A Preliminary Finite-Element Analysis of a Shallow Landslide in the Alki Area of Seattle, Washington

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Introduction

The Seattle area has a long history of landslide problems (Tubbs, 1974, Thorsen, 1989, Galster and Laprade, 1991, Baum, and others, 1998). Shallow landslides often initiate in colluvium derived from glacial deposits, are frequently triggered by winter rain storms (Tubbs, 1974), and may mobilize into debris flows that can cause considerable damage (Baum and others, 1998).

In this report we present a preliminary finite-element based stability analyses of a shallow landslide that occurred during the period from December 1996 to early January 1997 near Alki Beach and Duwamish Head at the north end of West Seattle (Figure 1). During this period a series of snowstorms, freezing rain and warm rain produced many debris flows and landslides in the Seattle area (Baum and others, 1998). The shallow landslide that we are analyzing was 18 m high and 75 m long. It mobilized into a debris flow that traveled down a 35-meter-high embankment below the slide damaging the bottom floors of two apartment buildings at the foot of the embankment (Figure 2). In what follows, we briefly outline the geology and hydrology of the Alki landslide site, give a short description of the computational algorithms used in the finite element program, and present the results of the finite element model of the landslide.

Figure 2. View of the Alki landslide area. (Photograph taken August 2001 by S. Debray.)

Figure 1. Alki landslide location.

Geology and hydrology of the Alki landslide site

Galster and Laprade (1991) identify the following sequence of glacially derived surficial geologic formations in the Seattle area. They are, from top to bottom, Recessional Outwash, Vashon Till, Advance Outwash, Lawton Clay, and the Pre-Vashon. Deposits in this sequence are often overconsolidated, have a wide range of hydraulic conductivities, are laterally heterogeneous, and form steep, landslide-prone, coastal bluffs.

According to Waldron and others (1962) only the Esperance Sand and the Lawton Clay are present at the Alki landslide site. However, Shannon and Wilson (2000) identify, from borehole logging, dense Pre-Vashon sands, silts, and clays below the Lawton Clay at the Alki site. The Esperance Sand is a unit in the Advance Outwash that has been overridden by glacial ice. Generally these outwash deposits are dense, brown and gray, and permeable with fine to coarse sand and silt. Lawton Clay is a glacio-lacustrine deposit that consists of very stiff to hard and relatively impermeable clays and silts. Where pervious sand overlies the clay, this clay acts as an aquiclude and ground water is perched in the sand. The Pre-Vashon sediments are interglacial fluvial and lake deposits.

The Alki landslide occurs in an 8- to 12-m thick layer of colluvium, a very loose to medium density soil that commonly covers upper, flatter slopes at the Alki site (Shannon and Wilson, 2000). Here the colluvium overlies Lawton clay and is laterally continous with the Esperance Sand. Its looseness results in a higher permeability than that of the underlying Lawton Clay, so that ground water is perched at the contact or in the lower part of the colluvial mantle (Shannon and Wilson, 2000).

Resistant and relatively impervious Vashon Till commonly caps Seattle-area hilltops (Tubbs, 1974, Galster and Laprade, 1991). This layer impedes water infiltration. However, at the Alki slide, till coverage is absent and, thus, surface water can percolate into the underlying Esperance Sand continuing downward until it reaches the relatively impervious Lawton Clay. Ground water then moves laterally in the Esperance Sand reaching the colluvium and emerging as springs on the hillside. If the rate of infiltration exceeds the capacity of the hydraulic gradient to transmit ground water to hillside seeps, pore pressures rise and slope failure ensues.

Geotechnical properties of Alki slide materials

A detailed geotechnical investigation of the Alki glacial deposits is beyond the scope of this work. Therefore Alki-site property values are taken from a previously published summary (Savage and others, 2000b) and from data reported by Shannon and Wilson (2000). Peak cohesion (C_p) for the Alki colluvium is taken by Shannon and Wilson (2000) to be zero. We estimate it to be to be 5 KPa (see below). The peak friction angle (Φp) for colluvium is 23° (Shannon and Wilson, 2000). Strength values for the Lawton Clay were those used by Savage and others (2000a) in a finite-element limiting-equilibrium analysis of stability of the Woodway landslide. The estimated geotechnical properties for the units at the Alki site that are used in the finite-element modeling are given in Table 1.

