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Title: Engineering Properties of Southeast Alaskan Forest Soils

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The strength of both undisturbed and compacted soils from 10 sites in the slide-prone Tongass National Forest in SE Alaska were studied. Index property tests were also conducted on disturbed samples. The index tests included natural water content, Atterberg Limits, specific gravity of solids, grain size distribution, and moisture-density relationship. The effect of drying on the soils was studied by conducting the Atterberg Limits tests on materials which had not been dried below their field water content and comparing the results to those of Atterberg Limits tests conducted on air-dried material. Nine of the 10 samples studied exhibited a marked decrease in plasticity as a result of drying. Consolidated-undrained triaxial shear tests with pore pressure measurements were conducted on both undisturbed and compacted samples to evaluate the soils' effective strength parameters. Test results on several undisturbed specimens from a single site often did not provide comparable results because of material variability. In general, an increase in effective angle of internal friction with decreasing plastic index and increasing dry density was observed. Applications of the test results to problems in slope stability analysis and use of the soils in engineered construction are discussed.

Engineering Properties of Southeast Alaskan Forest Soils

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Engineering Properties of Southeast Alaskan Forest Soils

INTRODUCTION

The lands of the Tongass National Forest in SE Alaska produce timber, supply water, provide a wildlife habitat, and offer recreational opportunities for man. These functions are all negatively impacted by mass wasting - the downslope movement of large masses of earth material, primarily under the force of gravity. Unfortunately, mass wasting, in the form of landslides and debris avalanches, is common in the Tongass. Within the last 150 years over 3800 large-scale debris avalanches have occurred (Swanston, 1974).

The stability of natural slopes depends on slope geometry, local hydrology, and slope material properties. Little is known about the engineering properties of soils in the Tongass. The objectives of the study were to evaluate certain index properties and measure effective strength parameters of soils from 10 sites. Soil strength is an important input variable for landslide risk analyses. Index properties serve as a guide to the suitability of natural materials for use as road subgrades. Knowledge of soil properties will help forest managers make decisions regarding the use of marginally stable lands, and of naturally occurring materials for construction purposes.

GEOLOGY AND HYDROLOGY OF THE TONGASS

There are extensive areas of granitic, metamorphic, volcanic, and calcareous rocks in SE Alaska (Stephens et al., 1969). Topography ranges from flatlands to precipitous mountains with summits generally less than 1500 m above sea level. The abundant steep slopes in the region have been produced by recent mountain building and glacial erosion (Swanston, 1967).

The recession of Pleistocene glaciation about 10,000 years ago was the start of development for most soils in the Tongass (Stephens et al., 1969). Weathering of exposed bedrock and till after glacial recession and a post-glacial history of mass wasting has resulted in widespread development of residual and colluvial soils. Locally, ash and pumice ejected from volcanos after glacial recession have formed soil deposits with unusual properties. Uplift following glacial recession has left beaches and marine deposits hundreds of meters above sea level.

The average annual precipitation in SE Alaska is about 2.5 meters at sea level (Stephens et al., 1969). Precipitation increases with increasing elevation. The five-year, 24-hour rainfall intensity ranges from 80 to 230 mm (Miller, 1963). Residual soils, glacial till soils, and volcanic ash soils are generally free draining (Swanston, 1967; Patrick and Swanston, 1968; Stephens et al., 1969). Exceptions occur when deposited soils exist over compact, impermeable till. Uplifted marine sediments are often somewhat poorly drained.

SOIL SAMPLING

Soils were sampled for this study at the 10 sites shown in Figure 1 during July of 1980. Tentative Soil Conservation Service soil series names and the geologic origin of the soils are listed in Table 1.

Both disturbed and relatively undisturbed samples were obtained at each site. The surface layer of forest litter was removed, exposing the mineral soil. A sampling frame, illustrated in Figure 2, was erected over the soil. A 76 mm diameter Shelby tube (thin-walled steel sampling tube) was then pushed into the soil to obtain a relatively undisturbed sample. The Shelby tube was driven with a heavy hammer when the soil resistance prevented pushing. Generally, it was possible to push the tube 0.2 to 0.3 m into the soil. It was this upper layer of mineral soil which was used in the triaxial tests described in the following section. After two or three tubes were pushed or driven, the soil was dug away, and the tubes were removed from the soil and sealed with wax to prevent moisture loss. Approximately 35 kg of disturbed sample were collected in plastic-lined canvas bags during this process. A half kilogram sample was placed in a glass jar for use in a subsequent water content determination.

The sealed Shelby tubes were carefully packed in padded, plywood boxes to minimize disturbance during shipment. Disturbed samples were sent through the U.S. Mail system to Oregon State University in Corvallis, Oregon. The Shelby tube samples were shipped by commercial airline to Portland, Oregon, and from there transported by Oregon State University staff. Samples were stored in an environment of controlled humidity prior to testing in order to preserve their natural water content.

