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Evaluating Topographically-Derived Vs30 Values for Seismic Site Class Characterization in Anchorage, Alaska, USA

E. C. Cannon[1], U. Dutta[2]

ABSTRACT

Analysis of topographic slopes is a useful method for providing average shear-wave velocity to 30 m depth (Vs30) estimates for seismic site classification. The United States Geological Survey Global Vs30 Map Server provides preliminary Vs30 estimates based on topography and prior correlations with Vs30 measurements. However, site-specific geological conditions and processes are fundamental to Vs30 values. To investigate improving the correlation between topographically-derived Vs30 values and Vs30 measurements in Anchorage, Alaska, USA, we analyze three digital elevation models, Vs30 values from downhole and surface measurements, and ten surficial geologic units, to develop specific topographic slope relationships to Vs30 measurements. We employ a composite approach of using our custom topographic slope coefficients with USGS Global Vs30 Map Server active tectonic coefficients to improve the correlation between topographic slope-derived Vs30 values and Vs30 measurements. This composite approach improves correlations between topographically-derived Vs30 values and Vs30 measurements for central, western, and southwest Anchorage.

Introduction

Determining the average shear-wave velocity to 30 m depth (Vs30) value is one method for establishing a National Earthquake Hazard Reduction Program (NEHRP) seismic site class for a site. The United States Geological Survey (USGS) operates the USGS Global Vs30 Map Server (USGS, 2013) using correlations between topographic slope and measured Vs30 values to provide estimates of Vs30 values. This tool is useful for sites where little to no measured Vs30 values are available. However, site-specific geology and geological processes influence the types of soils present at a site, and thus should also be considered when investigating Vs30 values using topographic slope correlations.

In this paper, we investigate the relationship between measured Vs30 values and geologic units for Anchorage, Alaska, USA, to develop improved correlations between measured Vs30 values and topographic slope. We provide an overview of the geologic setting of Anchorage, discuss the concept of using topographic slope to estimate Vs30 values, present our methods to improve correlation between measured Vs30 values and topographic slope, and discuss our findings. The glacial processes of the Anchorage area greatly influence sediment distribution, measured Vs30 values, and correlations between topographic slope and measured Vs30 values.

[1]Eric C. Cannon, CPG, Senior Geologist, Golder Associates Inc., Anchorage, Alaska, USA, ecannon@golder.com
[2]Utpal Dutta, PhD, Associate Professor, College of Engineering, University of Alaska Anchorage, Anchorage, Alaska, USA, udutta2@uaa.alaska.edu

Geologic Setting

Anchorage is situated along the active plate margin of the Aleutian Subduction Zone, with the oceanic Pacific Plate subducting northwest beneath the continental North American Plate at about 54-57 mm/yr (Carver and Plafker, 2008). In addition, the northwestward-moving Yakutat Microplate is colliding with the North American Plate at about 40-49 mm/yr (Haeussler, 2008). The combination of subduction and microplate collision results in the development of the Cook Inlet forearc basin, in which Anchorage is located, and right-lateral transpressional folds and faults (Haeussler et al., 2000).

Pleistocene glaciations have had a major influence on the sedimentary deposits and topography of Cook Inlet. The last major glaciation was the Naptowne glaciation, beginning about 27 to 32 cal kya (calibrated thousands of years ago), reaching a maximum about 23 cal kya, and ending about 11 kya (Reger et al., 2007). Anchorage is underlain by glacial deposits from the Naptowne and older glaciations. As the Naptowne glaciation receded northward from the maximum extent, glaciodeltaic and the glacioestuarine Bootlegger Cove Formation (BCF) deposits were deposited about 17.5 to 16.0 kya (Reger et al., 1995; 2007). As the Naptowne glaciation waned, the Elmendorf moraine reached a maximum extent about 15 cal kya. With the decline and end of the Naptowne glaciation, alluvial and colluvial deposits became more prevalent.

