Chapter 5:

GEOLOGIC HAZARD AREAS

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5.1 INTRODUCTION

Geological hazard areas include seismic hazard areas, erosion hazard areas, landslide hazard areas (including steep slopes), volcanic hazard areas and coal mine hazard areas. This chapter reviews the best available science associated with each geological hazard area. Overall conclusions and a list of scientific references are also provided.

5.2 REVIEW OF LITERATURE

Geology as a scientific discipline is second only to physics in the enormity of subdivisions and sub-disciplines that have been identified. A vast body of geological knowledge and literature has been developed beginning in 18th century England. Information for this analysis was selected, to the extent possible, on its' relevance to the geology and hazards found in King County. It should be understood that there remains a huge body of work that was not included in this analysis of BAS because: (1) it was not relevant to King County and the proposed Critical Areas Ordinance; (2) it was developed in another country and possibly in another language; or (3) because it was simply not available. It is also quite possible that applicable and relevant work was overlooked simply because of the immense volume of available information. An exhaustive review of all relevant and applicable geological information is far beyond the scope of this project and literally would take many years to complete.

5.2.1 Seismic Hazard Areas

King County lies in the Puget Sound Lowland, an area that is subject to daily seismic activity—though most is not detectable—and is historically subject to very large earthquakes. The most recent large earthquake was the February 28, 2001 Nisqually Earthquake. The Nisqually Earthquake created a great deal of damage but minimal loss of life. The Puget Sound Lowland lies in a larger area known as the Cascadia subduction zone. This zone comprises a series of tectonic plates that are moving with respect to one another. The Cascadia subduction zone is extremely complex in the western Washington region, involving local deformation of the subducting Juan de Fuca plate and complicated block structures within the crust. It has been postulated that the Cascadia subduction zone could be the source for a large thrust earthquake, possibly as large as Magnitude 9.0 (Stanley, et al., 1999). For purposes of this paper and for regional consistency, magnitude as used refers to Richter Scale rather than Modified Mercalli Scale. Large intraplate earthquakes from within the subducting Juan de Fuca plate beneath the Puget Sound region have accounted for most of the energy release in this century and future such large earthquakes are expected. Added to these possible hazards is clear evidence for strong crustal deformation events in the Puget Sound region near faults such as the Seattle fault, which passes through the southern Seattle metropolitan area. The Puget Sound area has been subjected to three fairly strong seismic events in the last century that are related to crustal deformation – Olympia, 1949, Seattle/Tacoma in 1965, and the Nisqually event in February, 2001. (Nelson, pers. Comm., 2003)

Seismic Hazard Areas are those areas within King County that are subject to severe risk of earthquake damage as a result of ground shaking/ground motion, surface faulting, subsidence and uplift, seismically induced landsliding and settlement, soil liquefaction, and tsunami. Severe risk of damage is loosely defined as the potential for damage that is structural rather than cosmetic in nature. Earthquakes and their causative mechanisms have been extensively studied around the world. Building codes that require earthquake resistant design and construction have been implemented in King County. However, the ability to predict locale and strength of earthquake events has not been achieved. Best Available Science at this time comprises efforts to reduce the impact of seismic events by requiring analysis of site periodicity and designing structures accordingly and by implementing building codes that require earthquake resistant construction.

Seismic Hazard Area Functions

Ground Shaking

Most earthquake damage is caused by ground shaking. The magnitude of an earthquake, distance to the earthquake focus, type of faulting, depth, and type of material are important factors in determining the amount of ground shaking that might be produced at a particular site. Where there is an extensive history of earthquake activity, these parameters can often be estimated; however, in many areas of Washington they are still poorly defined.

The magnitude of an earthquake influences ground shaking in several ways. Large earthquakes usually produce ground motions with large amplitudes and long durations. In addition, large earthquakes produce strong shaking over much larger areas than do smaller earthquakes. The 1949 magnitude 7.1 Olympia earthquake produced ground shaking lasting 30 seconds and was felt over an area of 550,000 square kilometers. In contrast, the 1964 magnitude 8.3 Alaska earthquake produced ground shaking for about 300 seconds and was felt over an area more than five times larger. The recent earthquake near Fairbanks, Alaska registered at magnitude 7.8 and was felt as far away as Louisiana.

The distance of a site from an earthquake affects the amplitude of ground shaking. In general, the amplitude of ground motion decreases with increasing distance from the focus of an earthquake. The considerable depth of the 1949 earthquake put even the closest sites, those directly over the earthquake focus, at least 50 to 65 kilometers from the source of the ground shaking, a factor that contributed to the lower intensity experienced near the epicenter

The frequency content of the shaking also changes with distance. Close to the epicenter, both high (rapid) and low (slow)-frequency motions are present. Farther away, low-frequency motions are dominant, a natural consequence of wave attenuation in rock. The frequency of ground motion is an important factor in determining the severity of damage to structures and which structures are affected).

Analyses of earthquake damage in Washington and elsewhere suggest that the severity of shaking depends on several factors besides the distance and magnitude of an earthquake. These factors include the kinds and thicknesses of geologic materials exposed at the surface and the subsurface geologic structure (Rasmussen and others, 1974; Newmark and Hall, 1982). Natural and artificial unconsolidated materials, such as sediments in river deltas and materials used as landfill, commonly amplify ground motions relative to motion in consolidated sediments or bedrock. Such areas, in general, have had higher levels of ground shaking in past Washington earthquakes. The thickness of unconsolidated material may also affect the amount of ground shaking produced. Certain frequencies of ground shaking may generate disproportionately large motions because of wave resonance in sedimentary basins. Just as the pitch of sound from an organ pipe depends on the length of the pipe and the density and compressibility of air, the various frequencies at which a sedimentary basin will resonate when shaken by seismic waves depend on the thickness, density, and stiffness of the sedimentary layers.

Subsurface structures, such as sedimentary layers that vary in thickness or degree of consolidation, may increase ground motion by focusing seismic wave energy at a particular site. The curved surfaces of buried bedrock topography may also focus waves. Langston and Lee (1983) suggested focusing as a mechanism to explain why the severity of damage observed in West Seattle during the 1965 Seattle-Tacoma earthquake seemed unrelated to surface geology in many places. The depth to bedrock changes from very near the surface in the West Seattle area to significantly deeper just a short distance away in downtown Seattle. Latest information suggests that this differential bedrock depth reflects the recently identified east-west trending Seattle Fault.

Studies of the 1949 and 1965 Seattle earthquakes have provided most of the data used to estimate future ground shaking in Washington (Langston, 1981; Langston and Lee, 1983; Ihnen and Hadley, 1986), though data from the Nisqually Earthquake of 2001 is now being analyzed and incorporated into these estimates. The depths of these two earthquakes (54 and 63 kilometers below Puget Sound in the subducting Juan de Fuca plate), their magnitudes, and the reports of damage at sites in Washington having a variety of geologic materials have led to estimates of future ground shaking for similar events. For example, the intensity of ground shaking in the epicentral area of a future large Puget Sound earthquake, if that earthquake occurred at a depth comparable to those of the 1949 and 1965 earthquakes, would be lower than the intensity that would be expected for a shallow earthquake of the same magnitude. The reduced intensity would be related to the effect of depth to the focus and the possible attenuation of ground shaking in some areas identified during past earthquakes caused by the nature of the geologic materials between the focus and the site.

