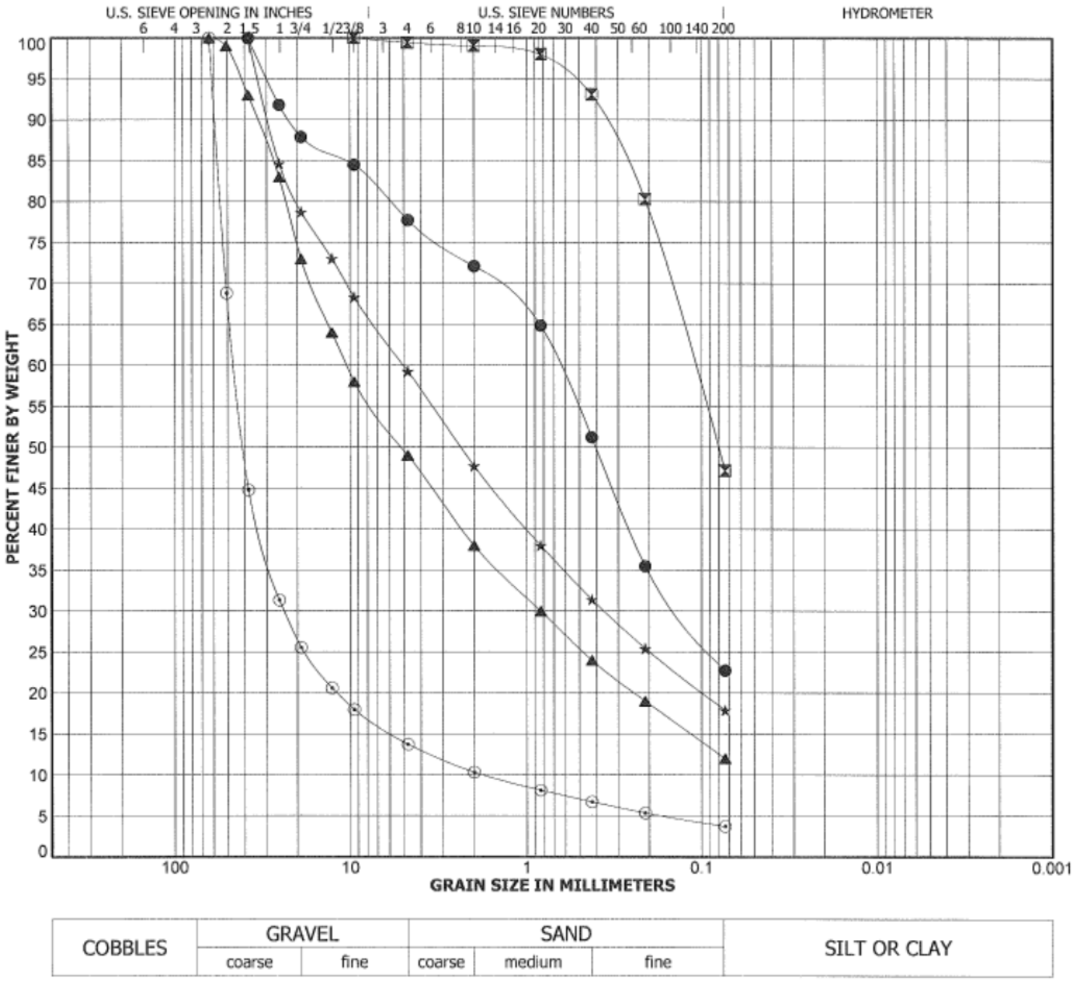
FIGURE-3



	Boring/Sample	Depth	Description	LL	PL	PI	Cc	Cu
●	B-3 /	70.2						
⧗	B-3 /	70.5						
▲	B-4 / Bulk D	0.0						
★	B-4 / 02	5.0						
⊙	B-4 / 03	10.0	POORLY GRADED GRAVEL(GP)				7.03	26.06

	Boring/Sample	Depth	D100	D60	D50	D30	D10	%Gravel	%Sand	%Silt	%Clay
●	B-3 /	70.2	38.1	0.655	0.402	0.134		22.3	54.8	23.0	
⧗	B-3 /	70.5	9.5	0.111	0.081			0.6	51.7	47.7	
▲	B-4 / Bulk D	0.0	63.5	10.465	5.13	0.833		51.0	36.9	12.1	
★	B-4 / 02	5.0	38.1	5.02	2.372	0.36		40.7	41.2	18.0	
⊙	B-4 / 03	10.0	63.5	45.703	40.55	23.74	1.754	86.3	10.0	3.8	

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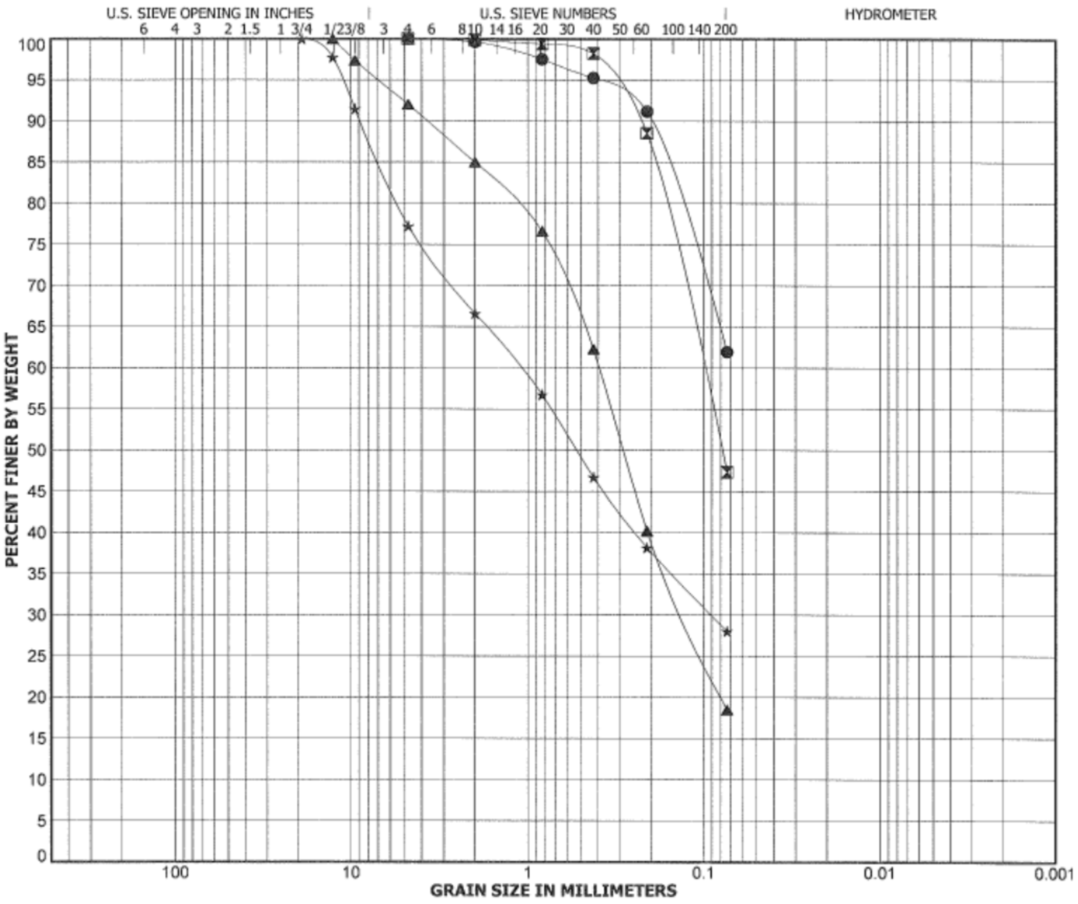
FIGURE-3