Using Topography to Infer Vs30 Values

Inferring Vs30 values using topographic slopes is based on the assumption that shear-wave velocities increase on steeper topographic slopes where soils have larger grain sizes. From Allen and Wald (2007) and Wald and Allen (2007), shear wave velocities generally increase in soils with larger grain sizes. Based on depositional energy, soils with larger grain sizes are generally deposited on steeper topographic slopes, and thus the soils would have higher shear-wave values. Conversely, soils with smaller grain sizes are assumed to be deposited on shallower topographic slopes, and these soils would have lower shear-wave velocities.

The USGS Global Vs30 Map Server incorporates 1,197 measured Vs30 values from California, Taiwan, and Italy and active tectonic coefficients which correlate measured Vs30 values to topographic slopes obtained from the Space Shuttle Radar Topography Mission 30 arc-second (SRTM30) digital elevation model (DEM) (Allen and Wald, 2007; USGS, 2013). Table 1 presents the topographic slope ranges for active tectonic coefficients with respect to Vs30 range and NEHRP seismic site class from Allen and Wald (2007).

Table 1. NEHRP seismic soil site class, Vs30 range, and topographic slope ranges (Allen and Wald, 2007).

NEHRP Seismic Site Class	Vs30 Range (m/s)	Topographic Slope Range (m/m) Active Tectonic Coefficients
B	>760	>0.138
C	360-760	0.018-0.138
D	180-360	0.0001-0.018
E	<180	<0.0001

Analysis of Vs30 Measurements, Topography, and Geology in Anchorage

To investigate the correlation between measured Vs30 values and topographic slope in Anchorage, and to compare these data sets to geologic units, we incorporated and updated a geologic base map, evaluated three DEMs of different resolutions to understand DEM influences on topographic slope values, and analyzed measured Vs30 values to evaluate correlations with active tectonic coefficients and improve topographic slope correlations.

The geologic map analyzed (Figure 1) is an integrated map derived from four sources: Combellick (1999), Schmoll and Dobrovolny (1972), Updike and Ulery (1986), and Port of Anchorage (CH2M HILL, 2013). Following Combellick (1999), geologic units are defined as: alluvium; artificial fill; bedrock; colluvium; glacial drift; glacioestuarine or eolian deposits; glacioestuarine or lacustrine deposits; glaciofluvial, glaciodeltaic, and alluvial fan deposits; landslide deposits; and tidal deposits. Earthquake faults are obtained from Koehler (2013). The geologic map was developed in a Geographic Information System (GIS) format.

As part of our analysis, three DEMs were analyzed of different resolutions, in order to evaluate the influence of grid sizes on topographic slope values: SRTM30 (2009), GMTED2010 (2014), NED (2013). Grid characteristics for the different DEMs are shown in Table 2.

Table 2. Grid characteristics of DEM data sets.

DEM	**Grid Size (arc-second)**	**Approximate Grid Spacing in East-West Direction (m)**	**Approximate Grid Spacing in North-South Direction (m)**	**Average Topographic Slope for 51 Vs30 Stations (m/m)**
SRTM30	30	391.4	926.0	0.022
GMTED2010	7.5	98.8	231.5	0.026
NED2	2	26.1	61.7	0.034

In our analysis, three different resolution DEMs were evaluated. The average topographic slope for the 51 Vs30 stations for each DEM is shown in Table 2. As the grid size decreases, topographic slope values generally increase, possibly due to larger grid sizes smoothing out local topography. As grid sizes decrease, local topographic features, some with steep topography, can result in greater topographic slope values. As the USGS Global Vs30 Map Server active tectonic coefficients are based on the SRTM30 DEM, we maintained use of the SRTM30 DEM for this study. In future efforts, with additional measured Vs30 values available, topographic slope analysis with higher resolution DEMs can explored further.

To develop a data set of Vs30 measurements in Anchorage, we used three sources to obtain 51 Vs30 measurements across Anchorage (Figure 2a): 22 records from downhole and surface CXW measurements (Dutta et al., 2000); 28 records from the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation (NGA) database for the Nenana Mountain earthquake (Central Alaska Range) of October 23, 2002 (PEER NGA 2005); and one estimated Vs30 value interpreted from an idealized soil profile in an artificial fill area for expansion of the Port of Anchorage (CH2M HILL, 2013). Vs30 values range from 191.3 m/s to 582 m/s, representing Site Class C and D conditions.

