Maps Showing Seismic Landslide Hazards in Anchorage, Alaska

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CONVERSION TABLE

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)

Abstract

The devastating landslides that accompanied the great 1964 Alaska earthquake showed that seismically triggered landslides are one of the greatest geologic hazards in Anchorage. Maps quantifying seismic landslide hazards are therefore important for planning, zoning, and emergency-response preparation. The accompanying maps portray seismic landslide hazards for the following conditions: (1) deep, translational landslides, which occur only during great subduction-zone earthquakes that have return periods of ≈300–900 yr; (2) shallow landslides for a peak ground acceleration (PGA) of 0.69 g, which has a return period of 2,475 yr, or a 2 percent probability of exceedance in 50 yr; and (3) shallow landslides for a PGA of 0.43 g, which has a return period of 475 yr, or a 10 percent probability of exceedance in 50 yr. Deep, translational landslide hazard zones were delineated based on previous studies of such landslides, with some modifications based on field observations of locations of deep landslides. Shallow-landslide hazards were delineated using a Newmark-type displacement analysis for the two probabilistic ground motions modeled.

Introduction

The great magnitude (M) 9.2 earthquake of 1964 in south-central Alaska caused extensive damage in Anchorage, most of which resulted from the triggering of several large landslides. Much of downtown Anchorage and the nearby Turnagain Heights residential area was destroyed by movement of deep landslide blocks, and extensive reaches of the bluffs rimming the city collapsed. In fact, most of the deaths and economic damage from the 1964 earthquake resulted either directly or indirectly from landslides (Keefer, 1984). One of the most important lessons of the 1964 earthquake is that, of the many geologic hazards that threaten lives and property in Anchorage, earthquake-triggered landslides rank near the top.

In the years following the 1964 earthquake, numerous studies were conducted to determine the causes of the large landslides and to identify areas susceptible to failure in future earthquakes. In 1979, Harding-Lawson Associates, a consulting firm contracted by the Municipality of Anchorage, published a map portraying susceptibility to seismically induced ground failure in Anchorage; this map has formed the basis for planning and regulation with respect to landslides ever since (Harding-Lawson Associates, 1979; Weems and Combellick, 1998). Hazard zones portrayed on the 1979 map were based principally on the locations of major landslides triggered in 1964, and on the correlation of minor ground failures with various geologic units. Significant advancements in understanding and modeling earthquake-triggered landslides and in characterization of seismic shaking hazards in Anchorage have been made since the publication of the 1979 map. These advancements facilitate updating the seismic landslide hazard map of Anchorage.

The accompanying maps (sheets 1 and 2) portray hazards related to seismically triggered landslides. The maps do not specifically address hazards from other types of ground failure, including rainfall-induced landslides, thermokarst, snow avalanches, or liquefaction. Although many of the hazard zones portrayed on the maps also are susceptible to some of these other types of ground failure, the maps are only rigorously applicable to landslides triggered during earthquakes.

The sections that follow (1) define the terminology used in this study, (2) briefly review some of the previous studies relating to earthquake-triggered landsliding in Anchorage, (3) outline the analytical and mapping methodology used and describe the data sources, (4) present the results of the analysis, and (5) discuss the resulting maps and how they should be understood and used.

Terminology

Maps that deal with potentially damaging geologic processes can be portrayed in terms of (1) susceptibility, (2) hazard, or (3) risk. In the case of landslides, susceptibility maps delineate areas that have physical characteristics (such as steep slopes, weak materials, or high ground-water levels) that render them susceptible to landsliding regardless of the presence or frequency of the necessary triggering conditions (such as earthquakes or storms). Hazard maps quantify the likelihood of landsliding in terms of the probability of landsliding given a specific triggering event, or in terms of the temporal probability that a triggering event will occur, or both. Risk maps combine hazard maps with information regarding elements exposed to the effects of the hazard, such as buildings, infrastructure, or populations. Risk maps thus estimate losses in the context of the probability of occurrence of a specific geologic process.

The accompanying maps are hazard maps. They portray hazards from two types of landslides in two different ways. Hazards from deep, translational landslides are portrayed simply as zones in which such landslides could occur owing to the presence of specific geologic conditions. According to the definitions just given, this could be considered a portrayal of susceptibility rather than hazard. However, the text provides the hazard element by (1) describing the earthquake conditions required to trigger such landslides, and (2) estimating the return periods of such earthquakes. Hazards from shallow landslides are portrayed using a range of colors that represent different probabilities of failure for specific levels of earthquake shaking that have specified recurrence intervals.

Throughout the text, the terms *hazard* and *susceptibility* are used variously according to context, but this should not obscure the fact that the maps, along with the information in the text, portray seismic landslide hazard.

Previous Studies

The destructive landslides triggered by the 1964 earthquake were the subject of numerous articles and reports. Hansen (1965) provided perhaps the most succinct overview and description of triggered landslides in the Anchorage area; a later report by Long (1973) addressed triggered landslides throughout Alaska. Some of the larger landslide complexes, the Turnagain Heights landslide in particular, were the subjects of research articles aimed at determining the mechanism of failure (Seed and Wilson, 1967; Updike, Egan, and others, 1988) and characterizing the unusual soil properties making these areas susceptible to the formation of large, sub-horizontal block-type landslides (Shannon and Wilson, Inc., 1964; Mitchell and others, 1973; Updike, 1984; Lade and others, 1988; Updike, Olsen, and others, 1988).

Dobrovolny and Schmoll (1974) published a slope-stability map of Anchorage. The map used five zones to portray relative slope stability; the zones were based on specific combinations of (1) slope angle (divided into six ranges) and (2) geologic materials (divided into three groups). The Harding-Lawson Associates (1979) map—widely used for planning, zoning, and other regulatory purposes—used the 1964 landslide distribution and associated correlation with similar geologic conditions to produce a map that used five zones to portray susceptibility to various types of ground failures. Moriwaki and Idriss (1987) used more rigorous analytical techniques to refine the evaluation of areas that could produce deep, translational block landslides; their results contributed to the production of the present maps, as discussed in the next section.