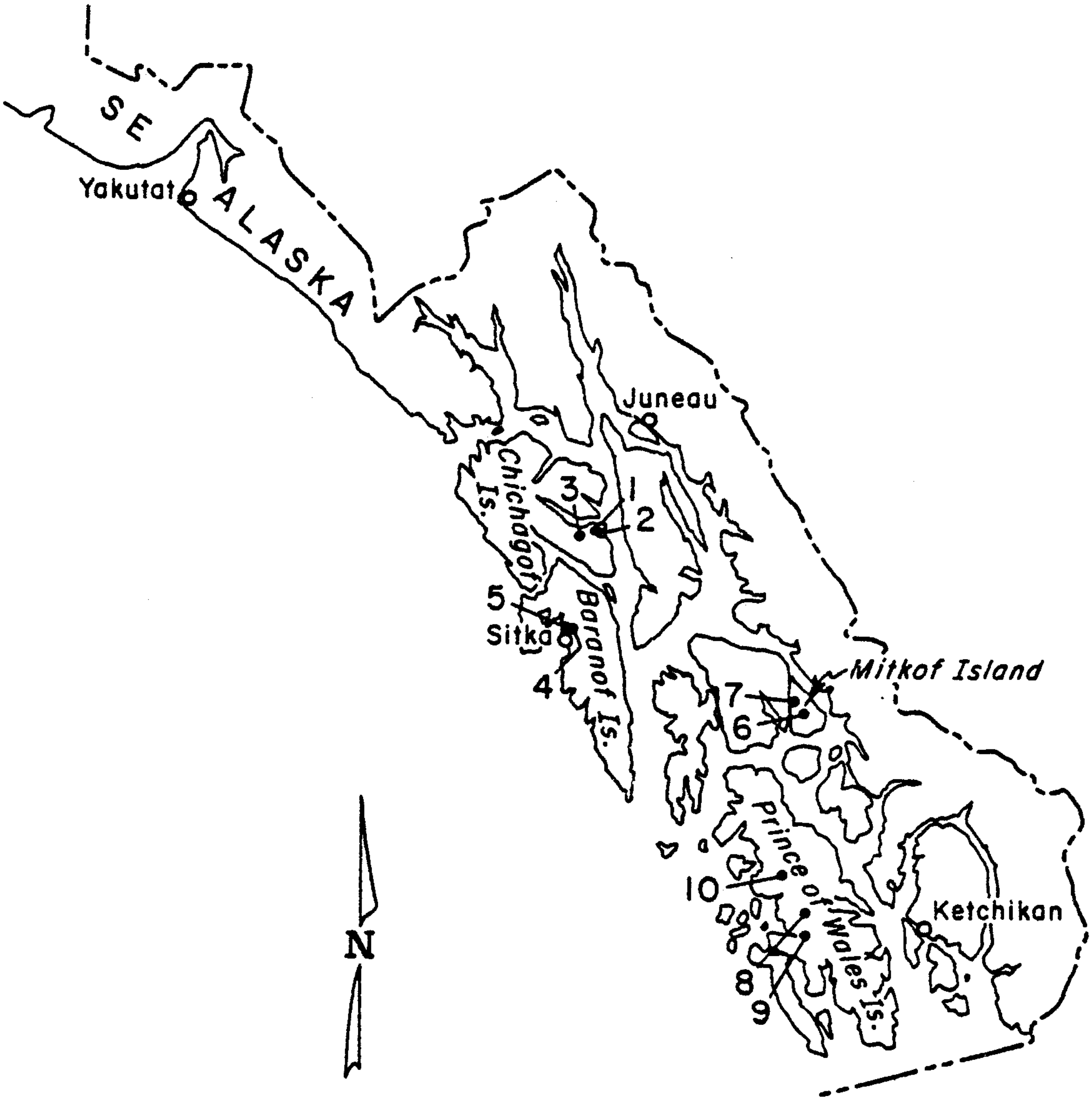

Figure 1. Soil sampling sites in SE Alaska.

Table 1. Geologic formation of the soils studied

Site	Soil Series[a]	Geologic Origin
1	Kupreanof	Alluvium derived from estuarian sediments
2	Tolstoi	Colluvium derived from graywacke
3	Karta	Glacial till soil
4	Shelikof	Weathered volcanic ash and pumice
5	Sitka	Weathered volcanic ash and pumice
6	Tokeen	Residual soil derived from graywacke
7	Gunnuck	Uplifted marine sediments
8	Karta	Glacial till soil
9	Ulloa	Residual soil derived from limestone
10	Wadleigh	Weathered glacial till

[a] Tentative Soil Conservation Service names

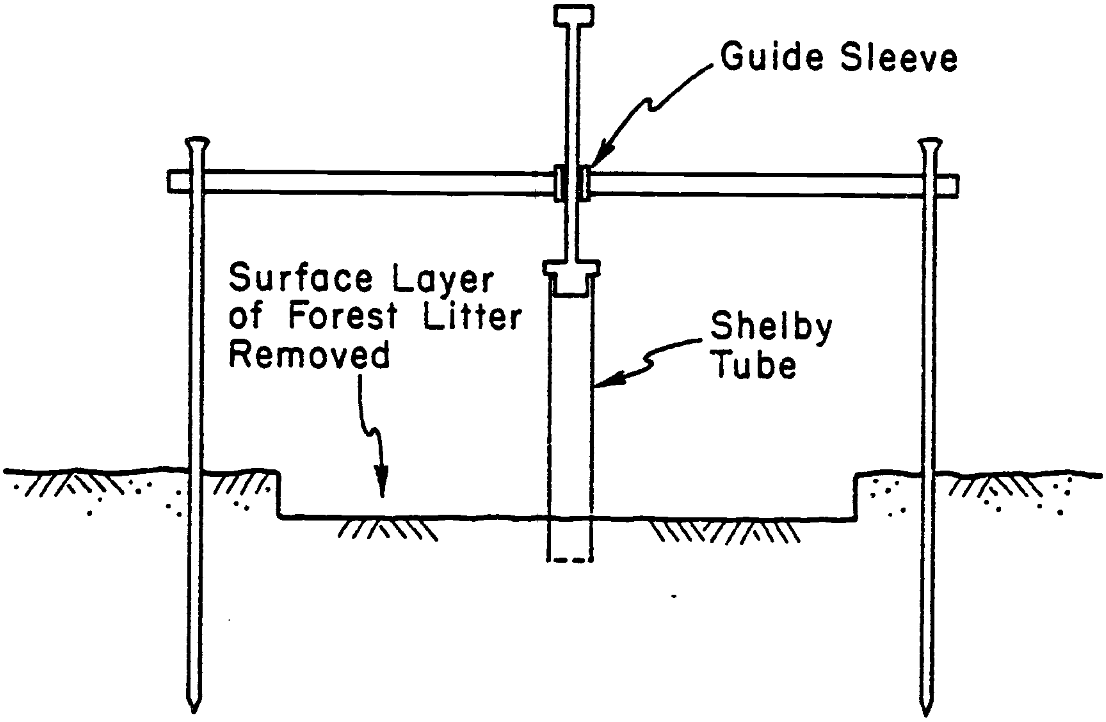

Figure 2. Soil sampling frame with Shelby tube.

TESTING PROGRAM

The objectives of the testing program were to evaluate index properties and measure effective strength parameters. The index property tests conducted included natural water content, Atterberg Limits, specific gravity of solids, grain size analysis (mechanical and hydrometer methods), standard Proctor moisture-density relationship, and bulk unit weight. These tests were conducted in accordance with ASTM guidelines (ASTM, 1979).

During the course of the laboratory work, it became apparent that most of the soils lost appreciable plasticity upon drying. To study the effect of drying, the Atterberg Limits tests were conducted using a special technique. A representative sample of each soil was washed through a No. 40 U.S. Standard sieve. Part of the material passing through the sieve was then air dried until it reached the liquid limit, and was subsequently further dried to the plastic limit. In this manner, a set of Atterberg Limits was obtained by a procedure which did not dry the material below its field water content prior to testing. The remainder of the material passing the No. 40 sieve was air dried for several days. This material was then rewetted and allowed to stand for a few more days. A set of Atterberg Limits tests was conducted on the dried and rewetted material.

Effective strength parameters were measured in consolidated-undrained triaxial shear tests with pore water pressure measurements on undisturbed and remolded samples. Samples obtained in Shelby tubes were extruded directly into the rubber membrane to be used in the triaxial test. The membrane was held open in a split cylinder which was designed for that purpose and for protection of the sample during handling prior to placement in the triaxial cell. This procedure was used instead of sample trimming, which was not practical for several of the gravelly soils tested. Prior to extrusion of the sample from the Shelby tube, the rubber membrane was lined with several strips of filter paper to facilitate consolidation and pore pressure equalization. After extrusion, the sample ends were trimmed and the sample was placed in the triaxial cell. Distilled, de-aired water was circulated through the sample overnight to increase the degree of sample saturation. The pore fluid pressure in the sample was elevated in steps until a rise in cell pressure produced an essentially equal rise in pore pressure. This procedure was used to saturate the sample so that meaningful pore water pressure measurements could be made. The sample was then consolidated under a confining pressure of 34, 69, or 103 kPa by increasing the cell pressure while keeping the pore pressure constant. A compressive load was applied to the consolidated sample at a strain rate of 0.6 percent per minute until it failed in undrained shear. The compressive load, sample deformation, and change in pore pressure were recorded during this phase of the test.

Customarily, at least three specimens are used to establish the strength envelope for a particular soil. Unfortunately, the samples obtained at many of the sites were so variable that data from shear tests on three separate specimens was not suitable to define an envelope. Consequently, multi-stage triaxial shear tests (Kenney and Watson, 1961) were conducted on single specimens for most of the sites.

In the multi-stage test, a specimen is prepared and saturated as described above. The specimen is then consolidated to 34 kPa and a strain-controlled compressive load added until failure is initiated.

The same specimen is then consolidated to 69 kPa and again sheared until it fails. The process is repeated at a consolidation pressure of 103 kPa. Undisturbed materials from Sites 1, 2, 6, 7, 8, 9, and 10 were evaluated using multi-stage tests while three specimens were used from each of Sites 3, 4, and 5.