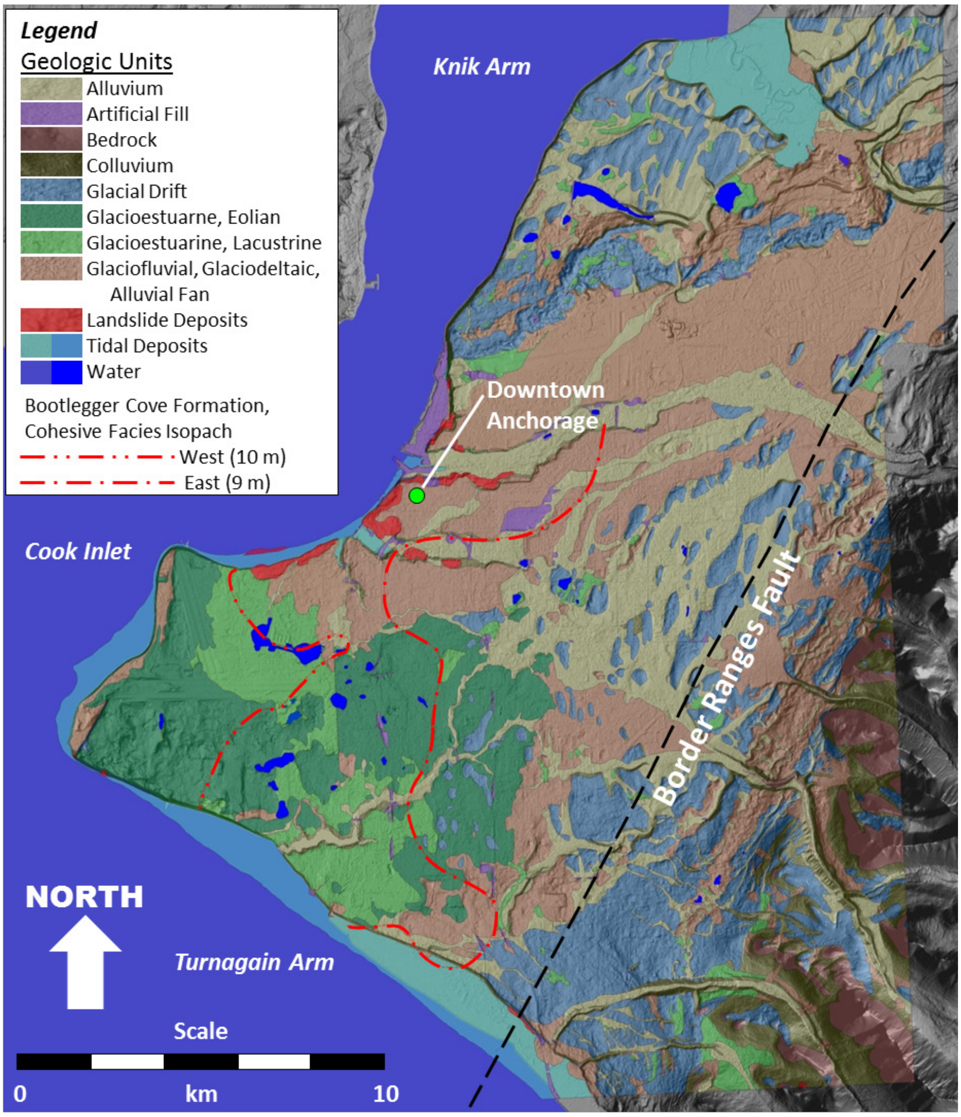

Figure 1. Geologic map of the Anchorage, Alaska area based on Combellick (1999), Schmoll and Dobrovolny (1972), Updike and Ulery (1986), CH2M HILL (2013), and Koehler (2013).