Surface Faulting

The consequences of major fault rupture at the surface can be extreme. Buildings may be torn apart, gas lines severed, and roads made impassible. Damage by faults is more localized than the widespread damage caused by ground shaking. Nevertheless, the identification of active surface faults is an important part of estimating future earthquake losses.

Many maps of surface faults in Washington have been published (for example, McLucas, 1980, and Gower and others, 1985). Most of the faults on these maps are presently inactive including the recently identified Seattle Fault. Geologic evidence indicating active fault movement within the last 10,000 years has been reported for only a few small faults in Washington. The best-documented active surface faults in the state are located near Lake Cushman in western Washington. More recent mapping has become available through the Seattle Area Geologic Mapping Project and the 1998 USGS Seismic Hazards Investigation of Puget Sound (SHIPS.)

Much of this data is still being analyzed, though preliminary information on local surface and subsurface faulting is very promising.

Seismicity, another indication of active faulting, has only rarely been associated with recognized surface faults in Washington. However, seismic activity has been used to define faults that do not currently rupture the surface, such as the St. Helens Seismic Zone.

Subsidence and Uplift

Sudden elevation changes during earthquakes can have severe long-term economic impact on coastal development. Some parts of Prince William Sound were uplifted by several meters during the 1964 Alaska earthquake. Conversely, parts of the Kenai Peninsula and Kodiak Island subsided as much as 2 meters during that earthquake (Plafker, 1969). Some raised harbors on Prince William Sound could no longer be used by boats. In other areas streets and buildings subsided so much that they were flooded at high tide. Major subsidence or uplift of large regions often occurs as a result of great subduction-style, thrust earthquakes. Such elevation changes have been reported after earthquakes in New Zealand, Japan, Chile, and southeast Alaska (Plafker, 1969). Submerged marshlands in several estuaries along Washington's coast suggest that similar episodes of sudden subsidence have also occurred in the Pacific Northwest (Atwater, 1987). Preliminary dating indicates that many of the subsidence events at different sites in Washington occurred at the same time. For this reason, Atwater (1987) and Hull (1987) have attributed these subsidence events to the occurrence of large subduction earthquakes.

Secondary Causes of Earthquake Damage

While earthquakes may produce ground shaking, surface faulting, and vertical movements that cause direct damage to buildings and land, damage and personal injury may also be caused by several additional factors.

Earthquakes may trigger ground failures such as landslides, differential compaction of soil, and liquefaction of water-saturated deposits like landfills, sandy soils, and flood plain deposits. Such ground failures may cause more damage to structures than the shaking itself. Earthquakes may also cause destructive water waves such as tsunamis and seiches. Non-structural building components like ceiling panels, windows, and furniture can cause severe injury if shaking causes them to shift or break. Broken or impaired lifelines (gas, water, or electric lines and transportation and communication networks) can produce hazardous situations and distress to a community. A reservoir can be a hazard, should shaking cause the dam to fail.

Ground Failure

Major property damage, death, and injury have resulted from ground failures triggered by earthquakes in many parts of the world. More than $200 million in property losses and a substantial number of deaths in the 1964 Alaska earthquake were caused by earthquake-induced ground failures. A 1970 earthquake off the coast of Peru triggered an ice and rock avalanche in the Andes that killed more than 18,000 people when it buried the city of Yungay. Earthquakes in the Puget Sound region have induced ground failures responsible for substantial damage to buildings, bridges, highways, railroads, water distribution systems, and marine facilities. Ground failures induced by the 1949 Olympia earthquake occurred at scattered sites over an area of 30,000 square kilometers, and ground failures induced by the 1965 Seattle-Tacoma earthquake occurred over 20,000 square kilometers (Keefer, 1983).

In reviewing records of the 1949 and 1965 Puget Sound earthquakes, Keefer (1983) noted that geologic environments in the Puget Sound region having high susceptibilities to ground failure include areas of poorly compacted artificial fill, postglacial stream, lake, or beach sediments, river deltas, and areas having slopes steeper than 35 degrees. The types of ground failures associated with past Washington earthquakes and expected to accompany future earthquakes include landslides, soil liquefaction, and differential compaction. Such failures commonly occur in combination; for example, liquefaction may cause a landslide or accompany compaction.

Landslides

Washington has many sites susceptible to landslides, including steep bluffs of eroded glacial deposits in the Puget Sound region and rugged terrain in the Cascade Mountains. Fourteen earthquakes, from 1872 to 1980, are known to have triggered landslides in Washington.

Dozens of ancient landslides have been identified in the bluffs along Puget Sound, indicating their susceptibility to ground failure. The landslides may also be susceptible to further failure if the headwall or toe areas are steepened by erosion or excavation (Keefer, 1983). Ground shaking produced by recent large Puget Sound earthquakes generated 20 landslides, some as far as 180 kilometers from the epicenter of the 1949 Olympia earthquake, and 21 landslides as far as 100 kilometers from the epicenter of the 1965 Seattle-Tacoma earthquake (Keefer, 1983).

Washington’s five stratovolcanos (Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams) offer many sites for rock and ice avalanches, rock falls, and debris flows on their steep slopes. The massive 2.8-cubic-kilometer rockslide/debris avalanche on the north side of Mount St. Helens during the catastrophic eruption of May 18, 1980 was triggered by a moderate (magnitude 5) earthquake that followed 8 weeks of intense earthquake activity beneath the volcano.

The impact of landslides on stream drainages and reservoirs also can pose significant danger to populations and developments downstream (Beget, 1983). Water ponded behind landslide-debris dams can cause severe floods when these natural dams are suddenly breached. Such outburst floods are most likely near volcanic centers active within the past 2 million years (Evans, 1986, p. 128). The Toutle River was blocked by a debris flow triggered by an earthquake during the 1980 eruption of Mount St. Helens. The debris flow dam raised the level of Spirit Lake by 60 meters. The U.S. Army Corps of Engineers constructed a tunnel through bedrock in order to lower the lake level and thereby reduce the danger of flooding from a sudden release of water and lessen the risk to persons living downstream.

Landslides or debris flows into reservoirs or lakes may displace enough water to cause severe downstream flooding (Crandell, 1973; Crandell and Mullineaux, 1976, 1978.) Communities and developments located downstream of reservoirs and lakes along drainages from Mounts Baker, Adams, and St. Helens must all be considered at some risk from earthquake-induced landslides. During the February 2001 Nisqually Earthquake, a large landslide blocked the Cedar River temporarily about 5 miles upstream of Renton, Washington. The slide mass was quickly breached with equipment to avoid catastrophic flooding downstream after a slide mass failure.