Geologic Unit	γ_{dry} KN/m³	γ_{wet} KN/m³	σ	*E* MPa	C_p KPa	Φp°
Pre Vashon	18	20	0.33	250	40	32
Lawton Clay—Qc	17	20	0.49	250	20	24
Esperance Sand (Advance Outwash)—Qva	17.6	19.2	0.30	200	20	32
Colluvium	15	19	0.33	160	5	24

Table 1. Estimated material properties used in finite-element modeling of the Alki landslide. In this table, dry and wet unit weights are denoted by γ_{dry}, and γ_{wet}, σ is Poisson's ratio, *E* is Young's Modulus, C*p* is peak cohesion, and Φp is the peak angle of internal friction.

Finite-element modeling of the Alki landslide

Stability of the Alki Landslide is modeled by using Version 7 of the PLAXIS© finite-element program. This program, designed for geotechnical analysis, features automatic mesh generation, pore pressure generation, a non-linear elastic-plastic Mohr-Coulomb iterative-solution algorithm, and a phi-c-reduction procedure for calculation of safety factors.

The factor of safety, FS, in PLAXIS© is defined by,

$$FS = \frac{C + \sigma_n' \tan\Phi}{C_R + \sigma_n' \tan\Phi_R}.$$

Where $\sigma_n{}'$ is effective normal stress acting on a plane, $\boldsymbol{C}$ and Φ are the input cohesion and angle of internal friction, and $\boldsymbol{C_R}$ and $\Phi_{\boldsymbol{R}}$ are a reduced cohesion and reduced angle of internal friction calculated in the program as products of the input values and a multiplier. The parameters $\boldsymbol{C_R}$ and $\Phi_{\boldsymbol{R}}$ are then iteratively changed until they are just large enough to maintain equilibrium and then used in the above equation to give the factor of safety on an element-by-element basis. When the factor of safety approaches 1, failure is imminent in critically stressed elements. The factor of safety for a slope is the mean of the factors of safety for all elements approaching failure in the finite-element model. The safety factor procedure in PLAXIS© gives results similar to conventional slip-circle analyses (Savage and others, 2000a) where the safety factor is the ratio of the true strength to the minimum strength required for equilibrium of a postulated slip surface.

The geometry of the site as used in the calculation is shown in Figure 3.

Since the Alki landslide failed after heavy precipitation in the area it is assumed that rising ground water levels were responsible for slide initiation. To simulate the effect of rising ground water on the initiation of the Alki landslide a perched water table near the top of the relatively impervious Lawton Clay is raised in the finite-element model from 0-4 meters head to give a factor of safety of 1.07; a value close to the failure value of 1.

Precise values for the cohesion of the colluvium are not available. Sensitivity results for a range of cohesion between 5 KPa and 17 KPa for a perched water table of 4.0 m yields a best model

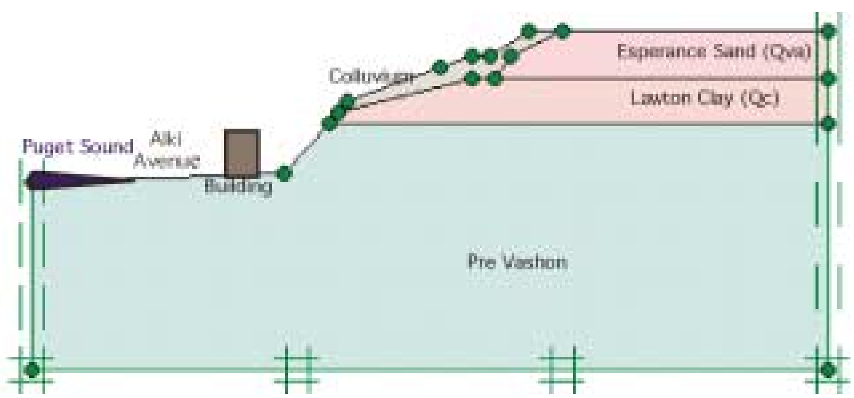


Figure 3. Model of the geometry and geologic layers of the Alki site. Double crosses indicate the model boundaries. Scale 1:3000.