Our data reduction and processing steps began with extracting the topographic slope value based on the SRTM30 DEM and the geologic unit for each of the 51 Vs30 values. The Vs30 stations were then grouped by geologic unit to compare ranges of Vs30 values and topographic slope values. Correlations between Vs30 values and topographic slopes were investigated. Some geologic units were segmented into subunits based on locations with respect to the 9 m or 10 m isopachs for the cohesive facies of the BCF deposits.

For the following geologic units, active tectonic coefficients from Allen and Wald (2007) were used to predict Vs30 values for bedrock, colluvium, landslide deposits, glacioestuarine or lacustrine deposits, with the first three units having no or only one Vs30 station.

For the remaining geologic units, topographic slopes were analyzed to identify the topographic slope value that would represent the Site Class C/D boundary. Custom coefficients were developed for the following geologic units to improve the match between measured Vs30 values and predicted Vs30 values based on topographic slope, with the approximate topographic slope value corresponding to the Site Class C/D boundary presented in [brackets]: alluvium [0.0100 m/m when located west of the 9 m BCF cohesive facies isopach, 0.0030 m/m when located east of the 9 m BCF cohesive facies isopach]; artificial fill [0.0670 m/m]; glacial drift [0.01078 m/m]; glacioestuarine or eolian deposits [0.0413 m/m when located west of the 9 m BCF cohesive facies isopach, 0.0042 m/m when located east of the 9 m BCF cohesive facies isopach]; glaciofluvial, glaciodeltaic, and alluvial fan deposits [0.0209 m/m when located west of the 9 m BCF cohesive facies isopach, 0.00278 m/m when located east of the 9 m BCF cohesive facies isopach]; and tidal deposits [0.0413 m/m].

The results of our analysis are shown in Figure 2. The seismic site class map for Anchorage is shown in Figure 2a, based on active tectonic coefficients from Allen and Wald (2007). Using our composite approach of using active tectonic and custom coefficients for correlations of topographic slope to geologic units, the updated seismic site class map is shown in Figure 2b.

Discussion of Results

By incorporating geologic-based coefficients, we improve the correlation between measured Vs30 values and the predicted Vs30 values based on topographic slope correlations. Using active tectonic coefficients from Allen and Wald (2007), 29 out of 51 Vs30 stations have consistent measured and predicted Vs30 values (Figure 2a). This correlation improves to 48 out of 51 stations using a composite approach of active tectonic and custom coefficients (Figure 2b). Plotting topographic slope (m/m) verses measured Vs30 values (m/s) in Figure 2c, the distribution of Vs30 stations as a function of active tectonic or custom coefficients shows clusters of stations. Note the group of 15 Site Class C Vs30 stations in Figure 2c with topographic slopes less than approximately 0.015 m/m (as shown by blue squares in the Site Class C division). By using custom coefficients, the measured Vs30 values correlate with predicted Vs30 values based on topographic slope correlations, and significantly improve the number of Vs30 stations with agreement between measured and predicted Vs30 values.

The improvements in correlation between measured and predicted Vs30 values are largely due to subdividing geologic units that are deposited across the 9 m (30 ft) isopach of the cohesive facies of the BCF deposits in central Anchorage. Vs30 stations located in areas west of this isopach are generally Site Class D, whereas in areas east of this isopach, Vs30 stations are generally Site Class C. This pattern of seismic site classes for Anchorage follows Dutta et al. (2000). The BCF deposits are geotechnically significant as liquefaction and sensitive-clay failure processes occurred within the deposits during the M_w 9.2 1964 Great Alaska earthquake (Updike and Ulery, 1986), resulting in extensive damage in the Anchorage area.