Future earthquakes in Washington are expected to generate more landslides and greater losses than reported for past earthquakes. Earthquakes with shallow focal depths or a longer duration of shaking will trigger more landslides than reported for the 1949 or 1965 earthquakes. In addition, a review of weather data indicates that precipitation during the rainy seasons preceding both the 1949 and 1965 events was near or below average throughout most of the Puget Sound area and may have been responsible for there having been fewer landslides than would have been expected in unusually wet weather. The same may be said for the Nisqually event. Continued population growth and development in areas of steep slopes further increase the possibility of substantial property damage and loss of life from landslides in Washington.

Liquefaction

Liquefaction occurs when very loose to loose, saturated sand or silt is shaken violently enough to increase pore water pressure between individual grains effectively reducing shear strength of the soil mass. Such rearrangement has a tendency to compact the deposit. If the intragranular water cannot escape fast enough to permit compaction, the load of overlying material and structures may be temporarily transferred from the grains of sand or silt to the water, and the saturated deposit becomes “quicksand”. The liquefied material may then cause lateral-spread landslides or loss of bearing strength under foundations or roadways, depending on the depth and thickness of the liquefied zone and local topography.

If the liquefied layer is near the surface it may break through overlying “dry” deposits, forming geysers or curtains of muddy water that may leave sand blows as evidence. Retaining walls may tilt or break from the fluid pressure of the liquefied zone. Shallow liquefaction zones can also cause severe damage to structures whose foundation support has suddenly become fluid. Liquefaction caused basement floors to break and be pushed upward in Seattle and Puyallup during the 1949 earthquake. Other basements cracked open and completely filled with water and silt. Lighter structures may float in liquefied soil. Buried fuel tanks, if sufficiently empty, may pop to the surface, breaking connecting pipes in the process. Pilings without loads may also float upwards. Heavy structures may tilt in response to the loss of bearing strength by underlying soil. During the 1964 Niigata, Japan, earthquake, four-story apartment buildings tilted on liquefied soils, one as much as 60 degrees.

If a thick section of unconsolidated deposits liquefies near the surface, it will tend to flow into and fill topographic depressions. For example, a stream channel may be narrowed as saturated and liquefied deposits on both sides of the stream flow into it. Compression resulting from such flow buckled or skewed spans and damaged abutments on more than 250 bridges during the 1964 Alaska earthquake. This form of liquefaction failure was so widespread that McCulloch and Bonilla (1970) coined the term “land spreading” to distinguish it from the more widely recognized lateral-spread landslides that tend to occur on slopes due to failure along a particular subsurface layer. Land spreading may have been responsible for the disabling of three drawbridges across the Duwamish Waterway in Seattle during the 1949 earthquake. The distance between the piers in the main span of the Spokane Street bridge was shortened by 6 to 8 inches, causing the bridge to jam in the closed position until the concrete and steel edges could be trimmed off sufficiently to permit reopening.

Earthquakes may trigger a phenomenon in certain clays that produces effects similar to liquefaction in water-saturated sand. When vibrated, these “quick” or “sensitive” clays undergo a drastic loss of shear strength. For example, a relatively thin sensitive zone in the Bootlegger Cove Clay, located about 25 meters below the surface, was blamed for the spectacular lateral-spread landslides that destroyed parts of Anchorage in 1964 (Hansen, 1966). The sensitive layer responsible for these landslides had been deposited in a marine environment, in contrast to the underlying and overlying fresh-water clays. Later leaching of the salt from the marine clay by fresh ground water may have increased the clay's sensitivity to vibration-induced loss of shear strength by shaking (Hansen, 1966).

Differential Compaction

Structural damage commonly occurs to buildings underlain by foundation materials that have different physical properties. Materials such as tide flat sediments, glacial outwash sands, dredging spoils, sawdust, and building rubble will settle by different amounts when shaken. These materials are prevalent under parts of the downtown and waterfront areas of Seattle, Tacoma, Olympia, and Aberdeen-Hoquiam. Dozens of water and/or gas line breaks occurred in these cities as a result of differential compaction during the 1949 earthquake, and virtually every building along the Seattle waterfront was damaged by settling during the 1965 earthquake. Many waterfront areas around Puget Sound are underlain by material susceptible to differential compaction and are thus vulnerable to damage in future earthquakes.

Water Waves

Tsunamis

Tsunamis are long-wavelength, long-period sea waves generated by an abrupt movement of large volumes of water. In the open ocean, the distance between wave crests can be greater than 100 kilometers, and the wave periods can vary from 5 minutes to I hour. Such tsunamis travel 600 to 800 kilometers per hour, depending on water depth. Large subduction earthquakes causing vertical displacement of the sea floor and having magnitudes greater than 7.5 are the most common cause of destructive tsunamis. Large waves produced by an earthquake or a submarine landslide can overrun nearby coastal areas in a matter of minutes. Tsunamis can also travel thousands of kilometers across open ocean and wreak destruction on far shores hours after the earthquake that generated them.

Tsunami wave heights at sea are usually less than one meter, and the waves are not frequently noticed by people in ships. As tsunami waves approach the shallow water of the coast, their amplitude increases and wave heights increase -- sometimes exceeding 20 meters. Historically, tsunamis originating in the northern Pacific and in South America have caused more damage on the West Coast of the United States than tsunamis originating in Japan and the South Pacific. The 1964 tsunami generated by the Alaska earthquake destroyed a small bridge across the Copalis River (Grays Harbor County) by hurling log debris against supporting piles. The tsunami was also detected on the Columbia River as far as 160 kilometers from the ocean. Besides causing property damage, the 1964 tsunami killed 103 people in Alaska, 4 in Oregon, and 12 in California. Newspaper accounts tell of narrow escapes along the Washington coast, but there were no fatalities. Recent work relating to analysis of coastal paleosediments in the form of sand deposits overlying shoreline and marine vegetation suggests that a large tsunami hit the Washington coast about 1,000 yrs BP. (Atwater and Moore, 1992)

The regional variations in damage caused by a tsunami from a particular source region can be estimated for future earthquakes. The basis for such estimates, particularly the influence of near-shore bottom topography and irregular coastline on the height of an arriving tsunami wave, is described by Wiegel (1970) and Wilson and Torum (1972). Past tsunamis have caused only minor damage in Washington but the potential for damage in the future is enormous.

In addition to a tsunami generated by a distant earthquake, a magnitude 8 or greater subduction earthquake between the Juan de Fuca and North America plates might create a large local tsunami on the coast of Washington. Atwater (1987) and Reinhart and Bourgeois (1987) have found evidence they believe indicates that a tsunami from a nearby great subduction earthquake did affect the coast of Washington about 300 years ago. In general, local tsunamis are much more destructive than tsunamis generated from a distant source. In addition, they may occur within minutes of the earthquake or landslide that produces them, allowing little time for evacuation. Estimates of the effect of a local tsunami in Washington are speculative because we have no written record of a large, shallow earthquake near the coast. However, the sudden submergence of coastal areas that may accompany great earthquakes might increase the amount of land in Washington susceptible to tsunami damage.