The distribution and geotechnical properties of the geologic materials in the Anchorage area have been characterized in several studies (Ulery and Updike, 1983; Updike and Ulery, 1986; Combellick, 1999; Combellick and others, 2001). Studies of the engineering geology of the Government Hill area, north of downtown Anchorage, described the properties and three-dimensional geometry of the Bootlegger Cove Formation in that area (Varnes, 1969; Updike, 1986; Updike and Carpenter, 1986). Detailed mapping in the Government Hill studies also revealed the presence of many older landslides similar to those triggered in 1964; some of these older landslides were partially remobilized in 1964, indicating that these landslides can be reactivated in multiple seismic events (Updike and Carpenter, 1986). Opportunities might exist to date these older slides and infer some characteristics of the triggering paleoearthquakes.

The post-earthquake stability of areas in and around the large 1964 landslides has been the subject of several studies. Updike (1983) compiled data from inclinometer surveys conducted between 1965 and 1980 in the areas upslope from the large 1964 landslides; results indicated no significant deformation around the Turnagain Heights and L Street landslides and modest deformation around the Fourth Avenue buttress. Ongoing development in the vicinity of the large landslides in downtown Anchorage required detailed studies analyzing the conditions leading to failure and non-failure of various areas (Woodward-Clyde Consultants, 1982, 1987). Likewise, the stability of the Turnagain Heights area was reevaluated to determine the parameters of possible continuing development on and around the 1964 landslide (Shannon and Wilson, Inc., 1989, 1994).

Mapping Methodology and Data Sources

Most of the landslides triggered in 1964 can be sorted into two broad categories: (1) deep, translational block-type landslides on sub-horizontal shear surfaces, and (2) shallower, more disrupted slides and slumps, on more steeply dipping shear surfaces, along coastal and stream bluffs and other steep slopes. The failure mechanisms of these two types of landslides differ significantly; thus, different methods were used for mapping hazards from these two landslide types.

Deep, Translational Block Landslides

The translational block slides triggered in 1964 destroyed large segments of both downtown Anchorage and the Turnagain Heights residential area. The locations of the 1964 block slides correlate closely with areas where thick (> 30 ft) layers of the fine-grained, sensitive facies of the Bootlegger Cove Formation occur within about 50 ft of sea level (Updike, Egan, and others, 1988; Combellick, 1999). These landslides formed as a result of long-duration (several minutes) shaking that caused cyclic degradation of shear strength within the sensitive facies of the Bootlegger Cove Formation (Updike, Egan, and others, 1988). This mechanism of failure is not adequately modeled using either traditional pseudostatic methods or unmodified displacement-based methods (Newmark, 1965; Makdisi and Seed, 1978).

Moriwaki and Idriss (1987) conducted a study in which they modified Newmark's (1965) method to account for both the reduction in shear strength in the sensitive clays and the longer duration of shaking that occurs in very large earthquakes such as that in 1964. They applied their method to areas in Anchorage that possess the geologic characteristics common to zones of deep landsliding in 1964, including (1) the presence of bluffs allowing the outward movement of soil blocks and (2) soil stratigraphy that includes the weaker, sensitive facies of the Bootlegger Cove Formation near the base of the bluff. Their report included a map of Anchorage showing areas their analysis indicated were susceptible to deep landsliding in future large earthquakes.

No methods of analysis have been developed since the Moriwaki and Idriss (1987) study that would more accurately model the translational block slides, and so the zones they delineated were used to identify areas susceptible to translational block slides on the accompanying maps. Some modifications were made to the zones delineated by Moriwaki and Idriss (1987): (1) the hazard zones along the bluffs of Ship Creek were extended eastward about 3,000 ft to include additional areas showing evidence of past landsliding, and (2) the hazard zone on the south edge of Westchester Lagoon was extended eastward along the bluffs south of Chester Creek, again to include areas of past landsliding. No significant disagreement exists in the published literature regarding the areas susceptible to translational landslides; therefore, using the areas delineated by Moriwaki and Idriss (1987), modified using geologic mapping of landslide deposits (Schmoll and Dobrovolny, 1972; Combellick, 1999), should not be an issue of controversy.

In 1964, the large block slides failed along sub-horizontal basal shear surfaces, which caused landslide blocks to translate outward from the original bluff face. This sliding mechanism created extensional zones of ground cracking and subsidence behind the main scarps of the landslides and compressional or inundation zones downslope of the landslides. Therefore, the mapped landslide-hazard zones are surrounded by "halo" zones that delineate areas of potential extensional or compressional deformation if translational landslides were triggered in the adjacent areas. The width of the halo zones is based on observations from the 1964 earthquake:

- Extensional cracks and minor ground disturbances in the downtown area were documented as far as 600 ft behind the Fourth Avenue landslide and about 100 ft behind the L Street landslide (Hansen, 1965). Therefore, the upslope halo zone in the downtown and Government Hill areas is 600 ft wide.

- The Turnagain Heights landslide complex presented a more complicated situation: two major lobes of the landslide moved somewhat independently of each other and coalesced in the center. The west lobe extended much deeper inland from the bluff face and appeared to have fully failed. Extensional cracks behind the west lobe extended about 500 ft behind the ultimate location of the main scarp. The east lobe appeared not to have fully failed but to have created a large zone of pervasive cracking behind the main scarp, indicating incipient failure. This zone of cracking extended about 2,200 ft behind the east-lobe main scarp (Hansen, 1965). Had the east lobe fully failed as far back from the bluff line as the west lobe, the zone of extensional cracking behind that main scarp would have extended about 1,000 ft farther back. Therefore, the upslope halo zone in the Turnagain Heights area is 1,000 ft wide.

- With the exception of the Turnagain Heights landslide, which moved about 2,000 ft offshore, the translational landslides in 1964 inundated or caused compressional deformation as far as about 500 ft downslope (Hansen, 1965). Therefore, the halo zones are 500 ft wide downslope of landslide-hazard zones.

