Geotechnical Properties for Landslide-Prone Seattle—Area Glacial Deposits

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Open-File Report 00-228

2000

USGS
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Introduction

The Seattle area has a long history of landslide problems (Tubbs, 1974, Thorsen, 1989, Galster and Laprade, 1991, Gerstel and others, 1997, Baum, and others, 1998a). Landslides commonly occur during winter storms, are typically shallow, initiate in loose surficial materials, and often mobilize into debris flows. However, less common slumps and deep-seated slides cause considerable damage to structures and transportation corridors (Baum and others, 1998a). Most Seattle-area deep-seated landslides occur in or near the transitional zone between the Esperance Sand and the underlying Lawton Clay (Tubbs, 1974). The Esperance Sand and the Lawton Clay are part of a sequence of Pleistocene glacial deposits in the Puget Sound Basin. Deposits in this sequence are often overconsolidated, have a wide range of hydraulic conductivities, are laterally heterogeneous, and form steep, landslide-prone coastal bluffs. A generalized section showing Seattle-area glacial deposits is shown in Figure 1.

In what follows, we summarize published geotechnical data for the geologic section shown in Figure 1. These data are being used in groundwater-flow and slope-stability models under development for analysis of landslide hazards in the Seattle area by the USGS Landslide Hazards Program.

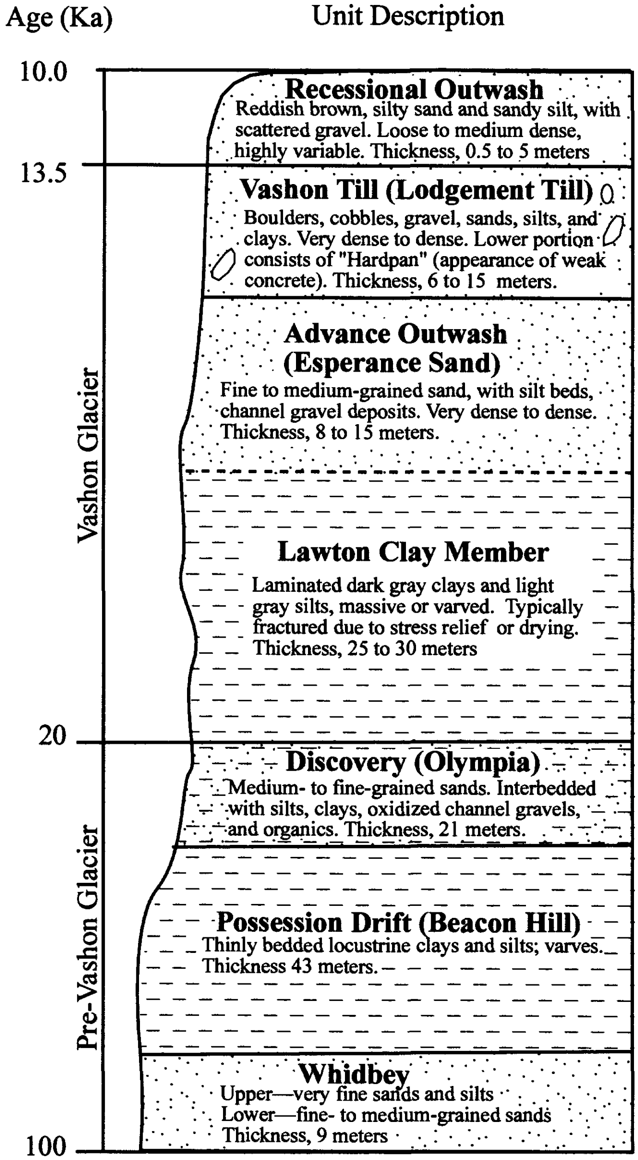

Figure 1. Generalized Quaternary geologic section for the Seattle area (From Galster and Laprade, 1991).

Generalized geotechnical properties for Seattle-area glacial deposits

The glacial deposits shown in Figure 1 have wide ranges of geotechnical properties. General ranges of dry densities for typical geologic materials of the Pacific Northwest (Koloski and others, 1989) are 1920 to 2240 kg/m^3 for glacial till, 1840 to 2080 kg/m^3 for glacial outwash, and 1600 to 1920 kg/m^3 for glacio-lacustrine materials. Published dry (ρ_{dry}) and wet (ρ_{wet}) densities for Seattle-area glacial deposits are presented in Table 1.