Seiches

A seiche is a standing wave in an enclosed or partly enclosed body of water and is analogous to the sloshing of water that occurs when bowl of water is moved back and forth. Earthquakes may induce seiches in lakes, bays, and rivers. More commonly, seiches are caused by wind-driven currents or tides. Seiches generated by the 1949 Queen Charlotte Islands earthquake were reported on Lake Union and Lake Washington in Seattle and on Commencement Bay in Tacoma. So far, no significant damage has been reported from seismic seiches in Washington caused by local or distant earthquakes.

Seismic Hazard Area Protection

The study of earthquakes and seismicity is a mature science, but the ability to predict location and magnitude of seismic events has not been achieved and is not imminent. Given that, the scientific literature reviewed above dictates that the impact of seismicity be mitigated to the extent possible via regulatory requirements, including preparation of site-specific seismic studies for essential facilities and lifelines and adherence to building codes that require earthquake resistant design and construction.

5.2.2 Erosion Hazard Areas

Excessive erosion can be very damaging to water quality in adjacent and downstream water bodies—waters that often support salmonid fish and other species. Silt and sand-sized particles are particularly damaging to the stream environment if excessive deposition occurs. The silt and sand can bury and asphyxiate fish eggs that are deposited in gravel, can fill the spaces between gravel that support aquatic insects, and can even kill fish by damaging or clogging the gill structure. Erosion also leads to deposition of materials downstream that can create a whole host of negative impacts. Including channel in-fill and avulsion, channel blockage and blockage to fish passage, burying of habitat(s), and loss of local flood storage.

Erosion Hazard Areas were originally mapped by King County as part of the original Sensitive Areas Ordinance in the late 1980s. Erosion Hazard Areas were mapped based on the grain size of the various soil units found in King County. In general, the finer-grained the soil, the more erosive it is. Geologists that did the original mapping also took slope, or gradient, into account as they assessed the likelihood of excessive erosion—the steeper the slope, the more likely was excessive erosion to occur because of higher runoff energy. As with all geologically hazardous areas, there are numerous variables at work including grain-size, soil cohesion, slope gradient, rainfall frequency and intensity, surface composition and permeability, and type of cover (e.g., pavement or forest). These elements, when combined, dictate the overall susceptibility of a slope to erosion. (KC SA Map Folio, 1990)

Erosion hazard is a measure of the susceptibility of an area of land to prevailing agents of erosion (Houghton and Charman 1986). It is determined by climate, topography, soil erodibility, and land use. Each specific land use has its own erosion hazard. An assessment of erosion hazard for non-concentrated flows, concentrated flows and wind erosion is given for permanent pasture, cultivation and urban development. In this study, it is assumed erosion hazard on land under cultivation and permanent pasture is long-term while erosion hazard in urban areas is often confined to the construction phase (from the time of initial disturbance until a good ground cover and appropriate stormwater drainage controls are established). Five categories are used to assess erosion hazard - slight, moderate, high, very high, and extreme. These assessments have been based on field observations of existing erosion, terrain factors and the erodibility of the soil materials in the soil landscape.

Slight. Indicates no appreciable erosion damage is likely to occur during and after the development or continuation of a particular land use under consideration. Soil conservation management should include simple practices such as rapid establishment of ground cover as soon as possible.

Moderate. Implies significant erosion may occur during development of a particular land use. Provided appropriate soil conservation measures are adopted during development, both short-term and long-term erosion problems may be avoided.

High. Implies significant erosion may occur. Intensive soil conservation measures are required to control erosion that will occur during development or continuation of a particular land use. Short-term measures are required in the initial stages of development. Long-term erosion control would involve intensive measures being implemented.

Very High. Implies that significant erosion will occur both during and after development of a particular land use is established, even with intensive soil conservation measures. Planning will need to carefully consider the balance between long-term erosion damage and the maintenance and repair needed to ensure the viability of the land use.

Extreme. Implies soil erosion will occur to such an extent that erosion control is impractical. These areas are best retained as green timber and not used. Where urban development proceeds in spite of this recommendation, detailed engineering, geotechnical and other studies will be necessary.

Erosion Hazard Area Functions

In general, rainfall or accidental surface-water discharges begin the erosion cycle. Individual raindrops impacting a disturbed or denuded surface cause soil particles of sand and silt size to break away from the surface and move downslope. As water accumulates on the surface, it tends to concentrate in small channels that develop as the soil particles are moved or "mobilized." As water accumulates in the small channels, it gains volume and energy and is able to mobilize ever-larger particles. In this way, erosion features develop on a surface—they start as very small channels, or rills, and tend to grow in size to large gullies and canyons over time. Material that is caught up in this process is carried downslope until the gradient flattens out and the energy of the water is reduced. When the energy drops below a certain threshold, the particles, or bedload, drop out of the water. This deposition of bedload generally occurs either on land in floodplains or within waterbodies like lakes or Puget Sound. Very fine particles of certain clay minerals, once mobilized, can take days or even years to drop out of suspension in the water.

One of the more obvious factors affecting erosion potential is the degree of development in the basin or subbasin area. Urban developments such as parking lots, roads, SFRs, and other buildings result in the replacement of permeable natural surfaces like forest floors with impermeable surfaces. This has two effects on stormwater runoff. First, the volume of runoff tends to increase significantly. Second, the peak rate of runoff also increases. Both effects result in a significant increase in the erosion potential within the basin or subbasin. (NSW-CMM, 1990)

Climatic stresses also increase erosion potential in any given area. These stresses include simple rainfall, especially very intense storm events that drop a large volume of water over a short period of time. They also include "rain-on-snow" events wherein warm rain falls on already melting snow. This is especially true in areas with significant gradient. The warm rainfall and moderating temperatures combine with melting snow to create torrents of concentrated runoff. This occurs in both urban and rural environments and can have dramatic impact on local erosion rates over short periods of time. (Terzhagi & Peck, 1948)

Erosion Hazard Area Protection

It should be understood that some erosion is natural and is in fact very important to the overall function and health of a stream system. The difficulty is in determining what is the natural background level of sediment input and what exceeds it. Natural erosion and landsliding processes provide the sand, gravel, cobbles, and boulders that streams need to remain productive with respect to fish and other aquatic organisms.

Erosion Hazard Areas should be protected by promoting sound development practices including the use of Best Management Practices (BMPs.) By requiring that BMPs be employed that limit erosion and sedimentation during construction, the amount of excess sediment that reaches stream systems can be limited. A Temporary Erosion and Sedimentation Control (TESC) plan should be prepared for all development activities requiring a permit. Appropriate BMPs and a construction sequence should be included in the TESC plan. The plan should be reviewed and approved by King County Department of Development and Environmental Services during the permitting process. BMPs that are commonly employed include covering bare ground with straw and/or plastic sheeting, using silt fences, and by planting denuded areas as soon as possible after development.

5.2.3 Landslide Hazard Areas

Landslide Hazard Areas and Steep Slope Hazard Areas, two Geologic Hazard Areas in the proposed King County Code, are combined for the best available science review below. The landscape characteristics that define these two types of hazards are identical and described in detail below.