COBBLES	GRAVEL		SAND			SILT OR CLAY
	coarse	fine	coarse	medium	fine	

	Boring/Sample	Depth	Description	LL	PL	PI	Cc	Cu
●	B-4 / 07	19.0	SANDY FAT CLAY(CH)	50	22	28		
⧗	B-4 /	29.6						
▲	B-4 / 10	34.0						
★	B-4 / 15	64.0	SILTY SAND with GRAVEL(SM)	34	26	8		

	Boring/Sample	Depth	D100	D60	D50	D30	D10	%Gravel	%Sand	%Silt	%Clay
●	B-4 / 07	19.0	4.75					0.0	37.5	62.5	
⧗	B-4 /	29.6	4.75	0.102	0.079			0.0	51.9	48.1	
▲	B-4 / 10	34.0	12.7	0.395	0.288	0.129		8.0	73.1	18.9	
★	B-4 / 15	64.0	19.05	1.11	0.529	0.09		22.8	49.0	28.2	

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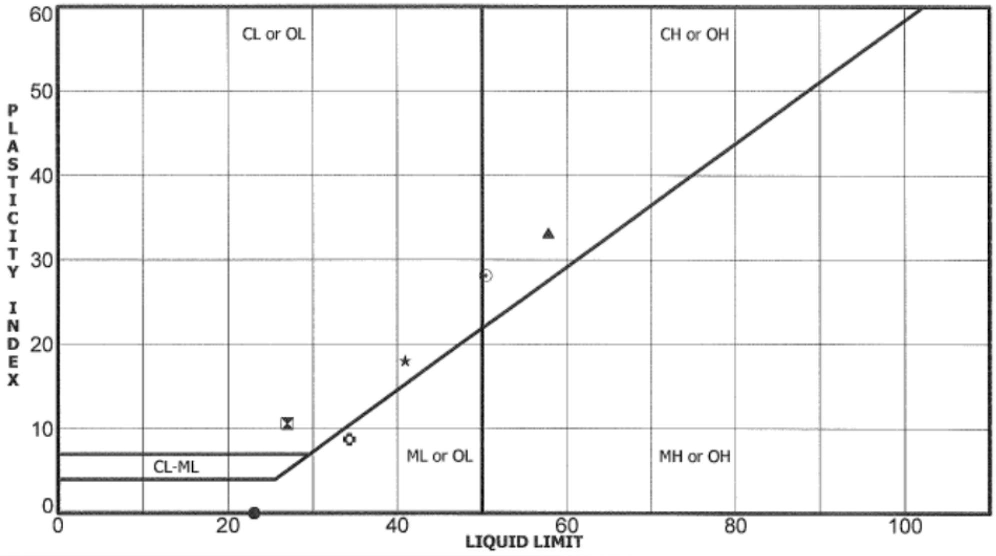
FIGURE-3



	Boring/Sample	Depth	Description	LL	PL	PI	Fines
●	B-3 / 01	5.0	SILTY SAND with GRAVEL(SM)	23	NP	NP	24
⧗	B-3 / 06	30.0		27	16	11	11
▲	B-3 / 09	44.0	FAT CLAY(CH)	58	25	33	91
★	B-3 / 12	59.0		41	23	18	
⊙	B-4 / 07	19.0	SANDY FAT CLAY(CH)	50	22	28	62
✪	B-4 / 15	64.0	SILTY SAND with GRAVEL(SM)	34	26	8	28

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ATTERBERG LIMITS RESULTS

Project No.

FIGURE-3

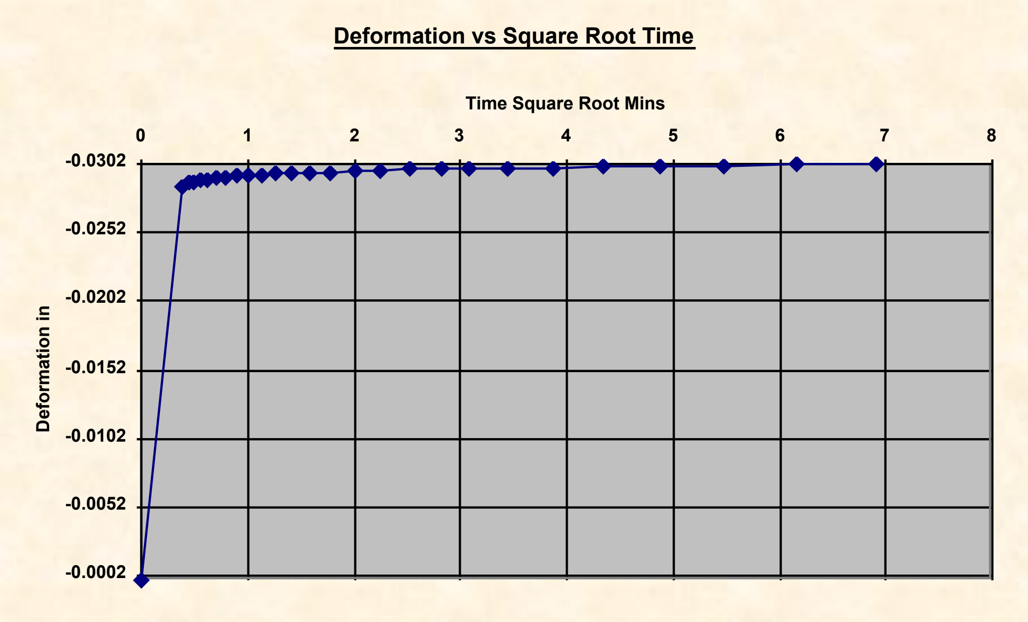
Appendix C – Direct Shear and Consolidation Test Results on Sample B-1-3

Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

Test Details			
Standard	ASTM D3080-03 / AASHTO T236-92	**Particle Specific Gravity**	1.65
Sample Type	Bulk disturbed sample	**Single or Multi Stage**	Single Stage
Lab. Temperature	70.0 deg.F	**Location**	
Sample Description			
Variations from procedure	None		

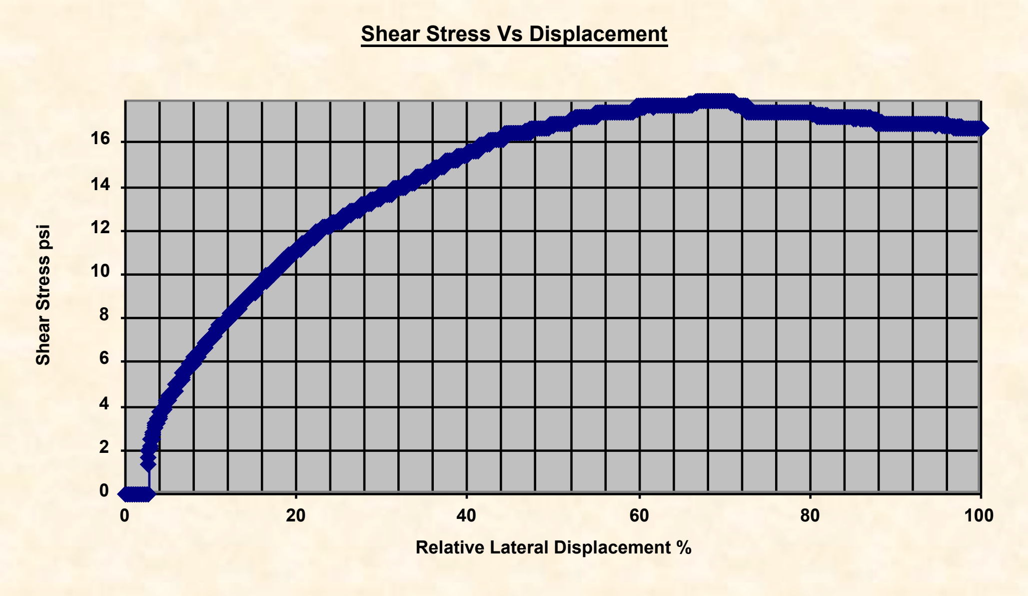
Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.6500in	**Orientation within Sample**	
Initial Height	1.3000 in	**Area**	4.87000 in2
Structure / Preparation		**Initial Water Content***	0.0 %
Initial Wet Unit Weight	90.60 lbf/ft3	**Degree of Saturation**	0.00 %
Initial Dry Unit Weight	90.60 lbf/ft3	**Initial Voids Ratio**	0.137
Final Wet Unit Weight	88.18 lbf/ft3	**Final Water Content**	0.00%
Final Dry Unit Weight	88.18 lbf/ft3	**Dry Mass**	0.3318 lb
Tested Dry or Submerged	Dry		
Comments			

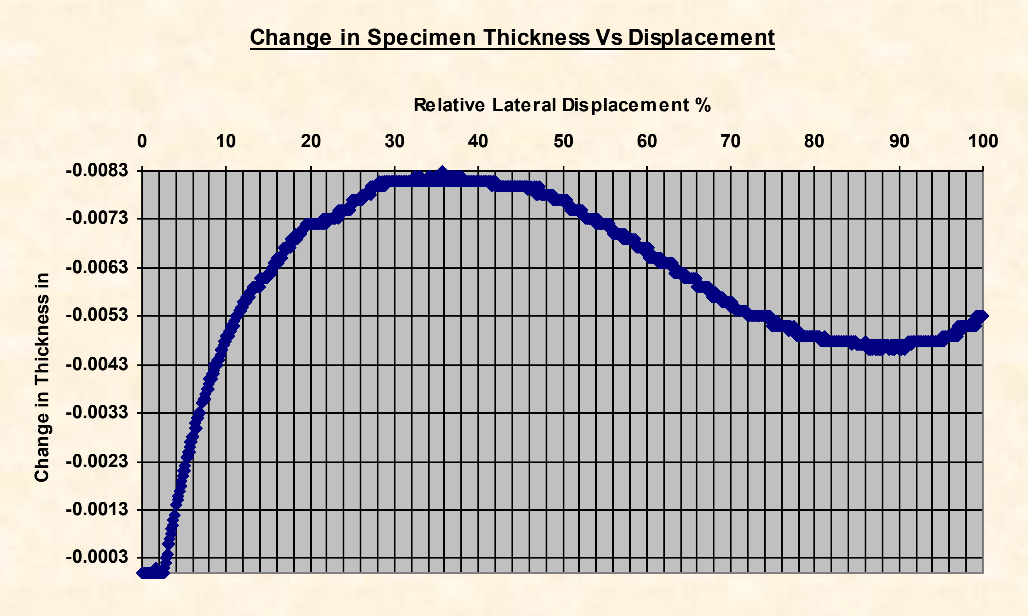
* Calculated from initial and dry weights of whole specimen



Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

Rate of Horizontal Displacement	Stage 1: 0.005000in/min





Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

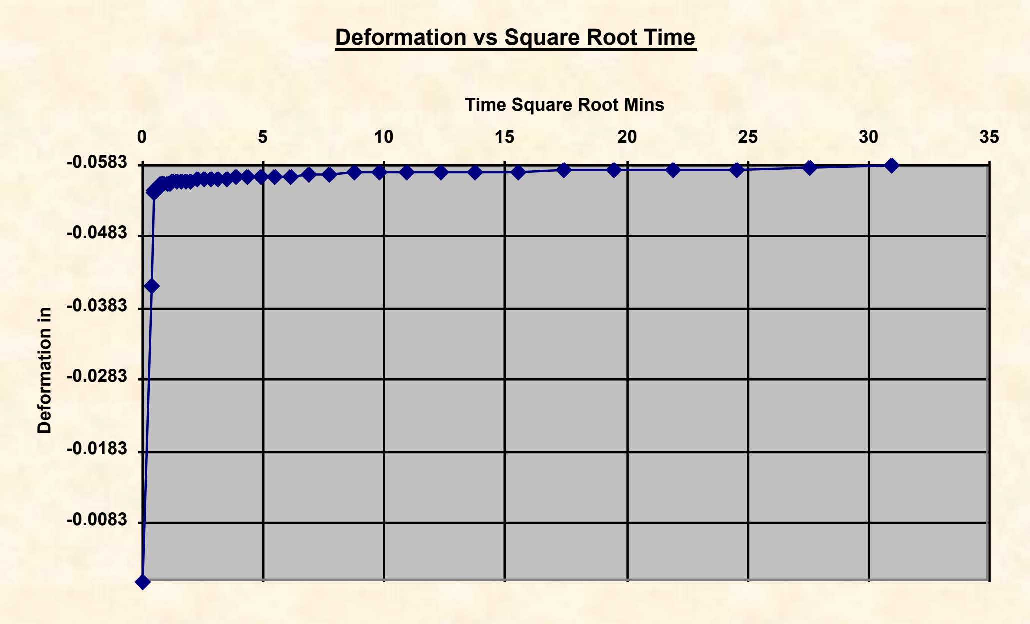
Conditions at Failure	
Normal Stress	18.1 psi
Peak Strength	17.92 psi
Horizontal Deformation	0.0034 in
Residual Stress	0.00 psi
Vertical Deformation	-0.0303 in

Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

Test Details			
Standard	ASTM D3080-03 / AASHTO T236-92	**Particle Specific Gravity**	1.65
Sample Type	Bulk disturbed sample	**Single or Multi Stage**	Single Stage
Lab. Temperature	70.0 deg.F	**Location**	
Sample Description			
Variations from procedure	None		

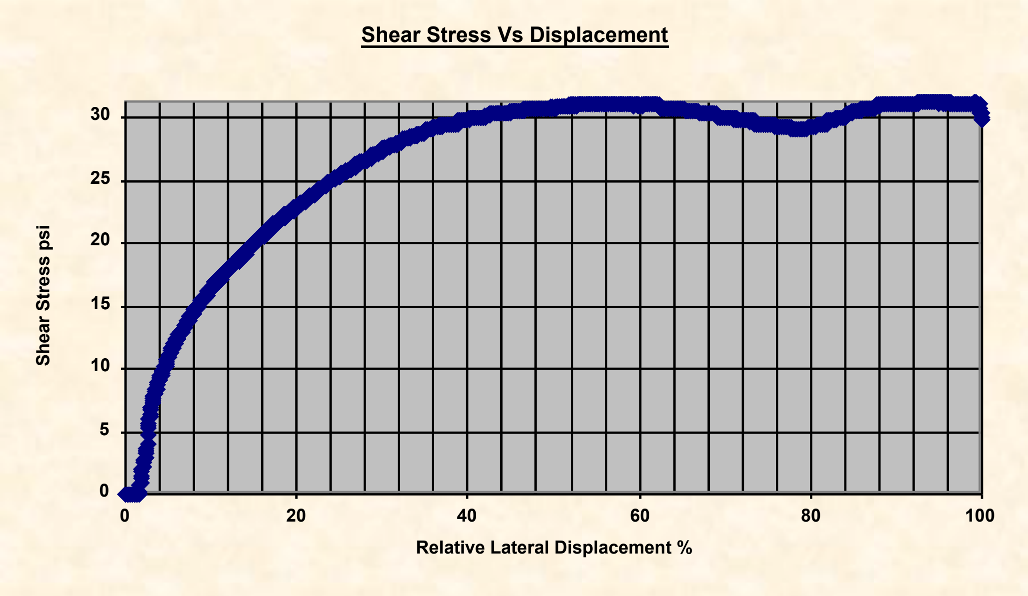
Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.6500in	**Orientation within Sample**	
Initial Height	1.3000 in	**Area**	4.87000 in2
Structure / Preparation		**Initial Water Content***	0.0 %
Initial Wet Unit Weight	87.05 lbf/ft3	**Degree of Saturation**	0.00 %
Initial Dry Unit Weight	87.05 lbf/ft3	**Initial Voids Ratio**	0.184
Final Wet Unit Weight	79.51 lbf/ft3	**Final Water Content**	0.00%
Final Dry Unit Weight	79.51 lbf/ft3	**Dry Mass**	0.3188 lb
Tested Dry or Submerged	Dry		
Comments			

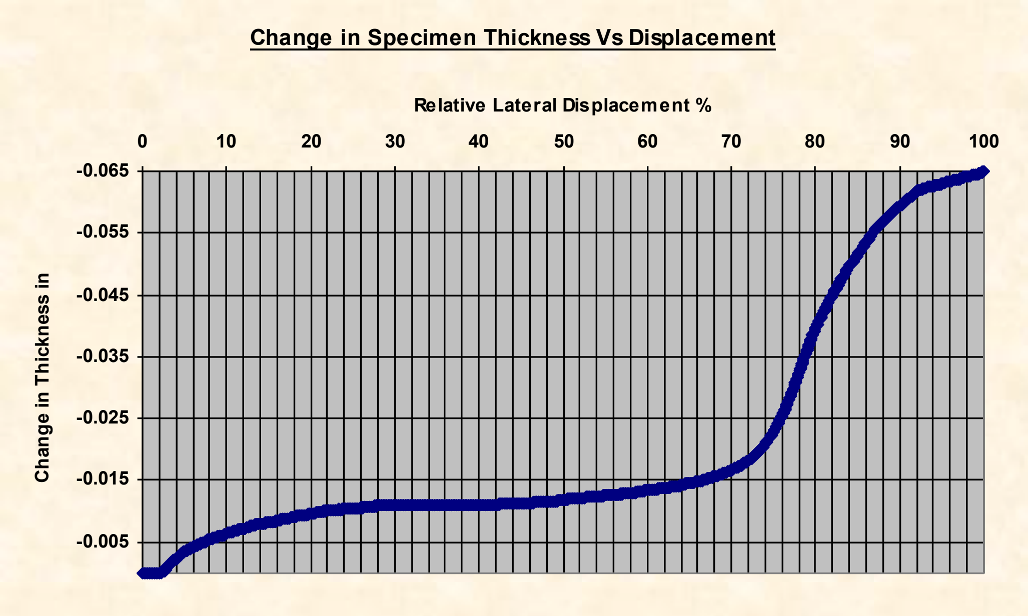
* Calculated from initial and dry weights of whole specimen



Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

Rate of Horizontal Displacement	Stage 1: 0.005000in/min





Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

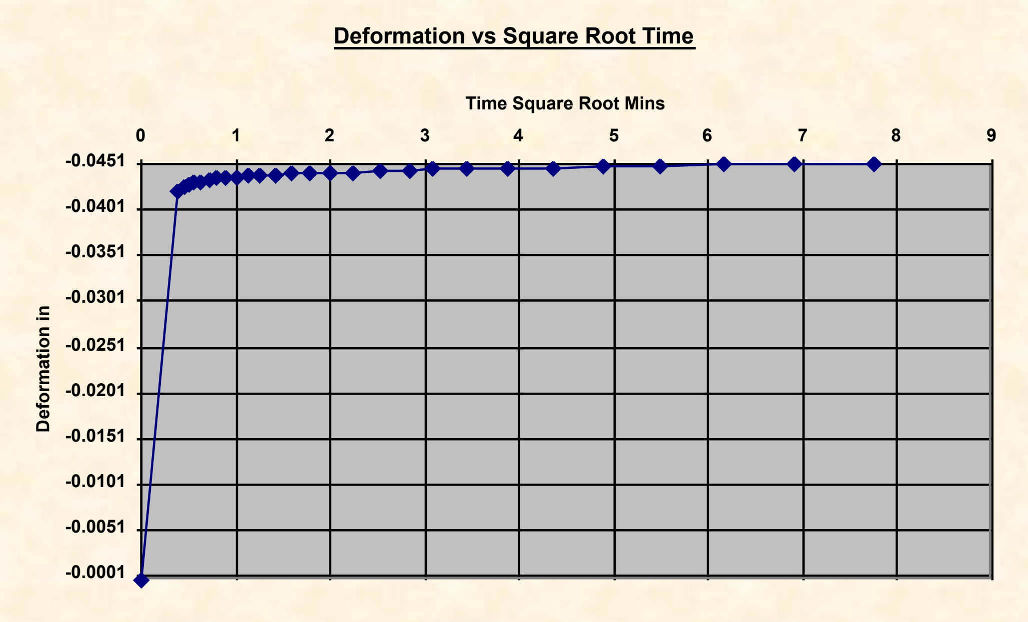
Conditions at Failure	
Normal Stress	36.2 psi
Peak Strength	31.12 psi
Horizontal Deformation	0.0034 in
Residual Stress	0.00 psi
Vertical Deformation	-0.0583 in

Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

Test Details			
Standard	ASTM D3080-03 / AASHTO T236-92	**Particle Specific Gravity**	1.65
Sample Type	Bulk disturbed sample	**Single or Multi Stage**	Single Stage
Lab. Temperature	70.0 deg.F	**Location**	
Sample Description			
Variations from procedure	None		

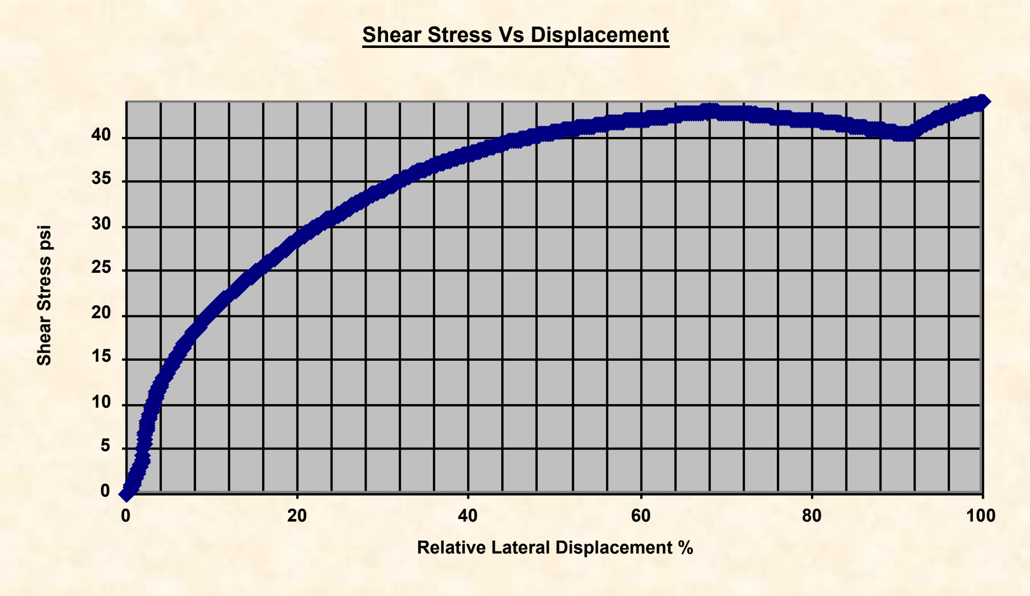
Specimen Details			
Specimen Reference	C	**Description**	
Depth within Sample	0.6500in	**Orientation within Sample**	
Initial Height	1.3000 in	**Area**	4.87000 in2
Structure / Preparation		**Initial Water Content***	0.0 %
Initial Wet Unit Weight	85.54 lbf/ft3	**Degree of Saturation**	0.00 %
Initial Dry Unit Weight	85.54 lbf/ft3	**Initial Voids Ratio**	0.205
Final Wet Unit Weight	78.23 lbf/ft3	**Final Water Content**	0.00%
Final Dry Unit Weight	78.23 lbf/ft3	**Dry Mass**	0.3133 lb
Tested Dry or Submerged	Dry		
Comments			

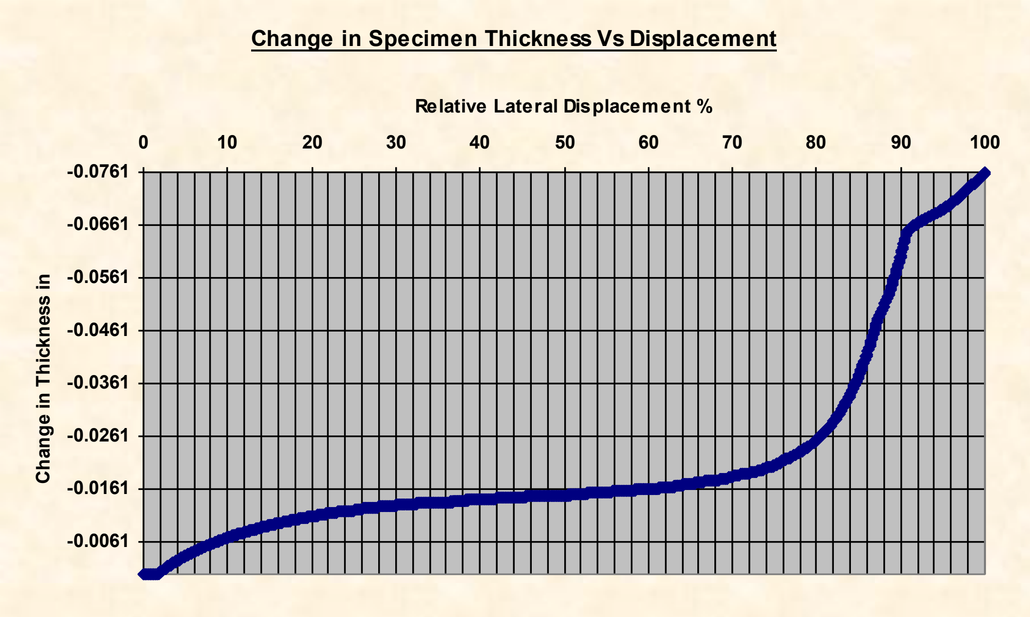
* Calculated from initial and dry weights of whole specimen



Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

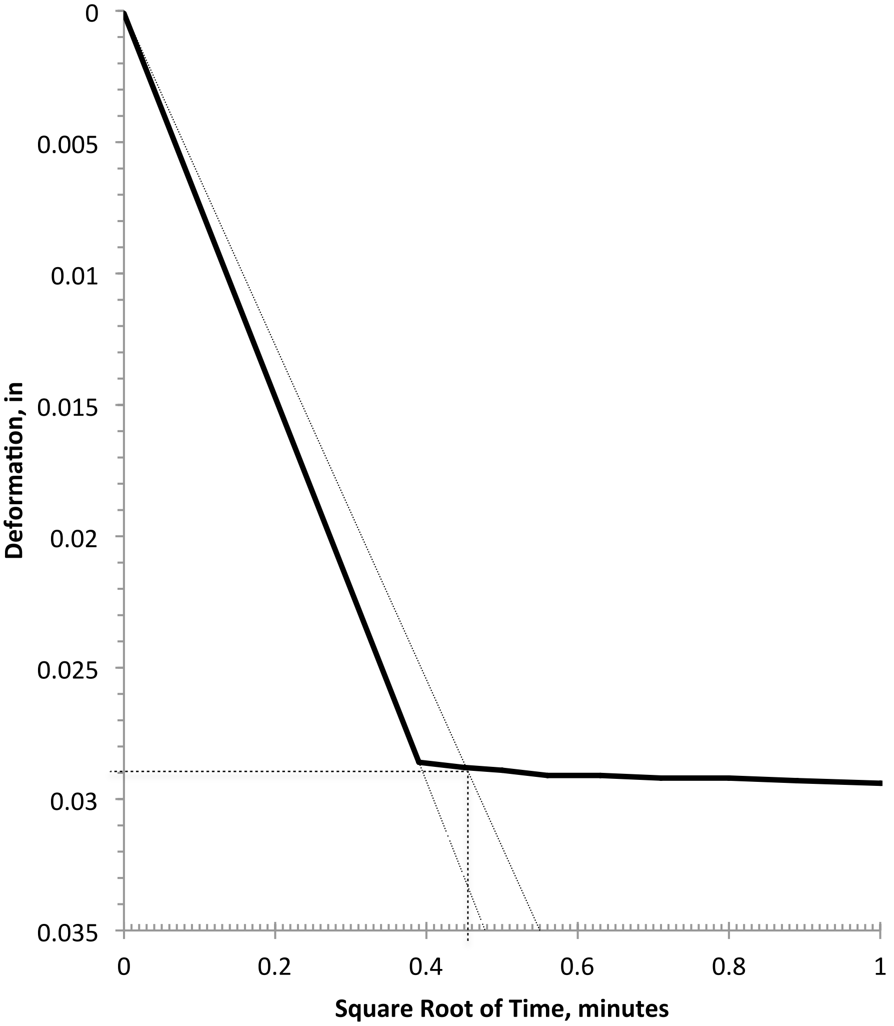
Rate of Horizontal Displacement	Stage 1: 0.005000in/min