Effective strength parameters were also evaluated using compacted samples. These samples were prepared in a Harvard miniature compaction mold using a small impact hammer which delivered about 1.3 J of energy per blow. Only soil passing the No. 4 U.S. Standard sieve was used. The samples were compacted with enough energy to produce dry densities approximately equal to 90 percent of the maximum dry densities indicated in the standard Proctor moisture-density tests. The soils were compacted at their natural water contents when possible. Some soils were too wet and required air drying to permit compaction to the required densities.

Multi-stage, consolidated-undrained triaxial shear tests were conducted on the compacted samples in the manner described above for undisturbed samples. For the material from Site 7, three additional remolded specimens were prepared and a conventional series of triaxial shear tests run to study the influence of multi-stage testing on remolded samples.

DATA REDUCTION

Data collected during the triaxial shear tests were reduced and plotted using a Hewlett-Packard HP9845B desktop computer and an HP9872A plotter. The strength parameters tabulated in the following section are the effective angle of internal friction and the effective cohesion intercept. These parameters were obtained from the data by the stress path method (Lambe, 1961). In this method, one half the deviator stress (the additional compressive stress used to cause failure) is plotted against one half the sum of the major and minor principal stresses (the maximum and minimum normal stresses acting on an idealized soil element during shear). A typical set of stress path plots from a multi-stage test is shown in Figure 3. A straight-line envelope is drawn enclosing the stress paths. The slope and the half deviator stress intercept for this line can be used to compute the angle of internal friction and the cohesion intercept for the specimen.

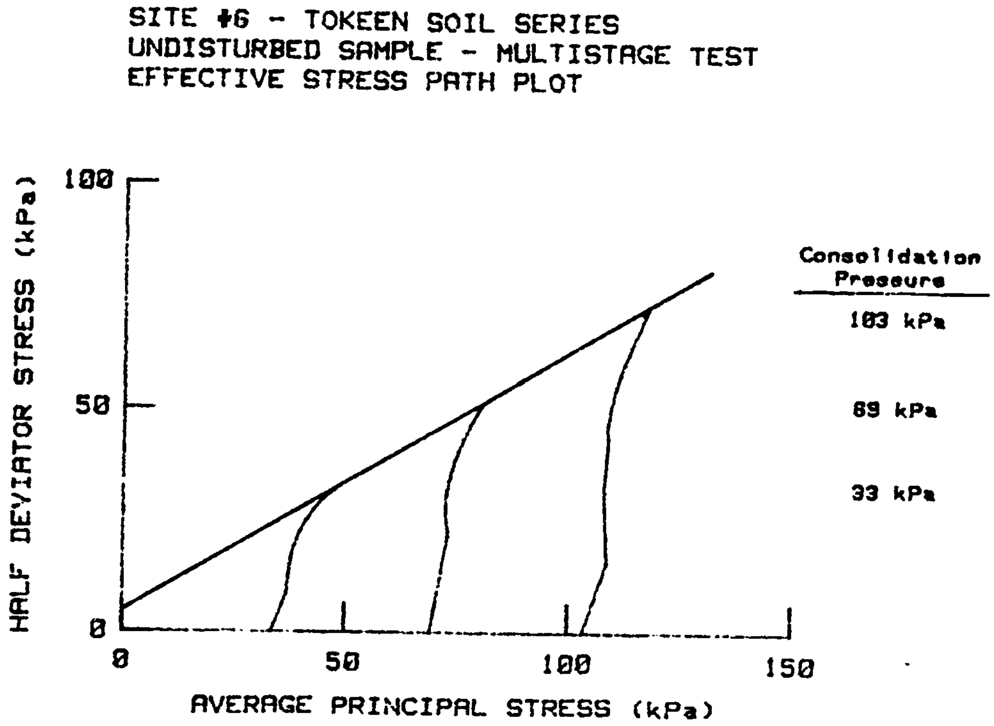

Figure 3. Typical effective stress path plot.

RESULTS

Index property test results are shown in Table 2. Triaxial shear test results for undisturbed and compacted samples are shown in Table 3. The conventional three-specimen triaxial shear test conducted on three remolded specimens of Site 7 material yielded an effective friction angle of 38.5 degrees and an effective cohesion intercept of -1 kPa. The multi-stage test on a compacted specimen of this material produced a friction angle of 39.6 degrees and a cohesion intercept of zero. The multi-stage test results for the Site 7 remolded material are shown in Table 3.

Table 2. Index property data

		"Wet" Atterberg Limits[a]			"Air-Dried" Atterberg Limits[a]				Grain Size Distribution			Standard Proctor Moisture-Density Relationship[b]		
Site	Natural Water Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plastic Index (%)	Liquid Limit (%)	Plastic Limit (%)	Plastic Index (%)	Specific Gravity of Solids	Gravel (%)	Sand (%)	Fines (%)	Maximum Dry Density (kN/m^3)	Optimum Water Content (%)	In-Situ Dry Unit Weight[c] (kN/m^3)
1	91	91	60	31			NP[d]	2.68	3	30	67	10.4	53	7.6
2	33	100	66	34			NP[d]	2.79	45	42	13	13.0	30	14.3
3	23	108	79	29			NP[d]	2.72	31	55	14	14.5	26	16.7
4	143	155	103	52			NP[d]	2.67[e]	1	62	37	8.5	68	5.3
5	154	154	115	39			NP[d]	2.74[e]	0	64	36	7.5	78	5.2
6	51	142	64	78			NP[d]	2.71	17	58	25	13.5	30	10.7
7	16	23	18	5	22	18	4	2.76	9	36	55	19.3	12	18.7
8	48	81	46	35			NP[d]	2.70	23	52	25	14.5	26.5	11.5
9	57	100	78	22			NP[d]	2.69	17	51	32	8.5	53	10.2
10	49	87	45	42			NP[d]	2.68	23	38	39	12.4	37.5	10.1

[a] Tests conducted according to ASTM D423 and D424 with the sample preparation described in the text.

[b] ASTM D698 Method A.

[c] In-situ weights obtained from Shelby tube samples.

[d] NP denotes non-plasticity.

[e] Sample burned at 550°C for 1 hour to remove organics.

Table 3. Effective strength parameters

Site	Undisturbed Samples Friction Angle (degrees)	Undisturbed Samples Cohesion Intercept (kPa)	Compacted Samples Friction Angle (degrees)	Compacted Samples Cohesion Intercept (kPa)
1	36.0	14	43.6	6
2	43.0	5	36.1	5
3	35.1[a]	6[a]	31.8	20
4	24.9[a]	11[a]	37.3	25
5	38.9[a]	12[a]	36.8	14
6	35.6	5	35.9	22
7	43.7	12	39.6	0
8	37.5	8	39.8	16
9	34.4	6	34.8	0
10	32.4	5	37.9	8

[a] Three specimens used to define the strength envelope in a conventional test. All other envelopes were determined with a multi-stage test on a single specimen.

DISCUSSION

Influence of Drying on Plasticity. As indicated in Table 2, nine soils exhibited no plasticity after air drying, though they possessed significant plasticity prior to drying. Only the Site 7 material did not show appreciable plasticity loss.

Plasticity depends on the proportions and properties of colloids, and their interaction with ions in a moist soil (Peck et al., 1974). There are at least two possible causes of the observed plasticity decrease; aggregation of colloids and drying of organic colloids. In an independent study (Thrall, 1981), it has been shown that the Site 4 and 5 soils contain allophane, a poorly crystalline material derived from volcanic ash. Allophane soils exhibit a decrease in plasticity due to aggregation of colloidal particles upon drying (Sherman et al., 1964). Many soils in SE Alaska possess a high organic colloid content. The ability of organic matter to hold water decreases irreversibly with drying (Maeda et al., 1977). These effects, and possibly others, contribute to the drying behavior of the soils studied.