Landslide Hazard Areas have long been recognized in the Puget Sound Basin and have been studied in depth by the academic community, government scientists, and the regional consulting engineering community. This regional information is in addition to a large body of knowledge about landslides that has been developed worldwide. The mechanics of landsliding processes are well understood, though the site-specific elements of each event, occurring as they do in natural materials and natural settings, are highly variable. It is safe to say that gaps in current knowledge of the technical aspects of landsliding and slope failure are relatively minor and are related to that inherent variability rather than to ignorance of more fundamental elements of these processes. It should also be noted that because of the variability associated with landslide hazards, evaluation of these areas is subject to some level of uncertainty. The uncertainty is generated by limited subsurface information and subtle changes in soil properties, structures, and groundwater elevations that can have significant impact on stability models.

Landslide Hazard Areas are areas of the landscape that are at high risk of future failure (prc – DM9, Dr. David Montgomery) or that presently exhibit downslope movement of soil and/or rocks and that are separated from the underlying stationary part of the slope by a definite plane of separation. That plane of separation may be very thin or very thick and may be composed of multiple failure zones depending on local conditions including soil type, slope gradient and groundwater regime. Sliding includes slow, long-term, and plastic deformation of slopes that occurs within a system of sliding planes.

Many of King County's major valleys and shoreline bluffs are underlain by steeply sloping glacial deposits that are highly susceptible to landslides. These unstable slopes can be very hazardous to people and structures. The identification of areas that are susceptible to landsliding is necessary to provide guidance when designing and constructing structures or clearing and grading. In 1990, King County published the King County Sensitive Areas Map Folio. The folio includes information relating to landsliding in the Puget Sound area. Information contained in the folio is a compendium of data collected over many years by a variety of sources. A great deal of local information was collected and mapped by University of Washington and United States Geological Survey personnel.

The surficial geology of the Puget Lowland consists mainly of Pleistocene glacial, alluvial, and marine sediments; little bedrock is exposed. Major Quaternary stratigraphic units exposed in coastal bluffs overlooking Puget Sound include nonglacial sand, silt, and clay which are overlain by a sequence of glacial deposits, primarily the Vashon Drift (Mullineaux and others, 1965). The basal member of the Vashon Drift is a widespread deposit of dense glacial clay and silt, called the Lawton Clay Member (Tubbs, 1974a). A deposit of sand, known as the Esperance Sand Member, overlies the Lawton Clay Member. For convenience we will refer to these units as the Lawton Clay and the Esperance Sand. The basal contact of the sand is transitional over a few tens of meters, where layers of sand and clay are interbedded. Within this transition zone, individual strata are laterally discontinuous. The Esperance Sand becomes pebbly near the top and grades into the Vashon Drift advance outwash. The Vashon Till, which is generally compact and hard, overlies the advance outwash or the Esperance Sand. The majority of landslides that have been extensively studied occurred in these glacial sediments, including outwash, till, Esperance Sand, and Lawton Clay. Landslides also occur in postglacial colluvial deposits derived from the glacial sediments and in fill placed by humans.

Landslides have been a significant problem in King County for many years, and several landslides occur every year during the rainy season (generally from November through April, Thorsen, 1989). Storms have triggered significant numbers of landslides in 1972, 1986, 1990, 1996, and 1997 (Tubbs, 1974a, b; Laprade, 1986; Miller, 1991; Gerstel, 1996; Harp and others, 1976). Tubbs reported on 1972 storm-induced landslides in the City of Seattle and noted that many of the landslides occurred in or near the transitional zone between the Esperance Sand and the underlying Lawton Clay. Thorsen (1989) attributed most landslides in the Puget Lowland to excess ground water, while Gerstel (1996) concluded that both seepage of perched ground water and infiltration of surface water contributes to instability of thin colluvium and fill overlying glacial materials.

Efforts to reduce landslide-related losses have been ongoing for at least 20 years. Relative-slope-stability maps at several scales were developed in the 1970s for many of the urbanized areas surrounding Puget Sound (Miller, 1973; Artim, 1976; Smith, 1976; Laprade, 1989). Despite these efforts, losses continue to mount because; (1) economic growth continues to exert pressure to develop in or near landslide-prone areas; (2) increased erosion and consequent downcutting caused by urban runoff has locally reduced slope stability (Booth, 1989); and (3) new or previously unidentified landslides damage structures that were built in unstable areas before regulations existed.

Landslide Hazard Area Functions

Sliding phenomena involve such a wide variety of processes and contributing factors that classification becomes a very complex problem. Many classification systems have been proposed over the years, but for purposes of simplicity, the following types of landslides have been identified for discussion (Laprade, 1998). These landslide types are as follows: (1) Rapid Shallow; (2) Block Fall; and (3) Deep-Seated. In very general terms, a landslide is movement downslope of a mass of soil, rock, or both and (nearly always) water. The downslope movement may be very swift or may be very slow depending on the type of material involved, groundwater regime and condition, slope gradient, and a host of other variables. The mass of material that is mobilized may be shallow or surficial in nature, rapidly moving and very small to very large in scale – (Type 1), or it may extend very deep underground (deep-seated,) slow moving, and huge in size (Type 3) or it may be a combination of these. Oftentimes, landslides are a “nested” series of failure planes that back-rotate against one another as the failure occurs resulting in a series of failure blocks or “benches” on the surface of the slide. In addition, very steeply sloping areas like bluffs above local rivers and Puget Sound may fail as large falling blocks of material (Type 2).

Debris Flows comprise a fourth type of slope failure and are oftentimes caused by or sourced by (Type 1) shallow landslides. These flows can move with great rapidity and are often responsible for blocked roads and slight to severe structural damage.

As described above, landslides in King County occur in sloping areas that are underlain by interbedded sediments that vary in grain size. For instance, a typical landslide along the Puget Sound bluffs will occur in the Esperance Sand Member that is deposited over the relatively impermeable Lawton Clay Member. Water from precipitation percolates down through the more permeable sands and silty sands until it hits the silt/silty clay layer. The water then flows laterally along the upper surface of the impermeable layer until it reaches the slope face or “daylights.” Oftentimes the water cannot move as fast laterally as it is being deposited by precipitation from above and the water builds up in the sand layer. As the water builds up, pore water pressure increases between the individual soil particles, and the soil mass as a whole begins to lose shear strength. At some point, the loss of shear strength allows particles that were formerly “locked” together to start sliding past one another under the influence of gravity.

Depending on a variety of factors including the gradient or “dip” of the soil layers, the amount of water and rate of accumulation and the type of material involved, the rate of movement may be very slow (creep) or very fast. In either case, the soil mass can and does cause catastrophic damage to structures that lie above it or that lie in its path. Landslides that move relatively swiftly may strike structures before they can be evacuated, and injuries or fatalities can and do occur. Landslides can also be triggered when there is a loss of lateral support at the bottom, or toe, of a slope due to the action of water, either in a stream or river or because of wave action in bluff settings. As the toe is eaten away, support for the overlying soil mass deteriorates and eventually gravity causes the slope to collapse. This often occurs as a block fall type of slope failure and is very rapid once initiated and for that reason can be extremely hazardous.