General ranges of hydraulic conductivity given by Koloski and others (1989) for typical glacial geologic materials of the Pacific Northwest are 0 to 0.5 m/day for till, 5 to 5000 m/day for outwash, 0 to 500 m/day for glacio-lacustrine materials. Published values of hydraulic conductivity, k, for the Seattle area are given in Table 2. Hydraulic properties for transitional silt and sand layers that lie between the Lawton Clay and the Esperance Sand are given in addition to those for the units shown in Figure 1. Morgan and Jones (1995) presented mean values of 0.1 m/day for transitional silt and 1 m/day for transitional sand. In addition to the data in Table 2, Sabol and others (1988) gave conductivity values for near-surface Seattle-area glacial-outwash deposits of 80 m/day for gravels, 50 m/day for mixed sands and gravels, and 30 m/day for sands.

Hydraulic conductivites in Table 2 are assumed to be horizontal. Morgan and Jones (1995) presented

Table 1. Dry (ρ_{dry}) and wet (ρ_{wet}) densities for the units shown in Figure 1.

Geologic Unit	ρ_{dry} kg/m^3	ρ_{wet} kg/m^3	Source	Reference
Recessional Outwash		2050	Laboratory	Robinson and others, 1983
		1600-1920	Not Specified	Galster and Laprade, 1991
Vashon Till	1920-2400	2160-2560	Laboratory	Olmstead, 1969
		2080-2400	Not Specified	Galster and Laprade, 1991
Esperance Sand (Advance Outwash)	1760	1920	Laboratory	Miller, 1989
		1920-2160	Not Specified	Galster and Laprade, 1991
Lawton Clay		1890	Laboratory	Robinson and others, 1983
		1600-1920	Not Specified	Galster and Laprade, 1991
Pre-Vashon		1910	Laboratory	Robinson and others, 1983
	1460	1920	Laboratory	Miller, 1989
		2080-2040	Not Specified	Galster and Laprade, 1991

Table 2. Hydraulic conductivities, k, for the units shown in Figure 1.

Geologic Unit	k m/day	Source	Reference
Recessional Outwash	$1x10^{-1}$- $1x10^{2}$	Not Specified	Laprade and Robinson, 1989
	$1x10^{-2}$- $1x10^{2}$	Not Specified	Galster and Laprade, 1991
	$1x10^{0}$-$1x10^{1}$	Field Tests	Morgan and Jones, 1995
	$1x10^{-2}$- $1x10^{2}$	Field Tests	Woodward and others, 1995
Vashon Till	$1x10^{-5}$- $1x10^{-2}$	Laboratory	Olmstead, 1969
	$1x10^{-5}$- $1x10^{-2}$	Not Specified	Laprade and Robinson, 1989
	$1x10^{-6}$- $1x10^{-1}$	Field Tests	Mills and Cordell, 1989
	$1x10^{-4}$- $1x10^{0}$	Not Specified	Galster and Laprade, 1991
	$1x10^{-5}$-$1x10^{1}$	Field Tests	Morgan and Jones, 1995
Esperance Sand (Advance Outwash)	$1x10^{-2}$- $1x10^{1}$	Not Specified	Mills and Cordell, 1989
	$1x10^{-1}$- $1x10^{2}$	Not Specified	Galster and Laprade, 1991
	$1x10^{0}$-$1x10^{1}$	Field Tests	Morgan and Jones, 1995
	$1x10^{-3}$-$1x10^{1}$	Field Tests	Woodward and others, 1995
Transitional silt-sands	$1x10^{-6}$-$1x10^{-1}$	Field Tests	Morgan and Jones, 1995
	$1x10^{-1}$-$1x10^{1}$	Field Tests	Woodward and others, 1995
Lawton Clay	$1x10^{-5}$- $1x10^{-3}$	Not Specified	Laprade and Robinson, 1989
	$1x10^{-4}$- $1x10^{-1}$	Not Specified	Galster and Laprade, 1991
Pre-Vashon	$1x10^{-5}$- $1x10^{-2}$	Not Specified	Laprade and Robinson, 1989
	$1x10^{-4}$- $1x10^{-1}$	Not Specified	Galster and Laprade, 1991

ratios of horizontal and vertical conductivities. The k_H/k_V values are 10 for Recessional and Advance Outwash, 100 for Vashon Till, and 200 for Transitional Bed silts and sands.