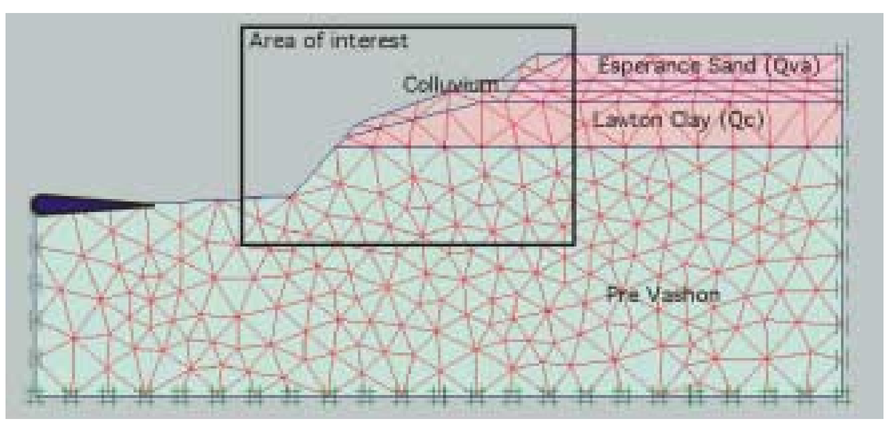


Figure 4. Finite-element mesh used to model the Alki landslide. Scale 1:3000.

Cohesion of the colluvium (KPa)	Factor of safety (calculated with the phi/c reduction procedure)
5	0.302
9	0.485
14	0.85
15	0.891
15.1	1.07
15.2	1.12
16	1.23
17	1.45

Table 2. Sensitivity of the factor of safety to cohesion (C) over the range 5-17 KPa.

fit for a cohesion of 15.1 KPa (the factor of safety for this value is 1.07).

Predicted displacement magnitudes, $[u_x^2 + u_y^2]^{½}$, (u_x and u_y are, respectively, horizontal and vertical displacements) when FS = 1.07 are shown in Figure 5. Displacements in this case are calculated using the elastic-Coulomb plastic algorithm in PLAXIS©.

Figures 6a and 6b show deformation of the mesh and concentration of displacements calculated by the PLAXIS© phi-c reduction procedure when FS = 1.07. No magnitudes are given for the displacements in Figures 6a and 6b as the phi-c reduction procedure in PLAXIS© generates additional, large, non-physical displacements. However, the shape of the deformed mesh and the pattern of the displacements give an indication of the shape of the failure surface. The predicted failure-surface shape is in reasonable agreement with that produced during the winter of 1996-1997 (Shannon and Wilson, Inc., 2000).

Concluding discussion

The finite element modeling results give a general idea of the mechanism of landsliding at the Alki site in response to a rising perched ground water table. The position and shape of the failure surface are simple; failure