An important consequence of the plasticity change on drying of many SE Alaskan soils is that the conventional Atterberg Limits tests or, for that matter, other tests which require drying for sample preparation, may not represent a soil's field behavior. Tests should always be performed in a manner which will not change a soil's behavior from that anticipated in the field.

Effect of Multi-stage Testing on a Remolded Material. The difference of 1 kPa in effective cohesion intercepts between the multi-stage and conventional tests on remolded samples of Site 7 material was probably not significant. That the multi-stage test produced an internal friction angle 1.1 degrees greater than the conventonal test could be attributed to an increase in dry density of the specimen during the course of the multi-stage test.

The pore water pressure in the multi-stage test specimen was greater following unloading than it was prior to the start of the shearing phase of the test. Before application of the next higher consolidation pressure in the multi-stage test, this shear-induced pore pressure was reduced by draining water from the specimen until the pore pressure reached its pre-shear value. The consolidation produced by dissipation of shear-induced pore pressure occurred in the multi-stage specimen but not in the conventional test specimens. Consequently, at the time of shear under the highest consolidation pressure, the dry density of the multi-stage specimen was higher than that of the specimen used in the conventional test, even though the specimens were at the same dry density before being placed in the triaxial cell. It is reasonable, then, that the sample of higher density (i.e., multi-stage test specimen) exhibited greater strength and a slightly greater internal friction angle.

Trends Relating Strength Parameters to Index Properties. A general increase in effective internal friction angle when plastic index decreases and dry density increases was noted and is illustrated in Figure 4. Tentative bounds are shown which provide friction angle estimates from index property test results. It is well known (Terzaghi and Peck, 1967) that for clays the internal friction angle increases as plasticity decreases and that for cohesionless materials the friction angle increases as dry density increases. Hence, it is reasonable that the trend shown in Figure 4 exists.

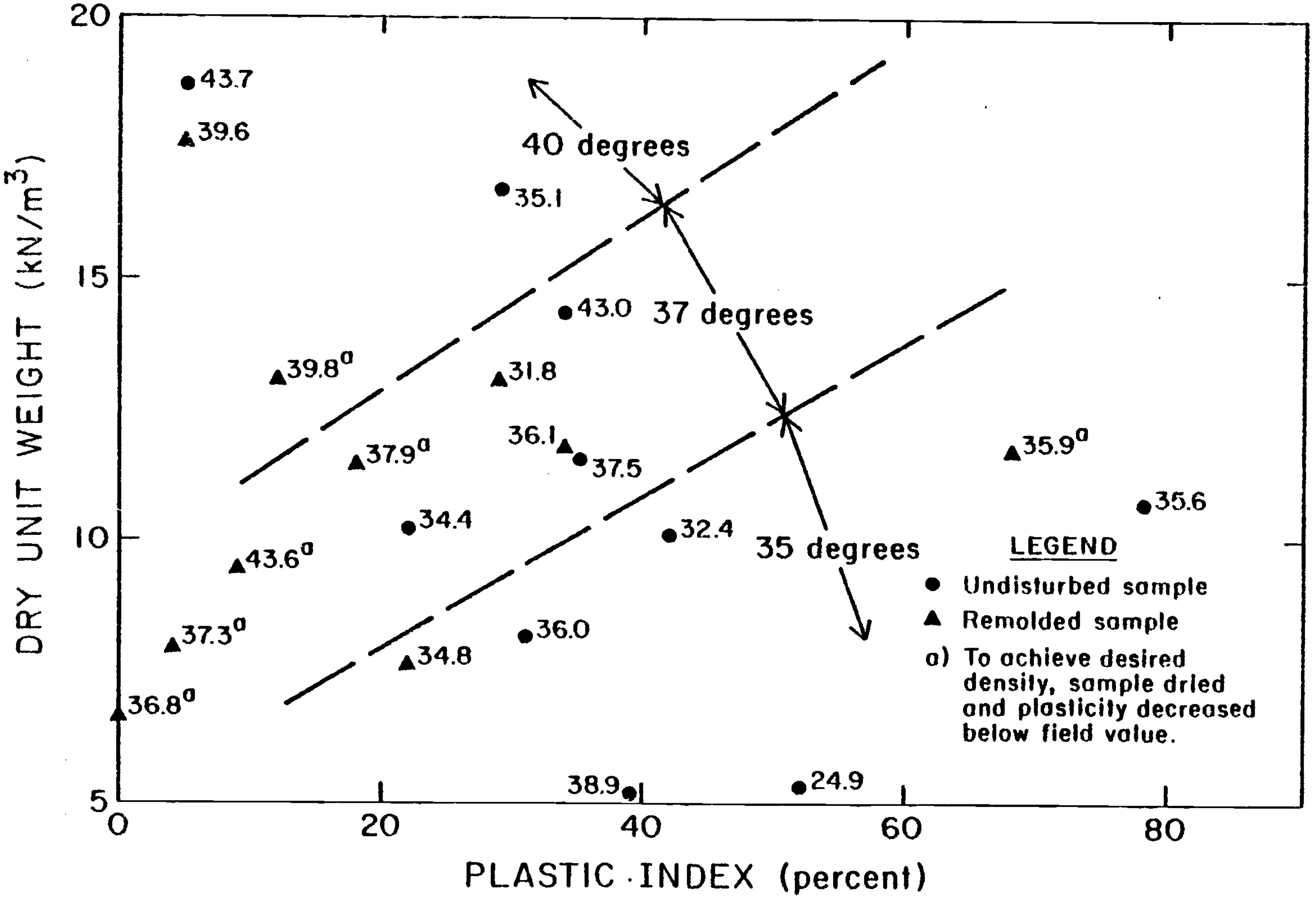

Figure 4. Tentative relationship among plasticity index, dry density, and effective angle of internal friction (degrees) for SE Alaskan soils. Numeric values shown adjacent to data points represent actual test results.

No trends relating the effective cohesion intercept to the material index properties were evident.

Application of Strength Parameters to Slope Stability Analysis. The effective strength parameters together with a knowledge of slope geometry and local hydrology can be used to assess the stability of natural or fill slopes. Other factors, including wind loading on trees and "apparent cohesion" produced by the anchoring effect of plant roots, while important, are beyond the scope of this discussion. Though the mechanics of a slope stability analysis are straightforward, the results may not predict the performance of an actual slope. It is Peck's (1967) contention that "we are, in fact, unable to make reliable assessments of the stability of many, if not most, natural slopes under circumstances of practical importance." Nevertheless, the stability of many natural slopes must be evaluated. An analysis based on effective strength parameters can be helpful. Sidle and Swanston (1981) have shown reasonable agreement between an effective strength analysis based on parameters reported here and slope performance for a small debris avalanche in Site 2 material.

Many of the soils studied possess variable effective strength parameters as evidenced by the lack of strength envelope definition when three specimens were used in a conventional triaxial shear test. This variability implies that the strength parameters listed in Table 3 do not uniquely define the soils' characteristics at each of the test sites. A statistical analysis of several sets of strength parameters evaluated with specimens from a single soil series would yield an improved understanding of each material's behavior. The strength values listed in Table 3 serve as a starting point for describing the characteristics of the soil series studied.

The measured effective cohesion intercepts were not large. They should not, however, be ignored when assessing the stability of thin soil covers over steep rock slopes. For example, consider a hypothetical soil slope with 0.6 m thickness perpendicular to bedrock and the water table at the surface of a material characterized by the properties measured for the Site 6 soil. An infinite slope analysis indicates that the slope is stable up to a critical angle of 16 degrees when cohesion is ignored. When the measured cohesion of 5 kPa is included in the analysis, the critical angle is 45 degrees.