Shallow, Disrupted Landslides

The 1964 earthquake also triggered many shallower, more disrupted landslides, principally along coastal and stream bluffs. No detailed studies have been undertaken to analyze conditions leading to these failures. Jibson and others (1998, 2000) used data from the 1994 Northridge, Calif., earthquake to develop a Geographic Information System (GIS)-based method to identify and quantify shallow-landslide hazards during earthquakes. This is a physically based method that uses limit-equilibrium analysis combined with a simplified displacement analysis based on Newmark's (1965) method. Seismically triggered shallow-landslide hazards in the Anchorage area were quantified using this method; the GIS model uses 20-ft grid cells to apply Newmark's method across the Anchorage urban area. The details of Newmark's displacement analysis and how it was implemented using Jibson and others' (1998, 2000) method are described in the following sections.

Newmark's Method

Newmark's method models a landslide as a rigid friction block that slides on an inclined plane. The block has a known critical (or yield) acceleration, a_c, which is the threshold base acceleration required to overcome shear resistance and initiate sliding. The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration-time history. Newmark's method is based on a fairly simple model of rigid-body displacement and thus does not necessarily accurately predict measured landslide displacements in the field. Rather, Newmark displacement is a useful index of how a slope is likely to perform during seismic shaking (Jibson and others, 2000; Jibson, 2007).

Newmark (1965) showed that the critical acceleration of a potential landslide block is a simple function of the static factor of safety and the landslide geometry, expressed as

$$a_c = (FS - 1)\, g \sin \alpha \qquad (1)$$

where a_c is the critical acceleration in terms of g, the acceleration of Earth's gravity; FS is the static factor of safety; and α is the thrust angle (the angle from the horizontal that the center of mass of the potential landslide block first moves), which can generally be approximated as the slope angle. Thus, conducting a rigorous Newmark analysis requires knowing the static factor of safety and the slope angle, and selecting an earthquake strong-motion record.

Applying Newmark's method regionally in a raster-based GIS requires using a simplified approach rather than conducting rigorous analysis in each grid cell (Jibson and others, 1998, 2000). Such a simplified approach is implemented using regression equations that estimate Newmark displacement as a function of critical acceleration (the measure of seismic landslide susceptibility) and some measure of earthquake shaking, commonly either peak horizontal ground acceleration (PGA) or Arias (1970) shaking intensity. Several such regression equations have been published; the current analysis uses the following equation (Jibson, 2007):

$$\log D_N = 0.215 + \log\left[\left(1 - \frac{a_c}{a_{max}}\right)^{2.341}\left(\frac{a_c}{a_{max}}\right)^{-1.438}\right] \pm 0.510 \quad (2)$$

where D_N is Newmark displacement in centimeters, a_c is critical acceleration, a_{max} is PGA, and the last term is the standard deviation of the model.

Factor of Safety

As indicated in equation 1, the critical acceleration depends on the static factor of safety (*FS*) and the thrust angle (α). Regional analyses commonly estimate *FS* based on an infinite-slope model (Jibson and others, 1998, 2000); in such a model the thrust angle is the slope angle, which further simplifies the approach. The following infinite-slope limit-equilibrium equation is used:

$$\mathrm{FS} = \frac{c'}{\gamma t \sin\alpha} + \frac{\tan \phi'}{\tan\alpha} - \frac{m\gamma_w \tan\phi'}{\gamma \tan\alpha} \quad (3)$$

where ϕ' is the friction angle, c' is the cohesion, α is the slope angle, γ is the material unit weight, γ_w is the unit weight of water, t is the slope-normal thickness of the failure slab, and m is the proportion of the slab thickness that is saturated (Jibson and others, 1998, 2000). The equation is written so that the first term on the right side accounts for the cohesive component of the strength, the second term accounts for the frictional component, and the third term accounts for the reduction in frictional strength due to pore pressure.

In each 20-ft grid cell, the unit weight (γ), slab thickness (t), and saturation factor (m) were set at constant representative values for simplicity. In the model used for the accompanying maps, a unit weight of 120 lb/ft^3, slab thickness of 50 ft, and saturation factor of 0.8 were used. The specified slab thickness is typical for shallow landslides in the area. The specified saturation and slab thickness yield an average ground-water depth of 10 ft. The parameters in equation 3 that vary spatially from cell to cell include the slope angle (α), cohesion (c'), and friction angle (ϕ').

Slope Angle

Slope angle was derived from a digital elevation model (DEM) based on Light Detection and Ranging (LIDAR) data procured by the Municipality of Anchorage in 2004. The LIDAR data have a spatial resolution of 5 ft and were processed to produce a model that eliminates vegetation and buildings. The DEM was then resampled to fill the 20-ft grid cells in the model. Modeled slope angles in the map area range from 0° to 77°.

Shear Strength

Shear strength is difficult to characterize on a regional basis. Typically, average or representative strengths are assigned to mapped geologic units (Jibson and others, 1998, 2000). Digitized versions of the surficial geologic maps of Schmoll and Dobrovolny (1972) and Yehle and others (1992) were used to portray the spatial distribution of geologic materials in the area. Geologic units from Yehle and others (1992), used only in the southernmost tip of the map area, were grouped into the generalized units used by Schmoll and Dobrovolny (1972).

Strength data for surficial geologic layers were compiled from copies of consulting reports on file at the Alaska Division of Geological and Geophysical Surveys in Fairbanks (Combellick and others, 2001). Strengths were compiled from triaxial-shear, direct-shear, vane-shear, and standard-penetration (SPT) test results of materials within 50 ft of the ground surface, consistent with an analysis of shallow landslides of that depth. For each geologic unit, available strength data were compiled, and average shear strengths were computed. Unit descriptions from the geologic maps (Schmoll and Dobrovolny, 1972; Yehle and others, 1992) as well as previous studies that characterized material strengths (Updike, 1984; Updike and Carpenter, 1986; Updike and Ulery, 1986; Lade and others, 1988) were used to further refine differences in strengths between units.