Our updated seismic site class map of Anchorage addresses one of the main inconsistencies with the USGS Global Vs30 Map Server map of Anchorage, the discrepancy between measured and predicted Vs30 values in central and northeastern Anchorage (labeled “CR” and “NE” respectively in Figure 2). In Figure 2a, predicted Vs30 values range from Site Class C to D, whereas measured Vs30 values represent Site Class C conditions. The topographic slopes are relatively gentle in central and northeastern Anchorage as a result of multiple glaciations. These areas are located on shallow slopes at the base of the Chugach Mountains. In addition, the geologic units are typically glacial or alluvial deposits. Using custom coefficients, the predicted Vs30 values based on topographic slope generally agree with Site Class C classification from measured Vs30 values (Figure 2b), and as discussed above, plot graphically as shown in Figure 2c. The custom coefficients incorporate the

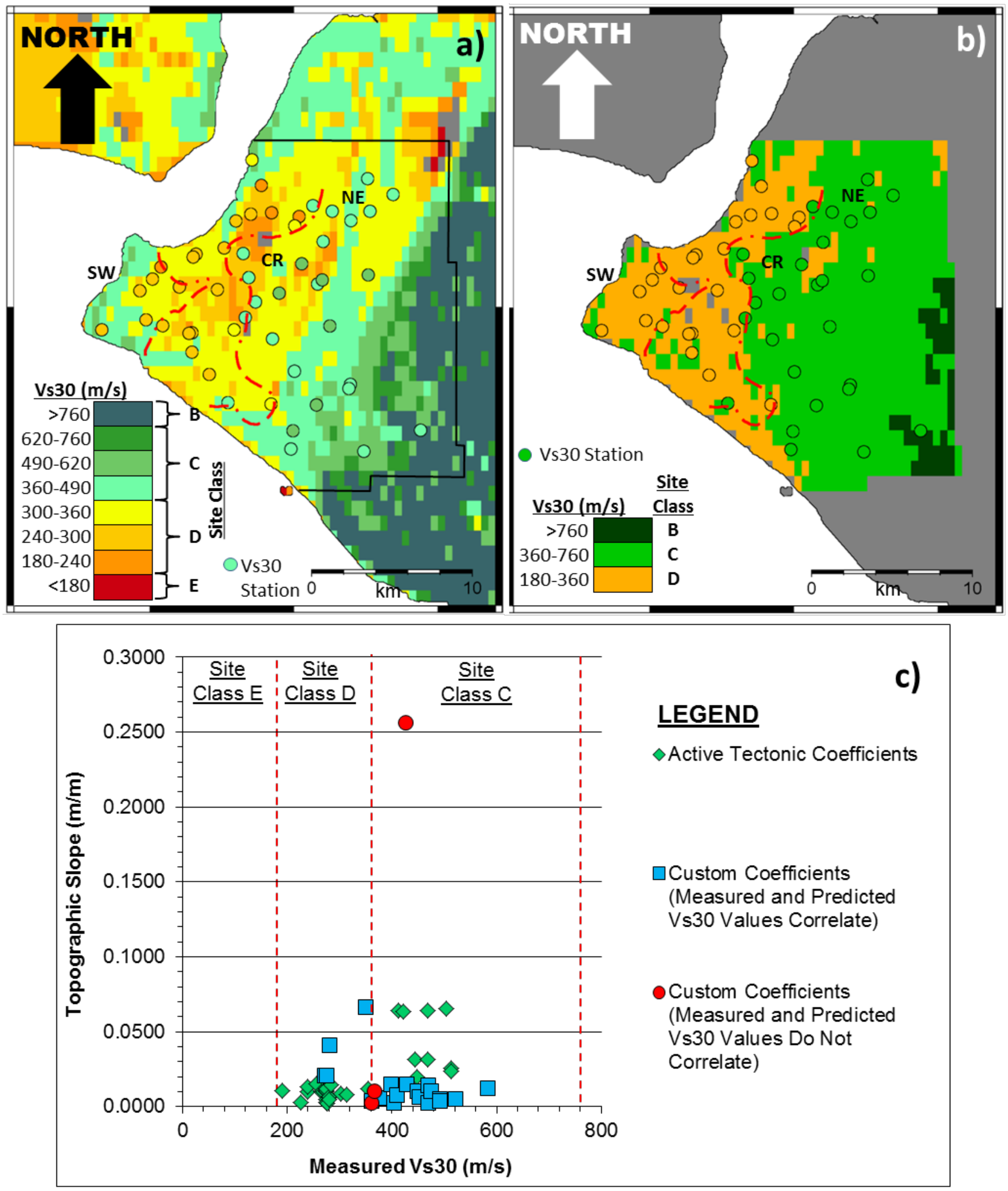

Figure 2. a) NEHRP Site Class map based on active tectonic coefficients in Allen and Wald (2007). Extent of Figure 2b shown by solid black line. b) Updated NEHRP Site Class map from this study. Vs30 stations from Dutta et al. (2000), PEER NGA (2005), and CH2M HILL (2013). Dashed lines represent cohesive facies of Bootlegger Cove Formation as shown in Figure 1. Locations mentioned in text include southwest (SW), central (CR), and northeast (NE) Anchorage. c) SRTM30 topographic slope (m/m) verses measured Vs30 (m/s) values for 51 Vs30 stations, grouped by active tectonic coefficients and two categories of custom coefficients.

glacially-influenced topographic slope characteristics and glacial deposits, conditions that may not be present at sites in California, Taiwan, and Italy, from which the active tectonic coefficients were derived.

In southwest Anchorage (labeled as "SW" in Figure 2), our updated model slightly improves the correlation between measured Vs30 values and predicted values based on topographic slope correlations. Southwest Anchorage is a complex sedimentary environment of glacioestuarine sediments. While Vs30 stations have measured values less than 360 m/s, topographic slopes range from shallow to moderate, with locally steep and hummocky terrain. Figure 2b shows this area as Site Class D, based on Vs30 stations. However, additional Vs30 measurements are needed in southwest Anchorage to better understand Vs30 conditions, and for correlations of Vs30 values to geologic units and topographic slopes.