Engineering Use of Index Properties. The index property data presented earlier can serve as a guide to the usefulness of these soils as construction materials. As indicated in Table 2, the natural water content was significantly higher than the optimum water content from the moisture-density test for the soils at several sites. It would be difficult to dry large quantities of these materials in the SE Alaskan climate since annual precipitation levels are high and there is no predominantly dry season. A soil that has a water content significantly higher than optimum cannot be compacted to densities required for many construction purposes. Consequently, several of the soils studied have limited potential for stabilization by compaction, and other methods must be employed if the materials are to be used effectively. On the other hand, some of the soils sampled existed at water contents below or near optimum at the time of sampling. A soil with a low water content and a significant proportion of gravel would be an adequate construction material in many cases. The soil at Site 2, for example, has these characteristics.

CONCLUSIONS

The plasticity of many soils in SE Alaska decreases if the soils are dried before testing. It is important to evaluate the plastic index and other properties of a soil with a procedure that will not change its behavior from that in expected field conditions. Special procedures may therefore be neeeded in testing soils from this region.

The effective angle of internal friction of the soils studied tends to increase with increasing dry density and with decreasing plastic index. Specimens from a single site exhibited significant variability in their shearing behavior. Multi-stage triaxial shear testing can be a useful technique to obtain strength parameters when there is variability among samples. A consequence of the observed variability in strength characteristics is that a slope stability analysis based on a single set of strength parameters should be used with caution. In particular, the stability of thin soil on slopes is sensitive to small changes in cohesion.

Index property data can serve as a guide to the suitability of a soil as a construction material. Many SE Alaskan soils remain too wet throughout the year to permit stabilization by compaction.

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APPENDIX A

SITE DESCRIPTIONS

Site Number:	1
Soil Series Name:	Kupreanof
Geologic Formation:	Alluvium derived from estuarian sediments.
Location:	Bank adjacent to small stream draining into Trap Bay, Chichagof Island.
Elevation:	30 m
Topography:	10 percent slope.
Vegetation:	Western hemlock and sitka spruce overstory. Blueberry and devil's club understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.5-1.3	Reddish grey, sandy silt
No. 2 (Shelby tube)	.5-1.3	Reddish grey, sandy silt
No. 3 (Shelby tube)	.5-1.3	Reddish grey, sandy silt
No. 4 (bag)	.5- .9	Reddish grey, sandy silt
No. 5 (bag)	.9-1.3	Reddish grey, sandy silt
No. 6 (jar)	.9	Reddish grey, sandy silt

Site Number:	2
Soil Series Name:	Tolstoi
Geologic Formation:	Colluvium derived from graywacke.
Location:	Hillslope near Trap Bay, Chichagof Island.
Elevation:	100 m
Topography:	Concave hillslope. Eighty-five percent slope at sampling site.
Vegetation:	Western hemlock and Sitka spruce overstory. Devil's club understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.5-1.3	Brown, sandy gravel
No. 2 (Shelby tube)	.5-1.3	Brown, sandy gravel
No. 3 (bag)	.5- .9	Brown, sandy gravel
No. 4 (bag)	.9-1.3	Brown, sandy gravel
No. 5 (jar)	.9	Brown, sandy gravel

Site Number:	3
Soil Series Name:	Karta
Geologic Formation:	Glacial till derived from graywacke and granite.
Location:	Slope adjacent to a small creek draining into Kadashan Bay, Chichagof Island.
Elevation:	20 m
Topography:	Rolling 5 to 20 percent slopes beneath a concave hillside.
Vegetation:	Western hmelock and Sitka spruce overstory. Blueberry understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.2-1.0	Yellow-brown, gravelly sand
No. 2 (Shelby tube)	.2-1.0	Yellow-brown, gravelly sand
No. 3 (Shelby tube)	.2-1.0	Yellow-brown, gravelly sand
No. 4 (bag)	.2- .6	Yellow-brown, gravelly sand
No. 5 (bag)	.6-1.0	Yellow-brown, gravelly sand
No. 6 (jar)	.6	Yellow-brown, gravelly sand

Site Number:	4
Soil Series Name:	Shelikof
Geologic Formation:	Weathered volcanic ash and pumice.
Location:	Cutbank 4 km up Harbor Mountain Road near Sitka.
Elevation:	300 m
Topography:	Gently sloping hills.
Vegetation:	Western hemlock and Sitka spruce overstory. Huckleberry understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.3-1.1	Orange-brown silty sand
No. 2 (Shelby tube)	.3-1.1	Orange-brown silty sand
No. 3 (Shelby tube)	.3-1.1	Orange-brown silty sand
No. 4 (bag)	.3- .7	Orange-brown silty sand
No. 5 (bag)	.7-1.1	Orange-brown silty sand
No. 6 (jar)	.7	Orange-brown silty sand

Site Number:	5
Soil Series Name:	Sitka
Geologic Formation:	Weathered volcanic ash and pumice.
Location:	Cutbank 3 km up Harbor Mountain Road near Sitka.
Elevation:	200 m
Topography:	Gently sloping hills.
Vegetation:	Sitka spruce and western hemlock overstory. Blueberry and menziesia understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.3-1.1	Orange-brown silty sand
No. 2 (Shelby tube)	.3-1.1	Orange-brown silty sand
No. 3 (Shelby tube)	.3-1.1	Orange-brown silty sand
No. 4 (bag)	.3- .7	Orange-brown silty sand
No. 5 (bag)	.7-1.1	Orange-brown silty sand
No. 6 (jar)	.7	Orange-brown silty sand

Site Number:	6
Soil Series Name:	Tokeen
Geologic Formation:	Residual soil derived from graywacke.
Location:	1 km off Three Lakes Loop Road south of Petersburg.
Elevation:	200 m
Topography:	Mountain sideslope. Sixty percent at sampling site.
Vegetation:	Western hemlock and Sitka spruce overstory. Blueberry and devil's club understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.3-.6	Brown, gravelly silty sand
No. 2 (Shelby tube)	.3-.6	Brown, gravelly silty sand
No. 3 (Shelby tube)	.3-.6	Brown, gravelly silty sand
No. 4 (Shelby tube)	.3-.6	Brown, gravelly silty sand
No. 5 (bag)	.3-.6	Brown, gravelly silty sand
No. 6 (bag)	.3-.6	Brown, gravelly silty sand
No. 7 (jar)	.5	Brown, gravelly silty sand

Site Number:	7
Soil Series Name:	Gunnuck
Geologic Formation:	Uplifted marine sediments.
Location:	Head scarp of a landslide near Fur Farm Creek, Mitkof Island.
Elevation:	275 m
Topography:	Hilly. Fifty percent slope at the sample site.
Vegetation:	Western hemlock, Alaska cedar, and Sitka spruce overstory. Blue huckleberry and rusty menziesia understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.3-1.1	Grey, sandy silt
No. 2 (Shelby tube)	.3-1.1	Grey, sandy silt
No. 3 (Shelby tube)	.3-1.1	Grey, sandy silt
No. 4 (bag)	.3- .7	Grey, sandy silt
No. 5 (bag)	.7-1.1	Grey, sandy silt
No. 6 (jar)	.7	Grey, sandy silt