Table 1 shows the shear strengths assigned to the surficial geologic units in the map area. Strengths of coarser grained, free-draining materials (sands and gravels) were characterized using drained (effective) friction angle and cohesion. Strengths of finer grained, less permeable materials (clays and silts) were characterized as undrained (total) strengths that are input as cohesion values in equation 3; in these cases a friction angle of zero was used (Jibson and Keefer, 1993). The relatively high value of shear strength for the Bootlegger Cove Clay (Schmoll and Dobrovolny, 1972) reflects the strength of the facies exposed at the ground surface rather than the weaker facies at depth that was related to the failure of the deeper landslides in 1964 (table 1). The unit description of the silt (s) unit mapped near the international airport indicates that in that area it is actually fine sand that grades into the sand (sl) unit; therefore, the silt (s) unit near the airport was lumped together with the nearby sand (sl) unit.

Earthquake Shaking

Earthquake shaking was characterized using PGA values having 2 percent (sheet 1) and 10 percent (sheet 2) probabilities of exceedance in 50 yr, corresponding to return periods of 2,475 and 475 yr, respectively. Two types of seismic sources contribute to the probabilistic model from which these PGA values result: deep subduction-zone earthquakes such as that in 1964, and shallow crustal faults such as the Castle Mountain fault, about 40 km north of Anchorage. Each of these seismic sources has different characteristic magnitudes and recurrence intervals, and each is likely to produce ground shaking having different durations and predominant frequencies. These issues are addressed subsequently in the “Discussion.”

The most recent probabilistic seismic hazard model of Alaska is that of Wesson and others (2007, 2008); their studies indicated that in Anchorage a PGA of 0.690 g has a 2 percent probability of exceedance in 50 yr, and a PGA of 0.433 g has a 10 percent probability of exceedance in 50 yr. These values are slightly higher than those shown on previously published seismic hazard maps (Wesson and others, 1999a, b). The reported ground motions are for site conditions at the B/C boundary (National Earthquake Hazards Reduction Program classification system), which corresponds to an average shear-wave velocity of 760 m/s in the top 30 m (Wesson and others, 2007). We did not modify the ground motions for local variations of site conditions in the map area. The spatial variability of estimated PGA across the current map area is insignificant; therefore, a constant PGA value is used for each of the two probability levels. In an actual earthquake, of course, PGA can be expected to vary significantly throughout the map area.

Estimation of Newmark Displacement

In each grid cell, the shear-strength parameters (corresponding to the geologic unit) and the slope angle were input into equation 3 to calculate the static factor of safety (*FS*). *FS* was then input into equation 1 along with the slope angle to

Table 1. Shear strengths of geologic units.

[Letters in parentheses are unit labels from Schmoll and Dobrovolny (1972)]

Geologic unit	Friction angle, ϕ'	Cohesion, c' (lb/ft^2)
Coarse-grained surficial deposits (an)	36°	500
Alluvium in abandoned stream channels and in terraces along modern streams (al).	36°	400
Deposits in alluvial fans, alluvial cones, and emerged deltas (af)	36°	500
Glacial alluvium in irregular-shaped hills (including kames, eskers, and kame terraces) (ga).	32°	800
Sand deposits in broad, low hills, and windblown sand deposits in cliffhead dunes near Point Campbell (sh).	34°	500
Sand deposits in a wide low-lying belt around Connors Lake (sl)	34°	400
Lake and pond deposits (l)	0°	3,000
Silt (s)	0°	1,500
Bootlegger Cove Clay (bc)	0°	2,500
Morainal deposits, generally in long ridges marking the margins of former glaciers (m).	38°	900
Glacial and (or) marine deposits, typically in elongate hills (gm)	38°	1,000
Marine, glacial, and (or) lacustrine deposits (mg)	37°	800
Colluvium derived from bedrock on slopes of the Chugach Mountains (c-br).	38°	800
Colluvium derived from glacial materials along coastal bluffs (c-bl)	0°	800
Landslide deposits (ls)	30°	500
Manmade fill (f)	34°	1,000
Bedrock (b)	40°	4,000

estimate the critical acceleration (a_c). The critical acceleration and the PGA were then input into equation 2 to estimate Newmark displacement; the mean displacement was calculated by ignoring the last term in equation 2. Ranges of Newmark displacement were then assigned to different hazard categories corresponding to a range of colors depicted on the maps, as discussed in the following section.

Results

Deep, Translational Block Landslides

Both maps (sheets 1 and 2) outline identical areas susceptible to deep, translational block landsliding. These areas include locations that produced such landslides in the 1964 earthquake as well as adjacent areas that have similar geologic conditions, as identified through the analysis of Moriwaki and Idriss (1987). Although it is not possible to accurately predict displacements of this type of landslide, these zones should be considered to have the potential to produce displacements ranging from a few feet to several tens of feet. Actual displacements will depend on the duration and frequency content of a triggering earthquake as well as local geologic, topographic, geotechnical, and hydrologic conditions.

The maps also show halo zones around susceptible areas; these halo zones should be considered susceptible to significant deformation if landslides are triggered in the adjacent hazard zone. In upslope halo zones, extensional cracking, subsidence, and other extensional deformation might be expected if landslides occur in the adjacent hazard area. The amount of upslope deformation in 1964 ranged from several inches to a few feet (Hansen, 1965), and similar deformations could be expected if deep, translational landslides are triggered in future earthquakes. The downslope halo zones delineate areas of possible compressional deformation and inundation in the event of a translational landslide from the adjacent bluffs. The amount of downslope deformation will depend on the magnitude of the displacement upslope; in 1964, pressure ridges downslope from translational landslides were tens to hundreds of feet long, tens of feet wide, and several feet high (Hansen, 1965).