Baum (unpublished data, 1999) conducted slug tests in the summer of 1999 in two open-tube piezometers at the Woodway landslide near Seattle (Baum and others, 1998b). The first test gave a hydraulic conductivity of approximately 9.0 x 10^{-4} m/day for an approximately 4-m-thick layer of fine-to-coarse sand with lenses of silt and clay in the transitional beds between the Esperance Sand and the Lawton Clay. The sand layer was saturated and confined between two layers of silt. The second test yielded a hydraulic conductivity of 7.0 x 10^{-4} m/day for the bottom of an 8 meter-thick layer of fine to medium sand resting on a layer of silt at the base of the Esperance Sand. At the location of this slug test, the borehole was initially wet but contained little if any standing water. This could indicate that a partially saturated zone was sampled. Both measurements are within the range of published values for the transitional beds between the Lawton Clay and Esperance Sand (Table 2)

Dry densities, shear and compressional wave velocities, Poisson ratios, σ, Youngs', E, and shear moduli, μ, for the units shown in Figure 1, are presented in Table 3. Because complete dry-density ranges (Table 1) are given only for the Vashon Till, we have estimated most dry densities for the remaining units in Table 3 to be 20 percent less than maximum and minimum wet densities in Table 1. The 20 percent figure is consistent with laboratory-measured moisture contents of materials collected from exposed units at the Woodway slide (Arndt, 1999). Estimated dry densities are indicated by parentheses in Table 3. Maximum and minimum shear wave, V_s, and compressional, V_p, velocities in Table 3 were measured by shallow seismic methods in the Seattle area (Williams and others, 1999 and Williams, personal communication, 2000). Assuming that low and high velocities, respectively, match low and high densities, elastic moduli have been calculated from these densities and the wave velocities by formulae given in Birch, (1966) and are presented in Table 3.

Koloski and others (1989) presented general ranges for cohesion and internal friction for typical geologic materials of the Pacific Northwest. The cohesion values are 48 to 192 kPa for glacial till, 0 to 48 kPa for glacial outwash, and 0 to 144 kPa for glacio-lacustrine materials. The internal friction angles are 35 to 45 degrees for glacial till, 30 to 40 degrees for glacial outwash, and 15 to 35 degrees for glacio-lacustrine materials. Koloski and others (1989) did not specify whether these values were peak or residual. However, from the given magnitudes, the values can be assumed to be peak values. For the Seattle area, peak and residual cohesion (c_p and c_r) and peak and residual internal friction angles (φ_p and φ_r) for the units shown in Figure 1 are given in Table 4.

Table 3. Dry densities, ρ_{dry}, shear and compressional wave velocities, V_s and V_p, Poisson ratios, σ, Youngs' modulus, E, and shear modulus, μ, for the units shown in Figure 1. Estimated dry densities are in parentheses.

Geologic Unit	ρ_{dry} kg/m^3	V_s m/s	V_p m/s	σ	E mPa	μmPa
Recessional Outwash	(1280)	250	630	0.41	225	80
	(1640)	500	760	0.12	917	410
Vashon Till	1920	360	1000	0.43	710	249
	2400	760	1800	0.43	3860	1386
Esperance Sand	(1540)	250	630	0.41	270	96
(Advance Outwash)	1760	500	760	0.12	984	440
Lawton Clay	(1280)	155	1520	0.49	92	31
	(1540)	400	1800	0.47	726	246
Pre-Vashon	1460	340	2040	0.47	1346	458
	(1920)	560	2340	0.47	1770	602

Table 4. Peak and residual cohesion (c_p and c_r) and peak and residual internal friction angles (φ_p and φ_r) for the units shown in Figure 1.

Geologic Unit	c_p kPa	φ_p°	c_r kPa	φ_r°	Source	Reference
Recessional Outwash	0	30-32			Not Specified	Wu, J., 1998, personal communication
Vashon Till	38-192	20-42			Not Specified	Wu, J., 1998, personal communication
Esperance Sand (Advance Outwash)	0-12	32-36			Not Specified	Wu, J., 1998, personal communication
Lawton Clay	62	35	0	14-18	Laboratory	Palladino and Peck, 1972
	0-383	26-32	0	16-20	Not Specified	Wu, J., 1998, personal communication
	0-38	15-27	0-24	6-27	Laboratory	Arndt, 1999
Pre-Vashon			2-17	11-29	Laboratory	Miller, 1989

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