Site Number:	8
Soil Series Name:	Karta
Geologic Formation:	Glacial till derived from graywacke and granite.
Location:	Cut slope near the Hollis-Harris River Road intersection, Prince of Wales Island.
Elevation:	120 m
Topography:	Toe slope of a glaciated valley. Fifteen percent slope at the sampling site.
Vegetation:	Western hemlock and Sitka spruce overstory. Huckleberry understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.3-.9	Yellow-brown, gravelly silty sand
No. 2 (Shelby tube)	.3-.9	Yellow-brown, gravelly silty sand
No. 3 (Shelby tube)	.3-.9	Yellow-brown, gravelly silty sand
No. 4 (bag)	.3-.6	Yellow-brown, gravelly silty sand
No. 5 (bag)	.6-.9	Yellow-brown, gravelly silty sand
No. 6 (jar)	.6	Yellow-brown, gravelly silty sand

Site Number:	9
Soil Series Name:	Ulloa
Geologic Formation:	Residual soil derived from limestone.
Location:	0.8 km south of the intersections of Roads 4100 and 4000, Prince of Wales Island.
Elevation:	100 m
Topography:	Karst topography. Twenty-five percent slope at the sampling site.
Vegetation:	Western hemlock and Sitka spruce overstory. Huckleberry understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.2-.5	Orange-brown, silty sand
No. 2 (Shelby tube)	.2-.5	Orange-brown, silty sand
No. 3 (Shelby tube)	.2-.5	Orange-brown, silty sand
No. 4 (Shelby tube)	.2-.5	Orange-brown, silty sand
No. 5 (bag)	.2-.5	Orange-brown, silty sand
No. 6 (bag)	.2-.5	Orange-brown, silty sand
No. 7 (jar)	.2-.5	Orange-brown, silty sand

Site Number:	10
Soil Series Name:	Wadleigh
Geologic Formation:	Glacial till derived from weathered graywacke and granite.
Location:	60 m up the east spur of Sale Unit 44-22 in the Control Lake Area, Prince of Wales Island.
Elevation:	275 m
Topography:	Hilly. Forty percent slope at the sampling site.
Vegetation:	Western hemlock, western red cedar, and some Sitka spruce in overstory. Devil's club, fern, and huckleberry understory.

Soil Sample Log

Sample identification	Depth below surface (meters)	Soil description
No. 1 (Shelby tube)	.3-1.1	Grey-brown, sandy silt
No. 2 (Shelby tube)	.3-1.1	Grey-brown, sandy silt
No. 3 (Shelby tube)	.3-1.1	Grey-brown, sandy silt
No. 4 (bag)	.3- .7	Grey-brown, sandy silt
No. 5 (bag)	.7-1.1	Grey-brown, sandy silt
No. 6 (jar)	.7	Grey-brown, sandy silt

APPENDIX B

SOIL SERIES DESCRIPTIONS

The following soil series descriptions have been taken with minor editing, from descriptions on file with the U.S. Forest Service in Juneau, Alaska. Some of the series names are tentative, awaiting final Soil Conservation Service correlation. The series names are, however, in common use among soil scientists in SE Alaska.

KUPREANOF SERIES

The Kupereanof series is a thixotropic-skeletal soil typically having gray A2 horizons over dark brown, strongly acid B horizons.

Taxonomic Class: Thixotropic-skeletal, mixed, Humic Cryorthods.

Type Location: Krupreanof Area, Alaska. N 1/2 SE 1/4, Sec. 12, T 57 S, R 73 E, Copper River Meridian. About 450 meters south of Boot Lake on the Hamilton Bay Road.

Range in Characteristics: Thickness of the solum ranges from 0.5 to 1.3 meters. Depth to bedrock ranges from one to many meters. Some pedons contain a buried sequum, but in others these horizons are missing. Lenses of volcanic ash may occur throughout the solum. The coarse fragment content of the control section ranges from 40 to 80 percent by volume. Large stones and boulders are common in the subsoil and substratum. The B22 horizon commonly is gravelly silt loam in the upper part and very gravelly or extremely gravelly silt loam in the lower part. Coarse fragments range from 30 to 80 percent by volume. The B3 horizon commonly is very gravelly silt loam, but ranges to an extremely gravelly sandy loam. Coarse fragments range from 40 to 80 percent and cobbles from 20 to 30 percent.

Setting: The Kupreanof soils occur on gently sloping to steep mountainsides and drumlinoids. The regolith is dominantly weathered graywacke or basalt. The climate is cool maritime with an average annual rainfall of about 2.4 meters. The average annual air temperature is about 7°C, and the average summer air temeperature is about 13°C. The average annual soil temperature is about 5°C. These soils are seldom frozen.

Drainage and Permeability: Well drained. Permeability is moderate in the surface layers and rapid below. Runoff is moderate to rapid.

Use and Vegetation: The Kupreanof soils are used for timber production, watershed protection, wildlife, and recreation. The principal trees are western hemlock, Sitka spruce, and Alaska cedar. The subordinate vegetation includes blueberry, menziesia, and mosses.

TOLSTOI SERIES

The Tolstoi series is a thixotropic-skeletal soil typically having thin A2 horizons over dark brown, strongly acid B22 horizons.

Type Location: Hollis Area, Alaska; approximately 0.4 km east of mouth of Karta River and 90 meters inland from the beach; NW corner NE 1/4 sec. 1, T. 73 S., R. 84 E., Copper River Meridian.

Range Characteristics: Thickness of solum and depth to bedrock typically are about 0.35 meters, but range from 0.2 to 0.5 meters. The coarse fragments range from 50 to 80 percent by volume. The average soil temperature above bedrock is about 5°C. The average summer soil temperature above bedrock is about 7°C. The A2 horizon is commonly very gravelly silt loam but ranges to extremely stony loam. The B horizon is commonly extremely stony silt loam but ranges to very gravelly or extremely stony sandy loam.

Setting: The Tolstoi soils occur on mountain sides, knobs and drumlinoids. The soils formed in dominantly weathered graywacke and diorite. The climate is humid maritime with average annual rainfall about 2.5 meters. The average annual temperature is 7°C, and the average summer temperature is 13°C.

Drainage and Permeability: Well drained. Moderately rapid permeability.

Use and Vegetation: The Tolstoi soils are used for timber production, watershed protection, wildlife habitat and recreation. The overstory vegetation is dominantly western hemlock with lesser amounts of Sitka spruce and western red cedar. The subordinate vegetation consists largely of blueberry, menziesia, devil's club, and mosses.

KARTA SERIES

The Karta series is a thixotropic skeletal, soil having thin extremely acid A2 horizons and very gravelly, very strongly acid variegated B2 horizons.

Type Location: Hollis Area, Alaska. 2.1 km from Hollis on No. 200 road, 50 meters west of road. (SW 1/4 SE 1/4, Sec. 5, T 74 S, R 84 E, Copper River Meridian).

Range in Characteristics: Depth to the fragipan ranges from 0.4 to 1.0 meters. Coarse fragments range from 50 to 80 percent in the solum. The A2 horizon ranges in texture from silt loam to gravelly loam.

Setting: The Karta soils occur on lower slopes of glaciated valleys and on drumlins and rock drumlins in the valleys. Slopes are rolling to very steep. The regolith is glacial till derived dominantly from graywacke argillite, and granitic rocks. The climate is humid maritime with average annual rainfall about 2.5 meters. The average annual air temperature is about 7°C, and the average summer air temperature is 13°C. The average annual soil temperature is about 5°C and the average summer soil temperature at 0.5 meters depth is about 8°C.

Drainage and Permeability: Moderately well drained. Permeability is moderate above the fragipan (Clx horizon), very slow within the fragipan.