Translational block landslides are likely to occur only in very long duration shaking that accompanies great subduction-zone earthquakes. The strongest shaking in the 1964 earthquake lasted 2–3 minutes (min), and the felt shaking lasted 4–7 min (Hansen, 1965; Steinbrugge, 1970; Housner and Jennings, 1973). Eyewitnesses stated that the deep block slides did not initiate until about 2 min of strong shaking had elapsed (Grantz and others, 1964, Shannon and Wilson, Inc., 1964). Such long shaking durations are highly unlikely during shallow crustal earthquakes. Moriwaki and Idriss (1987) also stressed that only very large earthquakes (M>7) contribute to large displacements of deep, translational landslides. Paleoseismic studies from the Girdwood area along Turnagain Arm of Cook Inlet showed evidence of six great earthquakes (similar to the 1964 earthquake) having occurred in the past 3,300 yr, which yields an average recurrence interval of 660 yr for earthquakes likely to generate strong shaking of sufficient duration to trigger deep, translational block slides (Hamilton and Shennan, 2005; Hamilton and others, 2005; Shennan and Hamilton, 2006; Wesson and others, 2008). A subsequent overview of paleoseismic data for the entire south-central Alaska region reported evidence for nine great subduction-zone earthquakes in the past 6,000 yr; recurrence intervals ranged from 333 to 875 yr, with a median of 560 yr (Carver and Plafker, 2008). Analysis of interseismic intervals and plate-convergence rates suggested that a repeat of the 1964 earthquake is unlikely in less than about 360 yr (Carver and Plafker, 2008).

Shallow, Disrupted Landslides

Hazard from shallower landslides is shown on the maps by a range of “stoplight” colors. These landslides are confined to steeper slopes, principally along coastal and stream bluffs and steep slopes bounding some glacial hills. The map colors correspond to ranges of Newmark displacement estimated for the ground-shaking conditions modeled, which have 50-yr exceedance probabilities of 2 percent (sheet 1) and 10 percent (sheet 2). The predicted Newmark displacements do not necessarily correspond directly to measurable slope movements in the field, and these displacements should not be used as a basis for structural design. Rather, the modeled displacements relate to different likelihoods of landsliding in future earthquakes. Rigorously quantifying these likelihoods for Anchorage would require a detailed investigation of a well-recorded earthquake large enough to trigger many well-documented landslides; unfortunately, no such study has yet been possible in Anchorage. The best documented study of this type was conducted following the 1994 Northridge, Calif., earthquake; Jibson and others (2000) compared the mapped distribution of earthquake-triggered landslides (Harp and Jibson, 1995, 1996) to regionally estimated Newmark displacements to estimate landslide probability as a function of predicted Newmark displacement:

$$P(f) = 0.335\left[1 - \exp\left(-0.048 D_N^{1.565}\right)\right] \qquad (4)$$

where $P(f)$ is the estimated probability of a landslide and D_N is the Newmark displacement in centimeters. Although geologic and seismic conditions in Anchorage differ significantly from those in southern California, equation 4 can be used to grossly estimate failure probabilities for the ground-shaking levels modeled. The map colors, Newmark-displacement ranges, and failure-probability estimates from equation 4 are as follows:

- Green: 0–1 cm of Newmark displacement. Low (0–2 percent) likelihood of landslide occurrence.

- Yellow: 1–5 cm of Newmark displacement. Moderate (2–15 percent) likelihood of landslide occurrence.
- Orange: 5–15 cm of Newmark displacement. High (15–32 percent) likelihood of landslide occurrence.
- Red: >15 cm of Newmark displacement. Very high (>32 percent) likelihood of landslide occurrence.

Numerous shallow landslides were triggered during the 1964 earthquake; as previously discussed, such earthquakes have an estimated return period of roughly 300–900 yr. Shallow landslides also can be triggered by shallow crustal earthquakes, which would produce strong shaking of shorter duration but perhaps higher frequency and peak acceleration. The most significant shallow-crustal earthquake source is the Castle Mountain fault, about 40 km north of Anchorage (Wesson and others, 2008). Results of paleoseismic investigations indicate that the average return period of four paleoearthquakes on the Castle Mountain fault is about 700 yr, but the last paleoearthquake was dated at 670±60 yr B.P.; thus, an earthquake (having an estimated moment magnitude of 6.9–7.3) on this fault in the foreseeable future could be likely (Haeussler and others, 2002; Willis and others, 2007).

Areas upslope from shallow landslides are subject to extensional cracking similar to that previously described for deep, translational landslides, and areas downslope are subject to compressional deformation and inundation. The complex distribution of shallow-landslide hazard precludes our showing halo zones where such deformation could occur, but a reasonable rule of thumb is that such deformation could be expected in a zone around the landslide whose width is about three times the local slope height.

Discussion

The seismic hazard in Anchorage, Alaska, derives from two very different types of earthquake sources: subduction-zone earthquakes and shallow-crustal earthquakes. The 1964 earthquake was a great subduction-zone earthquake; in Anchorage, it produced ground shaking having an extraordinarily long duration (3–7 min) but only moderate amplitude, estimated at 0.15–0.20 g (Shannon and Wilson, Inc., 1964; Newmark, 1965; Steinbrugge, 1970; Housner and Jennings, 1973). The 1964 shaking at Anchorage also lacked significant high-frequency energy and was predominantly concentrated at frequencies less than 2 Hz (Steinbrugge, 1970). This prolonged long-period shaking was responsible for the triggering of the deep, translational block landslides, as confirmed by the eyewitness accounts that these landslides started moving only after about 2 min of shaking had elapsed. Thus, it appears that such failures are most likely to occur in great subduction-zone earthquakes that generate long-duration, long-period shaking. The 1964 earthquake also, however, triggered many shallower landslides from steeper slopes along coastal and stream bluffs and along the margins of steep glacial hills.

Shallow-crustal earthquakes are likely to generate shorter durations of shaking having higher frequencies and higher amplitudes (Wesson and others, 2007). Such earthquakes are unlikely to trigger deep, translational landslides but are likely to trigger shallower landslides on more steeply dipping shear surfaces. Thus, shallow landslides should be expected to occur with greater frequency than deep, translational landslides because shallow landslides can be triggered by both types of earthquakes that affect the Anchorage area, whereas the deep block slides tend to occur only in great subduction-zone earthquakes.