Removal of vegetation either through development or urban forest practices can have a dramatic affect on the stability of slopes. Denudation results in rapid runoff and saturation of surficial soils that consistently lead to failures. Vegetation and its organic duff layer on the earth’s surface reduce the energy of rain splash and greatly reduce erosion. The duff layer effectively stores water from rainfall and snowmelt over the short term and slows down infiltration into the underlying soil mantle. Vegetation removes water from the soil matrix through its roots and stores it in the body of the plant. Water that is taken up into the plant is eventually released back into the atmosphere through the process of evapotranspiration. These processes enhance stability of slopes by reducing the volume of water in the underlying soil mantle. Undisturbed stands of mature trees can have a dramatic effect on the infiltration of water into the soil. For instance, an individual mature Loblolly Pine tree (a California species which has been extensively studied for this purpose) can remove upwards of 100 gallons of water from the soil mantle over a 24 hour period via evapotranspiration. It is believed that large conifers found in the Northwest approach that water uptake.

The effect of the vegetative root mass on slope stability has been studied for some time, by a number of different investigators, particularly by Donald Gray and Tuncer Edil at the University of Wisconsin at Madison. Depending on species, plant density, and slope geometry, the tensile strength that is imparted to the soil matrix by the root mass can be enormous. Removal or death of the plants and rotting of the root mass rapidly reduces this tensile strength and can destabilize an otherwise stable or marginally stable slope. (Gray and Meghan, 1981)

Large woody debris (LWD) is a term that describes large pieces of wood that have been naturally deposited in aquatic areas like streams, wetlands, and marine beaches through a process called recruitment. Recruitment occurs via deadfall, storms, and landslides. LWD is very important to the natural function and health of aquatic areas. It provides nutrients to the aquatic area, provides shelter from predators to fish and amphibians, provides some shade, and serves to stabilize stream channels and beach environments.

Large amounts of LWD are deposited as unstable forested slopes fail. A large "slug" of LWD input, which occurs during a landslide in a forested area, is retained in the aquatic area, particularly in stream systems, at a very high rate due to bulking of the LWD in the stream channel (Hauser, pers. Comm. 1996). Protection and regulation of landslide hazard areas promotes natural deposition of LWD by landsliding processes.

Landslide Hazard Area Protections

Literature indicates that buffers should be established around the perimeter of mapped landslide hazard areas. (Gerstel, Brunengo, Lingley Jr., Logan, Shipman, Walsh, *Washington Geology*, vol. 25, no. 1, March 1997). More specifically, buffers should be established from the tops and toes of 40 percent slopes. Alderwood and Kitsap Series soil types make up approximately 55 percent of the land area of King County Data specific to these King County soil types indicates that slopes of less than about 30 percent are relatively stable – the "slippage potential is moderate." Slopes greater than about 30 percent are significantly less stable and their "slippage potential is severe" (USDA Soil Survey for King County Area, Washington, pp. 7-11). Development that is proposed within those buffers or within the slide area itself should meet scientifically based rigorous design and construction standards. Because of the extreme variability that is exhibited by areas that are subject to landsliding, site-specific studies may be required in order to design, construct, and safely occupy a structure that is to be built in or adjacent to one. The hazard area and proposed development should be evaluated by a geotechnical engineer or engineering geologist, including subsurface exploration in the area, soil sampling and testing, and development of a detailed construction sequencing and monitoring plan.

5.2.4 Volcanic Hazard Areas

Volcanic Hazards comprise a variety of phenomena that occur in zones around an active volcano. In the Pacific Northwest, the presence of a series of subduction zones and stratovolcanos presents a unique and very dangerous hazard to local populations and infrastructure. Volcanoes of this type, like Mount St. Helens and Mount Rainier, erupt in a very violent fashion and deposit enormous amounts of material onto the landscape. These deposits occur in a number of different ways, all of which pose hazards to humans and the environment. As with Seismic Hazard Areas, which are only hazardous during and immediately after an earthquake, these areas generally only pose hazards during and immediately after eruptions of the local volcano. Because eruptions occur very infrequently, it all too easy to minimize the dangers associated with a volcano like Mount Rainier.

Tilling and Lipman (1993) estimate that worldwide, 500 million people will be at risk from volcanic hazards by the year 2004. In the past 500 years, over 200,000 people have lost their lives due to volcanic eruptions (Tilling, 1980). An average of 845 people died each year between 1900 and 1986 from volcanic hazards. The number of deaths for these years is far greater than the number of deaths for previous centuries (Tilling, 1991). The reason behind this increase is not due to increased volcanism, but rather to an increase in the amount of people populating the flanks of active volcanoes and valley areas near those volcanoes (Tilling, 1991 and Hall, 1991). As population in King County increases, encroachment into areas that may be subject to volcanic hazards increases. Regulatory restraints may help save lives during the next eruption on Mount Rainier.

In recent years, with the eruptions of Mount St. Helens and Mount Pinatubo, many advances have been made in the study of volcanoes particularly in eruption prediction. Difficulties arise because though there may be similarities between volcanoes, every volcano behaves differently and has its own set of hazards. That is why it's important for geologists, volcanologists, and geophysicists to study and monitor volcanoes

Mapped volcanic deposits and satellites are utilized to evaluate volcanic features, ash clouds, and gas emissions and produce hazard maps. Seismic activity, ground deformation, geomagnetism, gravimetrics, volcanic gases, flow rates, sediment transport, water level of area streams and lakes, and geoelectrical and geothermal changes are monitored in particular. Hazard maps indicate the types of hazards that can be expected in a given area during the next eruption. Dating of these volcanic deposits helps determine how often an eruption may occur and the probability of an eruption each year. Monitoring of a volcano over long periods of time will indicate changes in the volcano before it erupts. These changes can help in predicting when an eruption may occur. (See http://www.geo.mtu.edu/volcanoes/hazards/primer/images/volc-images/mshdome.gif for photo.)

Volcanic Hazard Area Functions

In King County, widespread damage is most likely to come from an eruption on Mount Rainier. It is less likely, though possible, that damage from ashfall and acidic aerosols could result from an eruption on one of the other subduction zone volcanoes found along the West Coast of the United States. In general, the major hazardous geological processes associated with the eruption of a volcano like Mount Rainier are as follows.

Tephra Fall

During explosive eruptions, a mixture of hot volcanic gases and tephra, which includes volcanic ash and larger fragments is ejected rapidly into the air from volcanic vents. The finer fraction of the tephra is commonly less dense than the air and rises into the air until no longer buoyant – in the case of the 1980 eruption of Mount St. Helens, the ash column rose about 25 km in less than 30 minutes. As the energy to keep them suspended diminishes, the particles begin to fall under the influence of gravity. Larger particles fall out first and nearer the volcano while sand-sized and finer particles may fall out many hundreds of kms away. The tephra forms a blanket-like deposit that is thicker near the volcano and thinner and finer with increasing distance from the vent. (Wolfe and Pierson, 1995).