Use and Vegetation: The Karta soils are used for tiber production, watershed protection, wildlife, and recreation. The overstory vegetation is dominantly western hemlock with lesser amount of Sitka spruce and western red cedar. The subordinate vegetation consists largely of blueberry, menziesia, devil's club and bunchberry dogwood.

SHELIKOF SERIES

The Shelikof series is an ashy soil having wet O horizons, thin A2 horizons, and black to dark reddish brown B horizons over a thin wavy indurated iron pan. Beneath this are several to many meters of weathered volcanic ash.

Type Location: Sitka area, Alaska. Cutbank about 4 km up Harbor Mountain road from Sitka. (NW 1/4 SW 1/4, unsurveyed Sec. 14, T 55 S, R 63 E, Copper River Meridian).

Range in Characteristics: Depth to bedrock ranges from one to many meters. Depth to the placic horizon ranges from 0.2 to 0.5 meters. Textures of the A2 horizon range from silt loam to coarse sandy loam.

Setting: The Shelikof soils occur on gently sloping side slopes. The substratum is glacial till. The climate is humid maritime with an average annual precipitation of 2.2 meters at sea level. Mean annual sea level air temperature is 7°C. The soils are seldom frozen.

Drainage and Permeability: Somewhat poorly drained. Moderate permeability.

Use and Vegetation: The Shelikof soils are used for timber production, watershed protection, wildlife, and recreation. The overstory vegetation is dominantly western hemlock, Sitka spurce, and Alaska yellow cedar. The suboridnate vegetation consists largely of blue huckleberry, rusty menziesia, devil's club, skunk cabbage, ferns, and mosses.

SITKA SERIES

The Sitka series is an ashy soil typically having thin extremely acid A2 horizons, very strongly to strongly acid B21 horizons, and medium to slightly acid B22 horizons, all formed in volcanic ash.

Type Location: Cutbank 3.2 km on Harbor mountain road from Sitka, Alaska. (SW 1/4 NE 1/4, unsurveyed Sec. 15, T 55 S, R 63 E, Copper River Meridian).

Range in Characteristics: Thickness of the solum ranges from 0.5 to 1.0 meters. Content of coarse fragments ranges from 0 to 20 percent. Texture of the A2 horizon ranges from sandy loam to loam. Texture of the B21 horizon ranges from sandy loam to loam.

Setting: The Sitka soils occur on gently sloping valley slopes. They are underlain by glacial till. The climate is humid maritime, with average annual precipitation of 2.2 meters at sea level. Mean annual sea level air temperature is 7°C. The soils are seldom frozen.

Drainage and Permeability: Well drained. Rapid permeability.

Use and Vegetation: The Sitka soils are used for timber production, watershed protection, recreation, and wildlife. The vegetation consists largely of Sitka spruce and western hemlock in the overstory, and blueberry and rusty menziesia in the understory.

TOKEEN SERIES

The Tokeen series is a thixotropic soil typically having thin A2 horizons over thick gravelly B horizons with variegated colors.

Type Location: Hollis Area, Alaska, Mile 0.06 on No. 1210 road from Thorne Bay. (SW 1/4 SW 1/4 SE 1/4, Sec. 9, T 71 S, R 84 E, Copper River Meridian).

Range in Characteristics: Thickness of solum ranges from 0.3 to 0.8 meters. Depth to bedrock ranges from 0.6 to 1.2 meters. The coarse fragment content of the soil ranges from 15 to 40 percent. Textures of the A2 horizon range from gravelly sandy loam to gravelly loam. The texture of the B2 ranges from gravelly sandy loam to gravelly loam. A C horizon ranging from 0.1 to 0.4 meters in thickness is sometimes present.

Setting: The Tokeen soils occur on rocky convex slopes. The regolith is highly weathered gneissic diorite. Rainfall averages 2.5 to 3.8 meters per year. The average annual air temperature is 7°C and the average summer air temprature is 13°C. The average annual soil temperature at 0.5 meters depth is about 5°C and the average summer soil temperature is about 8°C.

Drainage and Permeability: Well drained, moderate permeability.

Use and Vegetation: The Tokeen soils are used for timber production, watershed protection, wildlife, and recreation. The overstory vegetation is dominantly western hemlock with lesser amounts of Sitka spruce and western red cedar. The subordinate vegetation consists largely of blueberry, menziesia, devil's club, and mosses.

GUNNUK SERIES

The Gunnuk series is a soil having gray A2 horizons and dark reddish brown to dark brown B horizons over grayish brown fine marine deposits.

Type Location: Kupreanof Area, Alaska. South shore near the head of Big John Bay, about 100 meters from the beach.

Range in Characteristics: Thickness of the solum ranges from 0.4 to 1.0 meters. Coarse fragment content is commonly less than 10 percent, and never exceeds 30 percent in any horizon. Depth to bedrock ranges from 1.5 to many meters. Texture of the C horizon ranges from clay to silty clay loam.

Setting: The Gunnuk soils occur in valley bottoms and lower slopes of valleys close to the coast. Elevations range from near sea level to 460 meters. Slopes are normally gentle, but range up to 60 percent near the heads of valleys. Marine sediments make up the regolith. The climate is cool maritime. Annual precipitation is greater than 2.5

meters. The average annual air temperature is about 7°C, and the average summer air temperature is about 13°C.

Drainage and Permeability: Moderately well drained. Permeability is moderate in the A and B horizons, but slow in the C horizon. Runoff is slow to moderate.

Use and Vegetation: The Gunnuk soils are used for timber production, watershed protection, wildlife and recreation. The principal tree is western hemlock, with lesser amounts of Sitka spruce and Alaska cedar. The subordinate vegetation includes blue huckleberry, rusty menziesia, devil's club and bunchberry dogwood.

ULLOA SERIES

The Ulloa series is a thixotropic soil typically having thin A2 horizons, thin dark reddish brown to dusky red B21 horizons over slightly acid to neutral dark yellowish brown to dark brown B2 horizons.

Type Location: Hollis Area, Alaska. 1.9 km south of Klawock bridge on Klawock-Craig road, 110 meters east of road. (SW 1/4 SE 1/4, Sec. 16, T 73 S, R 81 E, Copper River Meridian).

Range in Characteristics: Thickness of solum ranges from 0.4 to 1.1 meters. Depth to bedrock ranges from 0.5 to 1.3 meters. Coarse fragment content of the solum ranges from 15 to 40 percent. Texture of the A2 horizon ranges from loam to silt loam. Texture of the B21 and B22 horizons ranges from silt loam to gravelly silt loam.

Setting: The Ulloa soils occur on steep side slopes of glaciated valleys. The regolith is weathered colluvium dominantly from limestone and marble. The climate is cool and humid with annual rainfall of about 2.5 meters. The average annual air temperature is about 7°C and the average summer air temperature is 13°C. The average annual soil temperature at 0.5 meters is 5°C and the average summer soil temperature at 0.5 meters is 8°C.

Drainage and Permeability: Well drained. Moderate permeability.

Use and Vegetation: The Ulloa soils are used for timber production, watershed protection, wildlife habitat, and recreation. The overstory vegetation is dominantly western hemlock, western red cedar and Sitka spruce. The understory vegetation is dominantly blueberry and devil's club.

WADLEIGH SERIES

The Wadleigh series is a loamy-skeletal soil typically having thin mottled A2 horizons and dark reddish brown and dark brown B2 horizons of extremely acid very gravelly loam which overlies indurated olive gray glacial till of very gravelly loam texture.

Type Location: Hollis Area, Alaska. 100 meters south of 12 mile marker on 2400 Road from Thorne Bay. (SE 1/4 SW 1/4, Sec. 24, T 71 S, R 82 E, Copper River Meridian).