Great subduction-zone earthquakes and shallow-crustal earthquakes have similar average recurrence intervals in the Anchorage area, about 600–700 yr (Wesson and others, 2007). Geologic studies have indicated, however, that the last shallow-crustal earthquake on the most significant source (the Castle Mountain fault) occurred nearly 700 yr B.P., suggesting the possibility of a significant earthquake on this fault in the foreseeable future (Haeussler and others, 2002; Willis and others, 2007). The more recent occurrence of the 1964 earthquake suggests that another great subduction-zone earthquake might be less likely in the near future; Carver and Plafker (2008), in fact, stated that a repeat of the 1964 earthquake is unlikely in less than 360 yr.

A regional-scale stability analysis such as that used to construct the accompanying maps is necessarily generalized and includes many simplifying assumptions. Moriwaki and Idriss (1987) discussed the assumptions and limitations of their modeling approach for deep, translational landslides. Shallow landslides were modeled using Newmark's method, which is highly idealized and contains many simplifying assumptions. Modeling for the accompanying maps assumed (1) slope-parallel failure of a slab having a uniform thickness of 50 ft (an infinite slope), (2) uniform shear strength and unit weight within each geologic unit, (3) a uniform groundwater depth of 10 ft, and (4) a rigid-plastic failure mechanism. These assumptions (or other, similar ones) are necessary to efficiently execute a GIS-based regional analysis, but they clearly do not reflect the complexity that actually exists. Also, Newmark analysis models only coseismic displacement; this initial displacement can weaken slope materials, reduce the static factor of safety, and lead to continuing post-seismic displacement, which is not modeled in this study. The modeled displacements, therefore, relate to the likelihood of continuing post-seismic failure and are not intended to predict actual landslide displacements during an earthquake. The objective of the analysis, therefore, is not to perfectly recreate actual conditions, which would be impossible, but rather to reasonably portray spatial variations in landslide susceptibility and hazard. Thus, the relative hazard between map pixels is of more concern than prediction of actual landslide displacements (Jibson and others, 1998, 2000; Jibson, 2007).

The use of mean Newmark-displacement estimates from equation 2 might seem unconservative. The standard deviation of this logarithmic equation is 0.510, which means that a range of ± one standard deviation spans about an order of magnitude.

As just stated, however, regional maps such as those accompanying this report are primarily concerned with the relative spatial hazard, and comparison of mean displacement values is a valid means of quantifying this relative hazard. Also, the failure-probability model from the Northridge earthquake study (equation 4) was based on mean displacement estimates; therefore, the probability model is calibrated to mean values (Jibson and others, 1998, 2000).

The estimated probabilities of failure for shallow landslides are based on empirical studies of the landslide distribution from a southern California earthquake, and their applicability to the Anchorage area is uncertain. These estimates are presented simply to provide a sense of the probability of landsliding in different shaking conditions. And these landslide-probability estimates are independent of the seismic-shaking probabilities. For example, yellow areas are estimated to have a 2–15 percent probability of landslide occurrence for the specified level of ground shaking. For sheet 1, which models a PGA of 0.69 g (having a 2-percent probability of exceedance in 50 yr), this means that yellow areas have an estimated probability of failure of 2–15 percent during shaking having a PGA of 0.69 g. This does not specify the exceedance probability of landslide occurrence in a 50-yr period; estimating temporally specific landslide exceedance probabilities would require a more detailed conditional probability analysis that is beyond the scope of the present study.

Portrayal of halo zones around areas susceptible to deep, translational landslides is based on observations from the 1964 earthquake but remains somewhat subjective. The hazard zones for deep landslides shown on sheets 1 and 2 generally include the areas behind the 1964 failures that experienced extensional cracking in that earthquake. The halo zones of possible future extensional cracking extend an additional 600–1,000 ft behind these zones. This should be amply conservative without being physically unrealistic. The zones of possible compression and inundation in front of the potential landslide areas are 500 ft wide, a reasonable value based on the maximum distance of disturbance in the 1964 earthquake. The Turnagain Heights landslide is an exception to this because it moved many hundreds of feet onto the tidal flats; however, the hazard zones do not extend past the coastline because the maps ignore areas offshore.

Hazard zones delineated on the maps show areas that are more or less likely to experience landslides in future earthquakes. Nothing that is portrayed on the maps should be construed to mean that a landslide is predicted to occur in any given location in any specific earthquake. Neither does anything shown on the maps preclude the possibility of a landslide occurring at any location. Zones showing higher seismic landslide hazard, either from deep, translational landslides or shallow landslides, might or might not be suitable for various uses. The zones depicted on the map simply identify areas of differing landslide hazard; determining appropriate uses within such zones, or what studies or mitigation activities might be required, is a public-policy responsibility that is beyond the scope of this study.

Summary and Conclusion

Hazards from earthquake-triggered landslides in Anchorage are portrayed on two maps for shaking conditions related to 50-yr exceedance probabilities of 2 percent (sheet 1) and 10 percent (sheet 2). Two types of landslide hazards are portrayed: (1) deep, translational landslides on sub-horizontal shear surfaces and (2) shallow landslides from steeper slopes. Deep, translational landslides are most likely to be triggered in subduction-zone earthquakes (such as in 1964), which are more likely to produce long-duration, long-period shaking; such earthquakes have return periods in this region of about 300–900 yr, and the most recent occurred in 1964. Shallow landslides also can be triggered in subduction-zone earthquakes but are expected to be most predominant in shallow-crustal earthquakes, which tend to produce shorter duration, higher frequency shaking. The closest active fault expected to produce shallow-crustal earthquakes is the Castle Mountain fault, which has produced earthquakes having estimated return periods of about 700 yr; the last major earthquake on the Castle Mountain fault occurred about 700 yr B.P.