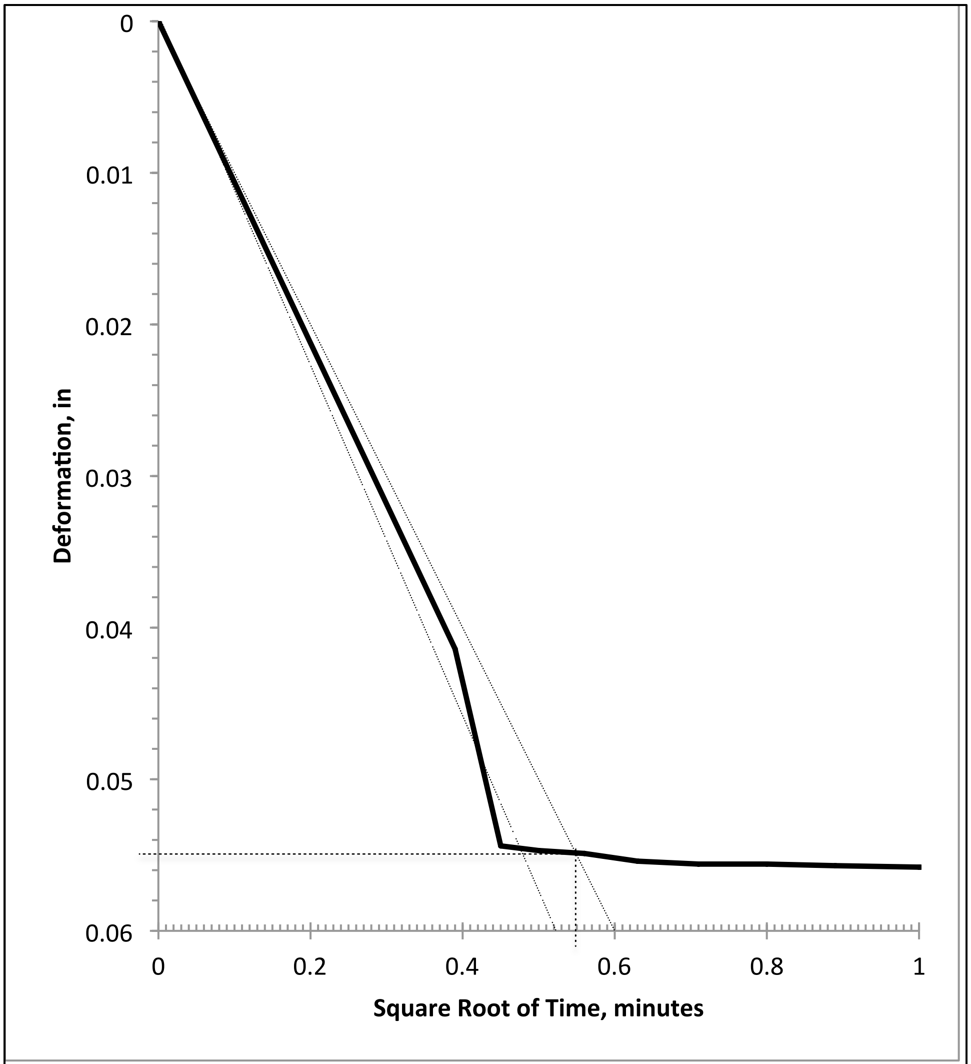


Client	Matt Lattin	**Lab Ref**	
Project	Thesis	**Job**	2011-0055
Borehole	B-1	**Sample**	3

Conditions at Failure	
Normal Stress	54.3 psi
Peak Strength	43.06 psi
Horizontal Deformation	0.1798 in
Residual Stress	0.00 psi
Vertical Deformation	-0.0626 in



0	0	
0.55	0.035	
sqrt t_{90} =	0.455	
t_{90} =	0.207025	min
d_{90} =	0.0259	in
$T_{90} = C_v t_{90}/H_{dp}^2$		
T_{90} =	0.848	
H_{dp} =	0.65	in
C_v =	0.18608697	cm^2/sec



0 0

0.6 0.06

sqrt t_{90} = 0.55

t_{90} = 0.3025 min

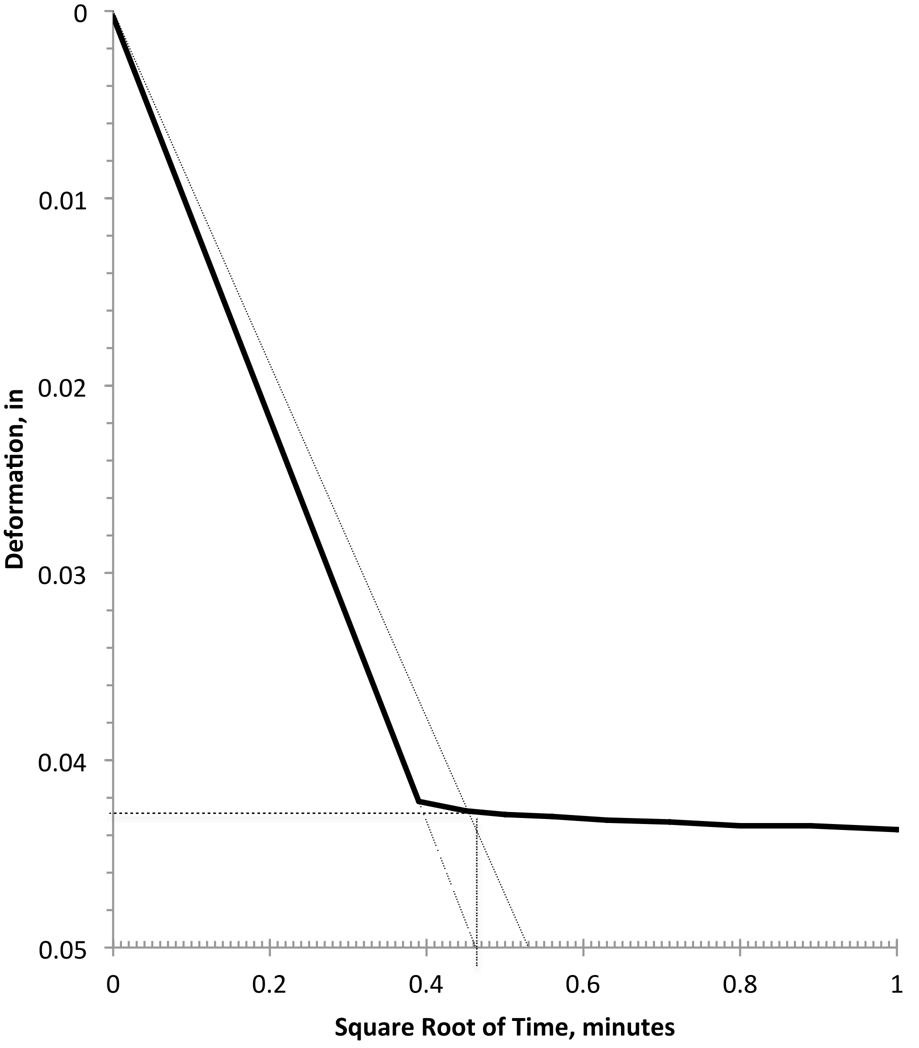
d_{90} = 0.055 in

$T_{90} = C_v t_{90}/H_{dp}^2$

T_{90} = 0.848

H_{dp} = 0.65 in

C_v = 0.12735423 cm^2/sec



0	0	
0.53	0.05	

sqrt t_{90} = 0.455

t_{90} = 0.207025 min

d_{90} = 0.043 in

$T_{90} = C_v t_{90}/H_{dp}^2$

T_{90} = 0.848

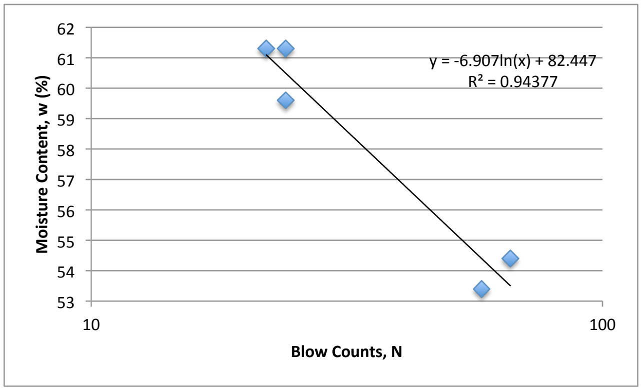
H_{dp} = 0.65 in

C_v = 0.18608697 cm^2/sec

Appendix D – Atterberg and Gradation Excel Sheets

B-4-8B/9/11/13/14 Liquid Limit

sample #	w (%)	Blow Counts, N
1	61.3	24
2	59.6	24
3	54.4	66
4	61.3	22
5	53.4	58



w = -6.907 ln(N) + 82.447
N = 152776.424 x (0.865212)^{w}
Where N = 25
w = LL = 60.2