The major hazards associated with tephra fall are: (1) impact of falling fragments; (2) suspension of abrasive fine particles in the air and water; and (3) burial of structures, lifelines, and vegetation. As learned in the 1980 eruptions of Mount St. Helens, tephra fall can cause severe social disruption over a vast area.

Fragments larger than a few centimeters (1 to 2 in), that have sufficient mass to cause severe injury or damage through impact, generally fall within about 10 km (6 mi.) of the vent. Thus, damaging or lethal impact from falling tephra is likely only in the immediate vicinity of a stratovolcano.

Ash suspended in the air from a large eruption can be a major source of aggravation and hazard even hundreds of kilometers (a few hundred miles) downwind from its source, both during its initial accumulation and later as fine dry ash is remobilized by wind or passing vehicles. Airborne ash (a) causes eye and respiratory irritation for some people and can cause severe air-quality problems at critical facilities such as hospitals; (b) can cause severe visibility reduction, even complete darkness during daylight hours, which can make driving particularly hazardous; (c) can damage unprotected machinery, especially internal-combustion engines; (d) can cause short circuits in electric-power transmission lines; and (e) can endanger aircraft flying through ash clouds, especially jet aircraft, which can completely lose engine power. Suspension of ash in water can lead to damage at hydroelectric facilities, irrigation pumping stations, sewage-treatment facilities, and stormwater systems.

Burial by tephra can collapse roofs of buildings and other structures, break power and telephone lines, and damage or kill vegetation. Wet tephra is 2 to 3 times heavier than dry uncompacted tephra and adheres better to sloping surfaces. Ten centimeters (4 inches) of wet tephra impose a load in the range of 100 to 125 kg/ m2 (approximately 20 to 25 lb/ft2), sufficient to cause some roofs to collapse (Wolfe and Pierson, 1995).

Before 1980, the hazard from tephra fall was generally considered smaller than from other volcanic phenomena, and was commonly ignored in planning responses to volcanic crises. Yet, the 1980 eruption of Mount St. Helens showed that even thin tephra accumulations can disrupt social and economic activity over broad regions. Ash can cause or exacerbate pulmonary problems in people and animals. Even thin tephra accumulations may ruin crops. Tephra can contaminate surface water, plug storm sewer and even sanitary sewer systems, and obstruct highways and irrigation canals. Airports and highways can be closed for days. Near the volcano clouds of falling tephra are commonly accompanied by lightning (Waitt, Masten, Beget, 1995).

Pyroclastic Flows

Pyroclastic flows are avalanches of hot (300 to 800C,) dry, volcanic rock fragments and gases that descend a volcano's flanks at speeds ranging from 10 to more than 100 meters/sec. (20–200 mph.). Because of their mass, high temperature, high speed, and great mobility, these flows are destructive and pose lethal hazard from incineration, asphyxiation, burial, and impact. Because of their high speed, pyroclastic flows are difficult or impossible to escape. Evacuation must take place before such events occur. These flows have been known to move many kilometers downslope from the volcano. They typically concentrate in valleys and move rapidly out into adjacent areas where they cause damage to life, limb, and property.

Just as mixtures of hot volcanic gas and tephra rise into the atmosphere when the mixture is less dense than the surrounding air, mixtures of hot volcanic rock fragments and gas that are more dense than the surrounding atmosphere flow down the volcano flanks as pyroclastic flows. Such flows can originate from high vertical eruption columns, from low fountains of erupting pyroclastic material that appear to "boil over" from the vent, and from gravitational or explosive disruption of hot lava domes. The first two mechanisms operated during the explosive eruptions of 1980 at Mount St. Helens and are likely again should eruptive activity be resumed. The third mechanism, disruption of a hot lava dome, has operated at numerous times in the past at Mount St. Helens but would be significant there only if new dome growth should become established.

Driven by gravity, pyroclastic flows seek topographically low areas and, beyond the steep flanks of the volcano, tend to be channeled into valleys. Pyroclastic flows from the May 18, 1980 eruption ran out only about 8 km (5 mi.) from the vent. As they impinged on Johnston Ridge, they were deflected westward down-valley and eastward to Spirit Lake. During the past 4,000 years, during which time the volcano's modern edifice formed, numerous pyroclastic flows are known to have traveled at least as far as 10- 15 km (6 to 9 mi), and at least one older flow is known to have traveled as much as 20 km (12 mi). Although the present crater geometry favors distribution of pyroclastic flows into the North Fork Toutle River valley, all flanks of the volcano are subject to pyroclastic-flow hazard during a large eruption.

Pyroclastic Surge

Pyroclastic surges are turbulent, relatively low-density (but still denser than air), mixtures of gas and rock that flow above the ground surface at high velocities similar to those of pyroclastic flows. Hot pyroclastic surges are generated similarly to pyroclastic flows as well as by lateral blasts and as mobile, turbulent ash clouds winnowed from pyroclastic flows. Hazards resulting from pyroclastic surges include incineration, destruction by high-velocity ash-laden winds, impact by rock fragments, burial by surge deposits, exposure to noxious gases, and asphyxiation. Like pyroclastic flows, pyroclastic surges are too fast moving to escape; evacuation must take place before they occur.

Because they are less dense, pyroclastic surges are less constrained by topography than are pyroclastic flows. Surges may climb or surmount valley walls, affecting areas well beyond the limits of pyroclastic flows. For example, pyroclastic surges surmounted Johnston Ridge and entered the drainage of South Coldwater Creek on May 18, 1980, even though the related pyroclastic flows were deflected by the steep north-facing escarpment of the ridge (Wolfe and Pierson, 1995).

Lahars

A lahar is a mixture of water, ice, and sediment that is generated during and sometimes after an eruption. Hot gases and magma that are ejected under and on top of snow and ice fields rapidly melt the snow and ice creating a mix of tephra, sediments and solidified lava that flow very rapidly down the flanks of the volcano. Lahars are gravity-controlled flows that are channeled into valleys as they move downhill. Lahars triggered during the 1980 eruption of Mount St. Helens were 3 to15 meters deep and traveled at speeds of 20 to 40 m/sec (45 to 90 mph) down the mountain's flanks. Upon reaching flatter river valleys, they slowed down to 10 to 20 m/sec. (22 to 45 mph.). Lahars typically grow in size as they move downslope by picking up sediment, water and organic materials (trees) through a process called "bulking." Volume commonly increases by a factor of 3 to 5. As lahar get farther away from their source, they slow down and flatten out destroying structures and lifelines in their path. An unusually extensive lahar originated near the top of Mount Rainier about 4,800 years BP. It swept down about 70 km through the Orting area and spread out in the lowlands around Tacoma. It formed a lobe about 30 km long and 5 to 17 km wide. A lahar of this size, if it occurred today, would do immense damage to the local population centers, infrastructure, and the environment.