Areas susceptible to deep, translational landsliding are delineated on the maps (sheets 1 and 2) based primarily on the analysis published by Moriwaki and Idriss (1987), which used a modified displacement analysis to identify areas that could produce landslides similar to the deep landslides of 1964 that devastated parts of both downtown Anchorage and Turnagain Heights. Halo zones around these areas delineate zones of possible extensional or compressional deformation around the margins of potential landslides. Shallow-landslide hazards are depicted in a range of colors that relate to different amounts of modeled coseismic displacement, which, in turn, relate to different probabilities of failure. Displacement leading to the failure of shallow landslides was modeled using the approach detailed by Jibson and others (1998, 2000), which estimates displacement using Newmark's (1965) method as applied in a regional GIS model.

The intended use of the accompanying maps is for regional planning, zoning, and other public-policy purposes. The maps are not intended as a substitute for a detailed site study prior to any proposed land use. The maps neither predict nor preclude landslide occurrence in any given location; rather, they portray areas that are more or less likely to produce landslides in the shaking conditions modeled.

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References Cited

Arias, A., 1970, A measure of earthquake intensity, *in* Hansen, R.J., ed., Seismic design for nuclear power plants: Cambridge, Mass., Massachusetts Institute of Technology Press, p. 438–483.

Carver, G., and Plafker, G., 2008, Paleoseismicity and neotectonics of the Aleutian subduction zone—An overview, *in* Freymueller, J.T., Haeussler, P.J., Wesson, R.L., and Ekström, G., eds., Active tectonics and seismic potential of Alaska: Washington, D.C., American Geophysical Union, Geophysical Monograph 179, p. 43–63.

Combellick, R.A., 1999, Simplified geologic map and cross sections of central and east Anchorage, Alaska: Alaska Division of Geological and Geophysical Surveys Preliminary Interpretive Report 1999-1, scale 1:25,000.

Combellick, R.A., Mayer, J.L., Sink-Blair, K.D., and Weems, S.M., 2001, Geotechnical borehole and well-log database for Anchorage, Alaska: Alaska Division of Geological and Geophysical Surveys Miscellaneous Publication 40, 8 p., 1 pl.

Dobrovolny, E., and Schmoll, H.R., 1974, Slope-stability map of Anchorage and vicinity, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I–787–E, scale 1:24,000.

Grantz, A., Plafker, G., and Kachadoorian, R., 1964, Alaska's Good Friday earthquake, March 27, 1964, a preliminary geologic evaluation: U.S. Geological Survey Circular 491, 35 p.

Haeussler, P.J., Best, T.C., and Waythomas, C.F., 2002, Paleoseismology at high latitudes—Seismic disturbance of upper Quaternary deposits along the Castle Mountain fault near Houston, Alaska: Geological Society of America Bulletin, v. 114, p. 1296–1310.

Hamilton, S., and Shennan, I., 2005, Late Holocene relative sea-level changes and the earthquake deformation cycle around upper Cook Inlet, Alaska: Quaternary Science Reviews, v. 24, p. 1479.

Hamilton, S., Shennan, I., Combellick, R., Mulholland, J., and Noble, C., 2005, Evidence for two great earthquakes at Anchorage, Alaska, and implications for multiple great earthquakes through the Holocene: Quaternary Science Reviews, v. 24, p. 2050.

Hansen, W.R., 1965, Effects of the earthquake of March 27, 1964 at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542–A, 68 p., 2 pl.

Harding-Lawson Associates, 1979, Geotechnical hazards assessment study, Municipality of Anchorage: Harding-Lawson Associates job no. 5502,009.08.

Harp, E.L., and Jibson, R.W., 1995, Inventory of landslides triggered by the 1994 Northridge, California, earthquake: U.S. Geological Survey Open-File Report 95–213, 17 p.

Harp, E.L., and Jibson, R.W., 1996, Landslides triggered by the 1994 Northridge, California, earthquake: Bulletin of the Seismological Society of America, v. 86(B), p. S319–S332.

Housner, G.W., and Jennings, P.C., 1973, Reconstituted earthquake ground motion at Anchorage, *in* The Great Alaska Earthquake of 1964, Engineering: Washington, D.C., National Academy of Sciences, p. 43–48.

Jibson, R.W., 2007, Regression models for estimating coseismic landslide displacement: Engineering Geology, v. 91, p. 209–218.

Jibson, R.W., Harp, E.L., and Michael, J.A., 1998, A method for producing digital probabilistic seismic landslide hazard maps—An example from southern California: U.S. Geological Survey Open-File Report 98–113, 17 p., 2 pl.

Jibson, R.W., Harp, E.L., and Michael, J.A., 2000, A method for producing digital probabilistic seismic landslide hazard maps: Engineering Geology, v. 58, p. 271–289.

Jibson, R.W., and Keefer, D.K., 1993, Analysis of the seismic origin of landslides—Examples from the New Madrid seismic zone: Geological Society of America Bulletin, v. 105, p. 521–536.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406–421.

Lade, P.V., Updike, R.G., and Cole, D.A., 1988, Cyclic triaxial tests of the Bootlegger Cove Formation, Anchorage, Alaska: U.S. Geological Survey Bulletin 1825, 51 p.

Long, E.L., 1973, Earth slides and related phenomena, *in* The Great Alaska Earthquake of 1964, Engineering: Washington, D.C., National Academy of Sciences, p. 644–773.

Makdisi, F.I., and Seed, H.B., 1978, Simplified procedure for estimating dam and embankment earthquake-induced deformations: American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, v. 104, p. 849–867.

Mitchell, J.K., Houston, W.N., and Yamane, G., 1973, Sensitivity and geotechnical properties of Bootlegger Cove Clay, *in* The Great Alaska Earthquake of 1964, Engineering: Washington, D.C., National Academy of Sciences, p. 157–178.

Moriwaki, Y., and Idriss, I.M., 1987, Evaluation of ground failure susceptibility, opportunity, and potential in the urban area of Anchorage, Alaska: Woodward-Clyde Consultants, Final technical report to U.S. Geological Survey, contract no. 14-08-0001-22031.