While our analysis indicates that incorporating custom coefficients improves correlations for predicting Vs30 values based on topographic slope, there are several areas of improvement for future work. Additional measured Vs30 values, either using downhole or surface methods, are needed spatially across Anchorage to increase the number of values in each geologic unit. For example, in southwest Anchorage, additional measured values would be helpful in constraining the seismic site class in this geologically complex area of glacioestuarine deposits. With additional measured Vs30 values, more advanced analysis techniques, such as the kriging-with-a-trend method (Wald et al., 2011), can be explored. Additional measured Vs30 values would also allow analysis of higher resolution DEMs to establish new coefficients for correlations between topographic slopes and seismic site classes. Our composite approach to topographic slope coefficients may be applicable to other areas in Alaska and elsewhere that have glacially-influenced topography, glacioestuarine deposits, and are located in an active tectonic regime.

Conclusions

We have improved the correlation between measured Vs30 values and the predicted Vs30 values based on topographic slope correlations in Anchorage, Alaska, USA, by incorporated geologic data to develop custom coefficients. The USGS Global Vs30 Map Server (USGS, 2015) uses active tectonic coefficients based on Vs30 measurements from California, Taiwan, and Italy and topographic slope data from SRTM30 DEMs (SRTM30, 2009). Using active tectonic coefficients, 29 of 51 Vs30 stations in Anchorage have consistent measured and predicted seismic site classes. This correlation improves to 48 out of 51 stations by using a composite approach of active tectonic and custom coefficients. Our composite approach allows for the influence of topography modified by multiple glaciations, and the glacial deposits of Anchorage, to be considered when estimating Vs30 values using topographic slopes.

Correlations between measured and predicted seismic site classes in central and northeastern Anchorage show the most improvement, with these areas generally representing Site Class C conditions. Our composite approach indicates Site Class D conditions in southwest Anchorage, but further investigation is needed in this geologically complex area of glacioestuarine deposits. Future efforts should focus on obtaining additional measured Vs30 values (both downhole and surface) spatially across Anchorage and within geologic units, and analyzing higher resolution DEMs, to develop new correlation coefficients between topographic slopes and seismic site classes. Our composite approach to topographic slope coefficients may be applicable to other areas in Alaska and elsewhere that have glacially-influenced topography, glacioestuarine deposits, and are located in an active tectonic regime.

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