Range in Characteristics: Thickness of the solum ranges from 0.1 to 0.5 meters. The coarse fragment content of the soil ranges from 50 to 80 percent. Depth to the fragipan ranges from 0.1 to 0.3 meters. The O horizon ranges in thickness from 0.1 to 0.25 meters. Texture of the A2 ranges from gravelly silt loam to very gravelly loam. The texture of the B21 horizon ranges from very gravelly loam to very gravelly silt loam. Depth to bedrock ranges from 0.5 meters to many meters.

Setting: The Wadleigh soils occur on drumlins and gently sloping to very steep lower slopes of U-shaped valleys. The regolith is glacial till derived primarily from weathered graywacke and granitic rocks. The climate is humid maritime with average annual rainfall about 2.5 meters. The average annual air temperature is 7°C and the average summer air temperature is 13°C. The average annual soil temperature above the compact till is about 5°C. The average summer soil temperature above the compact till is 8°C.

Drainage and Permeability: Imperfectly drained. Moderate permeability above the B3 horizon.

Use and Vegetation: The Wadleigh soils are used for wildlife, recreation, watershed protection, and timber production. The overstory vegetation is mainly western red cedar and western hemlock with some

Sitka spruce. The understory vegetation is dominantly blueberry, rusty menziesia, skunk cabbage, and marsh marigold.

APPENDIX C

THE STRESS PATH METHOD

Several methods exist for interpreting sample failure and subsequently evaluating effective strength parameters in triaxial shear tests. Three common methods are the maximum deviator stress method, the maximum principal stress ratio method, and the stress path method. Since it is desirable to limit strain in the early stages of a multistage test, the maximum deviator stress was not reached during shear at low consolidation pressures for several specimens. Therefore, the maximum deviator stress method was not used. Of the remaining two methods, the stress path method was preferred over the maximum principal stress ratio method for both practical and theoretical reasons.

In the maximum principal stress ratio method, failure is assumed to occur at the point where the ratio of the major principal effective stress to the minor principal effective stress is maximum. Let

$$p = \frac{\sigma'_1 + \sigma'_3}{2}$$

and

$$q = \frac{\sigma'_1 - \sigma'_3}{2}$$

where σ'_1 is the major principal effective stress, and σ'_3 is the minor principal effective stress.

The quantities p and q are evaluated at the strain corresponding to the maximum principal stress ratio. A point identified by a pair (p,q) is selected in this manner to represent each test conducted on a material with a particular sample preparation method. A "least squares" regression line is run through the chosen points. This line can be represented by an angle, α, with the p axis and an intercept, a, on the q axis. It can be shown that

$$\sin \phi' = \tan \alpha$$

and

$$c' = a \sec \phi'$$

where ϕ' = the effective angle of internal friction

and c' = the effective cohesion intercept

These relationships yield the desired effective strength parameters.

In the stress path method, a plot of p versus q for the entire data set obtained from each test on a material is made. A straight line envelope is drawn by visual approximation enclosing the stress paths. Since a stress path is a plot of p versus q, the stress path envelope can be converted to a conventonal Mohr's envelope using the equations given above.

The practical reason for preferring the stress path method in this study is that the stress path envlope is chosen subjectively. Usually, three or four shear tests are conducted on a given material in order to establish a strength envelope. If the shape of one stress path is significantly different from the rest, it is reasonable to consider disregarding that stress path when fitting the envelope. In a conventional three-specimen test, an oddly shaped stress path could result from differences in specimen composition, differences in specimen stress histories, or errors in testing technique. An unusually shaped stress path is less likely in a multi-stage test since differences in specimen composition and stress history are eliminated. The stress paths from the multi-stage tests in this study were generally consistent. When a single point is chosen to represent each shear test, as in the maximum principal stress ratio method, it is difficult to interpret inconsistencies. The element of judgement associated with estimating the position of the strength envelope in the stress path method permits an easy interpretation of inconsistencies.

The theoretical reason for preferring the stress path method is best illustrated by considering the case of an overconsolidated clay. Idealized stress paths and a stress path envelope for an overconsolidated material are illustrated in Figure 5. Also shown are tangents from the origin to each of the stress paths. It can be shown that the tangents, the lines from the origin to the stress paths which make the greatest angle with the p axis, intersect the stress paths at the points corresponding to the maximum principal stress ratios. These points are labeled A and B in Figure 5. The envelope determined by the maximum principal stress ratio method is obtained, by using the equations above, from the line connecting points A and B. It is clear from Figure 5 that this "envelope" does not necessarily contain all possible stress states of an overconsolidated material. The envelope obtained by the stress path method, on the other hand, does. In the case illustrated, the cohesion intercept is lower and the friction angle is higher when obtained by the maximum principal stress ratio method than when obtained by the stress path method. The discrepancy is probably not of practical consequence in most applications; nevertheless, the stress path method appears to be the better procedure.

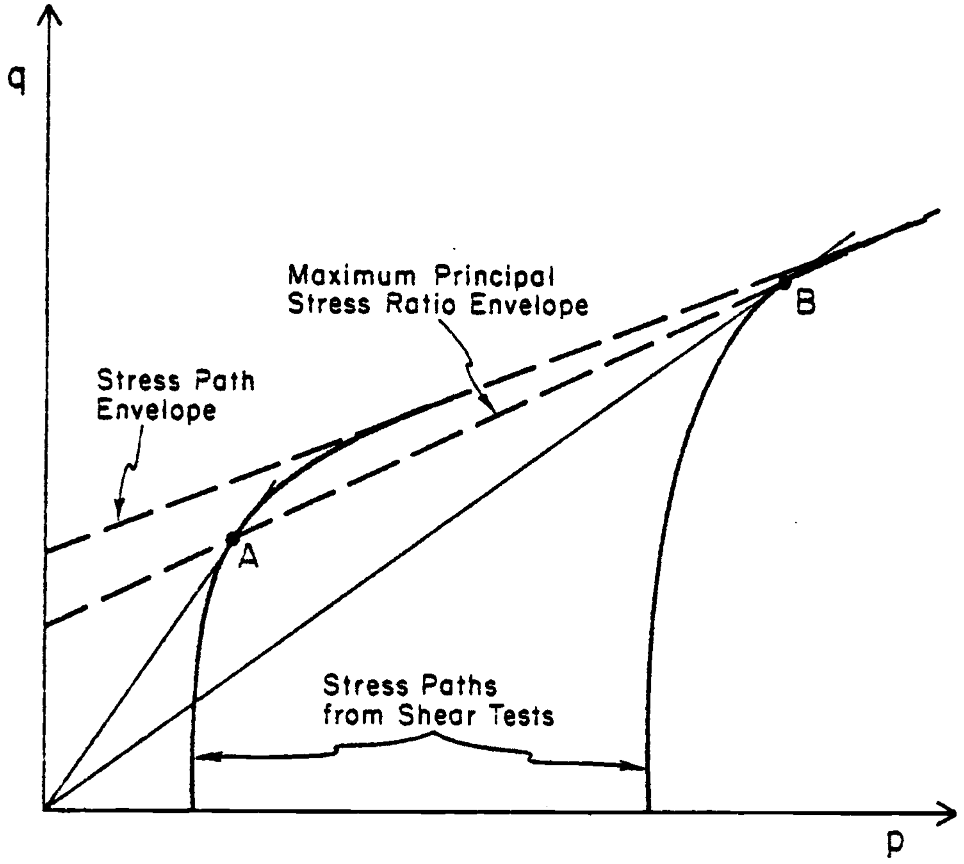

Figure 5. A comparison between the strength envelopes obtained by the maximum principal stress ratio method and by the stress path method.