Newmark, N.M., 1965, Effects of earthquakes on dams and embankments: Geotechnique, v. 15, p. 139–160.

Schmoll, H.R., and Dobrovolny, E., 1972, Generalized geologic map of Anchorage and vicinity, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I–787–A, scale 1:24,000.

Seed, H.B., and Wilson, S.D., 1967, The Turnagain Heights landslide, Anchorage, Alaska: American Society of Civil Engineers, Journal of the Soil Mechanics and Foundation Division, v. 93, p. 325–353.

Shannon and Wilson, Inc., 1964, Report on Anchorage area soil studies, Alaska, to the U.S. Army Engineer District, Anchorage, Alaska: Seattle, Wash., Shannon and Wilson, Inc., 109 p.

Shannon and Wilson, Inc., 1989, Geotechnical report—Turnagain landslide reevaluation, Anchorage, Alaska: Anchorage, Alaska, Shannon and Wilson, Inc., 57 p., 27 figs.

Shannon and Wilson, Inc., 1994, Geotechnical report—Northwest Turnagain landslide stability evaluation, Anchorage, Alaska: Anchorage, Alaska, Shannon and Wilson, Inc., 49 p., 16 figs.

Shennan, I., and Hamilton, S., 2006, Coseismic and pre-seismic subsidence associated with great earthquakes in Alaska: Quaternary Science Reviews, v. 25, p. 1–8.

Steinbrugge, K.V., 1970, Earthquake damage and structural performance in the United States, *in* Wiegel, R.L., ed., Earthquake engineering: Englewood Cliffs, N.J., Prentice-Hall, Inc., p. 167–226.

Ulery, C.A., and Updike, R.G., 1983, Subsurface structure of the cohesive facies of the Bootlegger Cove Formation, southwest Anchorage, Alaska: Alaska Division of Geological and Geophysical Surveys Professional Report 84, 5 p., 3 pl.

Updike, R.G., 1983, Inclinometer strain analyses of Anchorage landslides, 1965–80: Alaska Division of Geological and Geophysical Surveys Professional Report 80, 141 p.

Updike, R.G., 1984, The Turnagain Heights landslide—An assessment using the electric-cone-penetration test: Alaska Division of Geological and Geophysical Surveys Report of Investigations 84-13, 48 p.

Updike, R.G., 1986, Engineering geologic maps of the Government Hill area, Anchorage, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I–1610, scale 1:4,800.

Updike, R.G., and Carpenter, B.A., 1986, Engineering geology of the Government Hill area, Anchorage, Alaska: U.S. Geological Survey Bulletin 1588, 32 p.

Updike, R.G., Egan, J.A., Moriwaki, Y., Idriss, I.M., and Moses, T.L., 1988, A model for earthquake-induced translator landslides in Quaternary sediments: Geological Society of America Bulletin, v. 100, p. 783–792.

Updike, R.G., Olsen, H.W., Schmoll, H.R., Stokoe, K.H., III, and Kharaka, Y.F., 1988, Geologic and geotechnical conditions adjacent to the Turnagain Heights landslide, Anchorage, Alaska: U.S. Geological Survey Bulletin 1817, 40 p.

Updike, R.G., and Ulery, C.A., 1986, A geotechnical cross section of downtown Anchorage—An assessment using the electric-cone-penetration test: Alaska Division of Geological and Geophysical Surveys Report of Investigations 86-3, 41 p.

Varnes, D.J., 1969, Stability of the west slope of Government Hill port area of Anchorage, Alaska: U.S. Geological Survey Bulletin 1258–D, 61 p.

Weems, S.M., and Combellick, R.A., 1998, Seismically induced ground-failure susceptibility, Anchorage, Alaska: Alaska Division of Geological and Geophysical Surveys Miscellaneous Publication 32, scale 1:25,000.

Wesson, R.L., Boyd, O.S., Mueller, C.S., Bufe, C.G., Frankel, A.D., and Petersen, M.D., 2007, Revision of time-independent probabilistic seismic hazard maps for Alaska: U.S. Geological Survey Open-File Report 2007-1043, 41 p.

Wesson, R.L., Boyd, O.S., Mueller, C.S., and Frankel, A.D., 2008, Challenges in making a seismic hazard map for Alaska and the Aleutians, *in* Freymueller, J.T., Haeussler, P.J., Wesson, R.L., and Ekström, G., eds., Active tectonics and seismic potential of Alaska: Washington, D.C., American Geophysical Union, Geophysical Monograph 179, p. 385–397.

Wesson, R.L., Frankel, A.D., Mueller, C.S., and Harmsen, S., 1999a, Probabilistic seismic hazard maps of Alaska: U.S. Geological Survey Open-File Report 99–36, 43 p.

Wesson, R.L., Frankel, A.D., Mueller, C.S., and Harmsen, S., 1999b, Probabilistic seismic hazard maps of Alaska: U.S. Geological Survey Miscellaneous Investigations Map I–2679, 2 sheets, scale 1:7,500,000.

Willis, J.B., Haeussler, P.J., Bruhn, R.L., and Willis, G.C., 2007, Holocene slip rate for the western segment of the Castle Mountain fault, Alaska: Bulletin of the Seismological Society of America, v. 97, p. 1019–1024.

Woodward-Clyde Consultants, 1982, Anchorage office complex geotechnical investigation, Anchorage, Alaska, for Alaska Department of Transportation and Public Facilities: San Francisco, Calif., Woodward-Clyde Consultants, 3 vol.

Woodward-Clyde Consultants, 1987, Geotechnical investigation, Anchorage courthouse addition, Anchorage, Alaska: Anchorage, Alaska, Woodward-Clyde Consultants, 2 vol.

Yehle, L.A., Schmoll, H.R., and Dobrovolny, E., 1992, Surficial geologic map of the Anchorage A-8 SE quadrangle, Alaska: U.S. Geological Survey Open-File Report 92–350, scale 1:25,000.

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