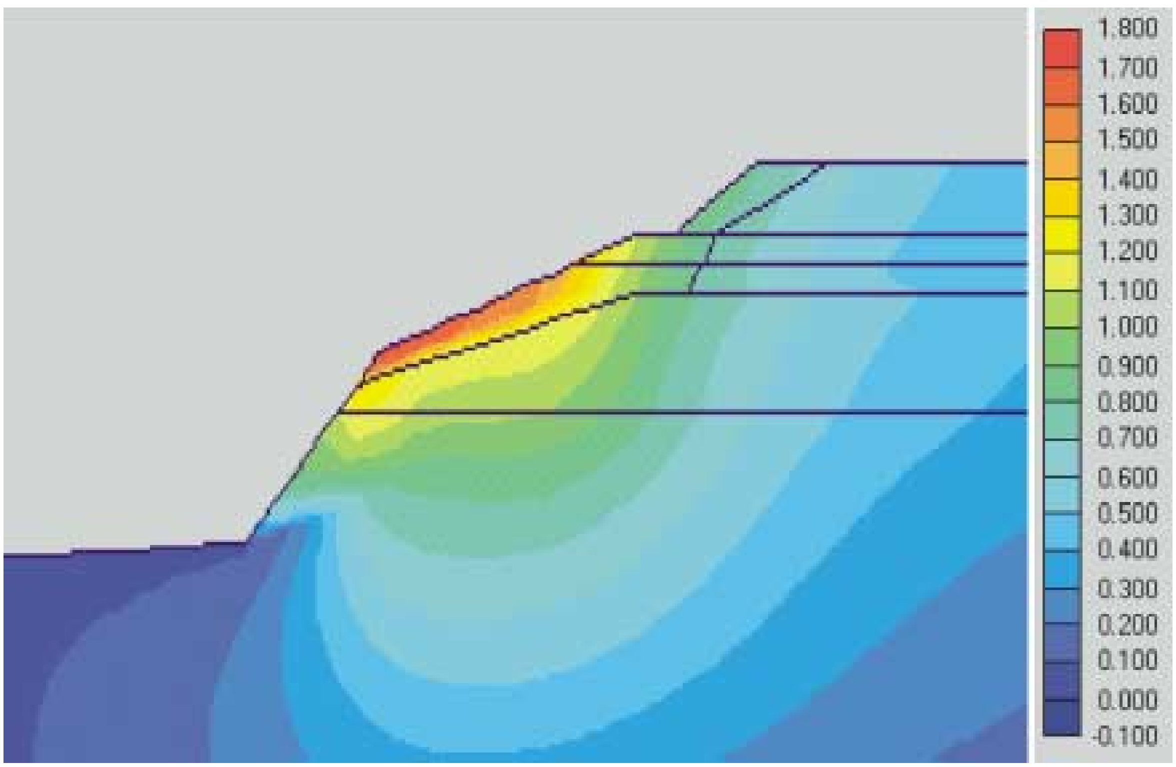
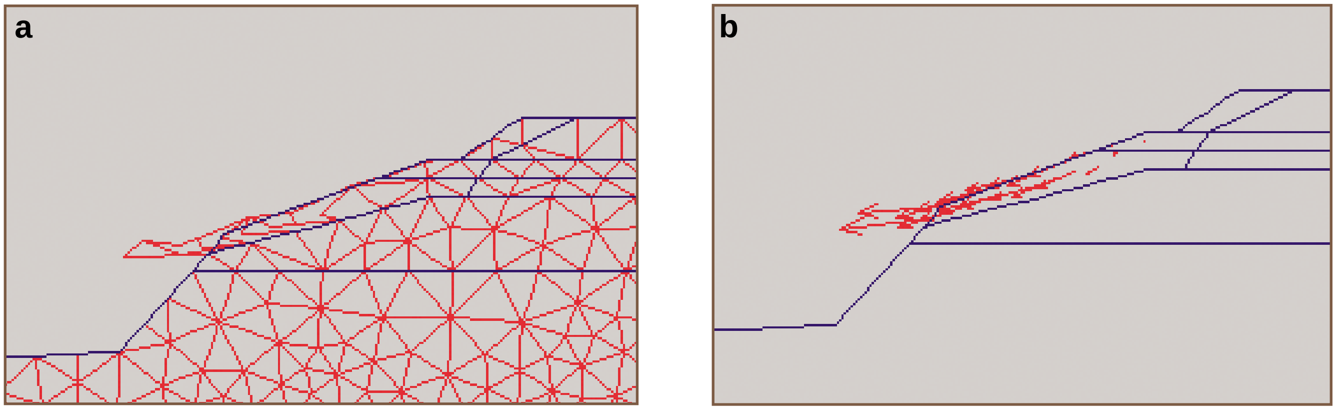


Figure 5. Predicted displacement magnitudes in millimeters. Only the area of interest outlined in Figure 4 is shown. Displacements elsewhere are negligible.

occurred on a surface at the contact between the colluvium and the clay and sand layers triggering a general movement of the colluvium which then mobilized into destructive debris flows.

In conclusion, we suggest that the slide occurred because of high pore pressures in the colluvium resulting from the juxtaposition of the weak colluvium on the transition zone between impervious Lawton clay and overlying Esperance Sand. Finally, although averaged and estimated geotechnical properties gave reasonable results for the Alki slide, a more complete sensitivity analysis for evaluating the effect of geotechnical property variation should be performed.



Figures 6a and 6b. Deformation of the mesh is shown in Figure 6a and displacement concentrations in regions at incipient failure are shown in Figure 6b.

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