B-4-8B/9/11/13/14 Plastic Limit

sample #	PL
1	43.3
2	41.4
3	44.4
4	47.8
	44.225

PI = 15.975

B-4-8B/9/11/13/14 Gradation

Sieve #	Sieve Opening (mm)	Sieve mass (g)	sieve + soil mass (g)	soil (g)	cumulative (g)	% finer
3/4-in	19	672.8	672.8	0	0	100
4	4.75	600.8	839.4	238.6	238.6	87
10	2	431.5	673.3	241.8	480.4	74
40	0.425	467.5	1063.7	596.2	1076.6	41
200	0.075	485	1152	667	1743.6	5
Pan	-	370	453.1	83.1	1826.7	0

vertical lines

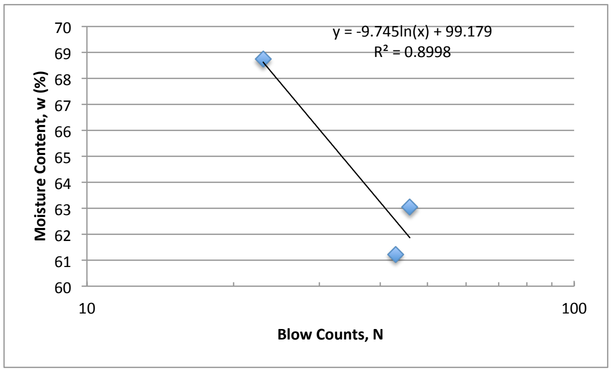
Sieve Opening (mm)	% finer
4.75	0
4.75	100
0.075	0
0.075	100

D60 = 1.34
D10 = 0.61

B-4-8A Liquid Limit

Test #	1	2	3
Can mass (g)	17.6	17.4	17.8
can + moist soil (g)	25.1	25.3	25.9
can + dry soil (g)	22.2	22.3	22.6
w %	63.0434783	61.2244898	68.75
Blows, N	46	43	23

y = -9.745ln(x) + 99.179
x = N and y = w
Where N = 25
w = LL = 67.8



B-4-8A Plastic Limit

Test #	1	2	3
Can mass (g)	17.8	16.9	16.5
can + moist soil (g)	19.5	18.7	18
can + dry soil (g)	19	18.2	17.6
w %	41.6666667	38.4615385	36.3636364

PI = 28.9693862

B-1-3 Gradation

Sieve #	Sieve Opening (mm)	Sieve mass (g)	sieve + soil mass (g)	soil (g)	cumulative (g)	% finer
3/4-in	19	662.7	662.7	0	0	100
4	4.75	641.7	671.2	29.5	29.5	96
10	2	535.6	603.7	68.1	97.6	87
40	0.425	391.6	510.2	118.6	216.2	71
200	0.075	485	673.5	188.5	404.7	45
Pan	-	370	699.7	329.7	734.4	0

vertical lines

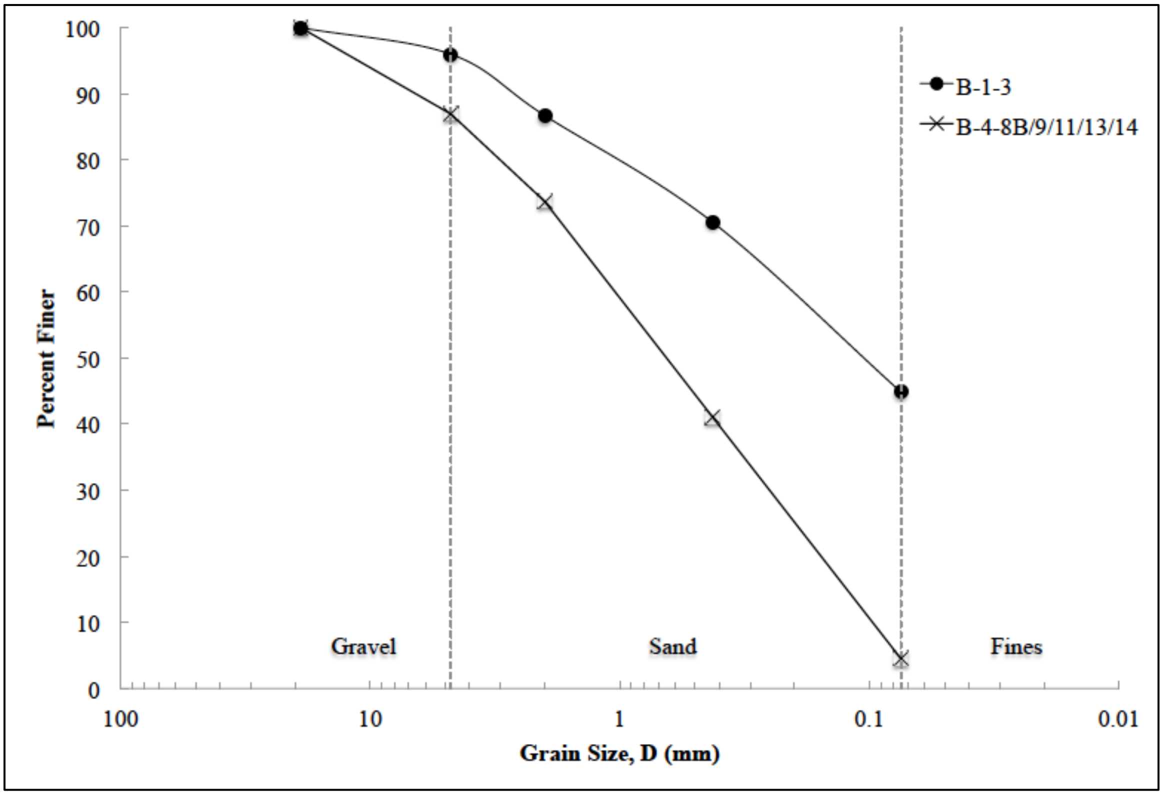
Sieve Opening (mm)	% finer
4.75	0
4.75	100
0.075	0
0.075	100

B-4-8A One Point Liquid Limit

Use test #3

Test #	1	2	3
Can mass (g)	17.6	17.4	17.8
can + moist s	25.1	25.3	25.9
can + dry soil	22.2	22.3	22.6
w %	63.0434783	61.2244898	68.75
Blows, N	46	43	23
LL = w(N/25)'	Where A' =	0.104	
LL =	67.1709081	64.7768959	68.156399

2
0.425
0.075



Grain Size Distribution of Samples B-1-3 and B-4-8B/9/11/13/14