Lateral Blast

A lateral blast is a volcanic explosion that has a significant low-angle component and is typically confined to less than 180 degrees of circumference. Lateral blasts can generate significant pyroclastic flows and can launch large particles or "ballistic projectiles" (Wolfe and Pierson, 1995) many kms from the mountain. Mount St. Helens erupted with a massive landslide that collapsed the magma body and attendant hydrothermal system within the mountain. This collapse resulted in a huge lateral blast that knocked over trees and structures for many hundreds of square km around the north side of the mountain.

Lava Flow

Lava that emanates from mountains such as Mount Rainier and Mount St. Helens is typically quite viscous and does not usually flow far from the vent. Rather, it forms very steep-sided domes atop the mountain that lead to dome collapse, explosive eruption, pyroclastic flows, and lahars. Lava flows like those seen in shield volcanoes (e.g. Kilauea on Hawaii) do not usually occur in Cascade volcanoes, but there is evidence that fluid basaltic flows have emanated from Mount St. Helens in the past, thus it would be prudent to be aware of such possibility. Recent research indicates that lava moving underground in dikes, upon striking mining adits, drifts, or other underground passages may move at speeds upwards of 300 m/sec making them extraordinarily dangerous to underground mine workings or storage facilities (Woods, 2002).

Volcanic Gases

Volcanic gases are also known as VOG (Tilling, 1991). All magmas contain gases that are released both during and between eruptions. Volcanic gases consist mainly of steam but also include carbon dioxide and compounds of sulfur and chlorine. Minor amounts of carbon monoxide, fluorine and boron compounds, ammonia, and several other volcanic gases may also be present.

Volcanic gases become diluted rapidly downwind from the vent. Yet within 10 km of a vent, volcanic gases can endanger life and health, and sometimes property. Eyes and lungs of people and animals can be injured by aerosolized acids, ammonia, and other compounds. People and animals can suffocate in denser-than-air gases such as carbon dioxide, which pond and accumulate in closed depressions. Metals, glass, and other susceptible materials can severely corrode when bathed in volcanic gases (Waitt, Masten, Beget, 1995).

Volcanic Hazard Area Protection

The scientific literature reviewed above and worldwide standards of practice indicate that the best way to regulate volcanic hazards is by way of zonation. Roughly circular zones that represent decreasing risk with distance from the mountain are established based on the geologic record of past eruptive events as mapped by geologists. Each zone is mapped based on the probability of occurrence of the various hazards. So-called "flowage hazards" (pyroclastic flows and surges, lahars, and lateral blasts) are the most deadly and damaging and are typically mapped in three zones – a proximal zone of high concentration or high density flow, a proximal zone of low concentration or low density flow, and a distal zone where well-channelized lahars represent the only significant hazard. Zones 1 and 2 are subject to the full gamut of hazards as discussed above and should be regulated with the understanding that these events occur with such rapidity that it is impossible to evacuate after an eruption has begun. Evacuation must happen before an eruption. Zone 3 is different in that regulation can be limited to those areas where lahars are expected to descend. That regulation could take the form of buffers around historical lahar deposits or could be a more generalized based on topographic elevation (Wolfe and Pierson, 1995).

5.2.5 Coal Mine Hazard Areas

A coal mine hazard area is an area underlain by abandoned coal mine workings including adits (a nearly horizontal mine entrance shaft,) drifts (secondary passages between main shafts,) tunnels, or air shafts (often nearly vertical). In King County, coal was first mined in underground workings in the Renton area in 1854. Underground mining continued in King County until about 1970. It is estimated that approximately 50,000 acres are underlain by underground mines in western Washington. Virtually all coal mines that are still producing today are surface mines. Underground coal mine workings present a number of hazards that can affect people, lifelines, and structures.

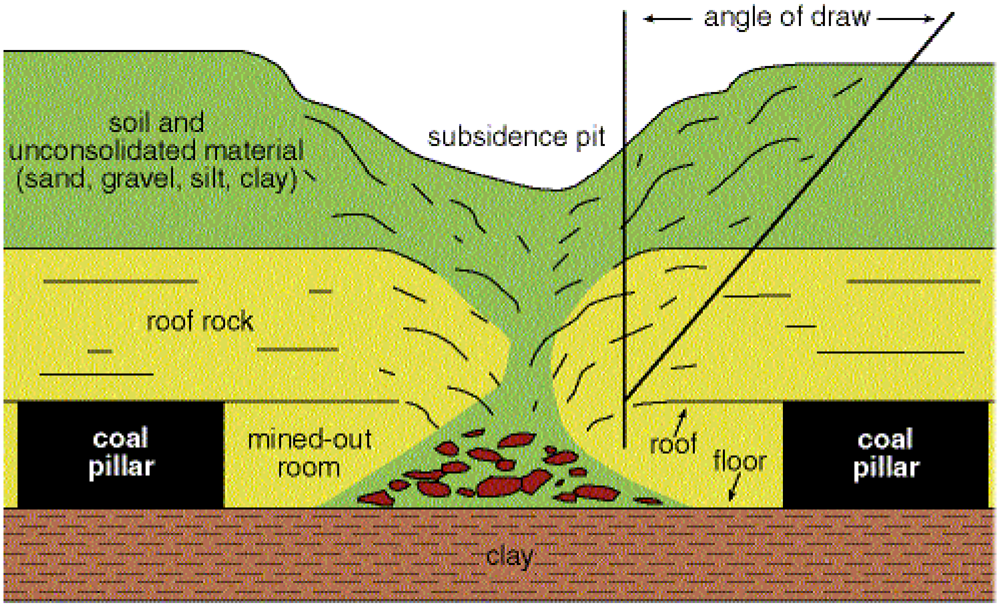
Hazards related to the presence of underground mine workings have been studied extensively in the United States, Scandinavia, the UK, and Eastern Europe. The physical hazards that manifest in these areas are well known and mitigation of these hazards has long been practiced. In general, the underground workings are mapped during the mining process or subsequent to mine closure and the overlying surface is identified accordingly. The standard of practice is to require surface and subsurface studies in these areas to define the scope of the potential problem. Typically, when airshafts or adits are discovered they are sealed or filled to prevent unauthorized entry and to the extent possible, subsidence. Geotechnical and geophysical analyses can estimate the potential for subsidence based on depth of workings, soil or rock type, and surface and subsurface geometry. Based on these parameters, an area is defined as a Coal Mine Hazard Area. Appropriate study prior to development will reveal how or if development can occur in a safe manner.

Coal mine hazard areas were mapped by King County using detailed coal mine maps prepared by mining companies for annual submittal to the State. The Washington State Department of Natural Resources, Division of Geology and Earth Resources is responsible for the regulation of mining in the State. Not all mine workings will appear on the available maps, either because the mines were worked prior to 1900 or because they were small and unregistered by the State.

Coal Mine Hazard Area Functions

Subsidence, in the context of underground mining, is the lowering of the Earth's surface due to collapse of bedrock and unconsolidated materials (sand, gravel, silt, and clay) into underground mined areas.

There are two types of subsidence: (1) pit, also called sinkhole or pothole; and (2) sag or trough. (The term "sinkhole" more properly refers to solution collapse features in limestone.) Pit subsidence is characterized by an abrupt sinking of the surface, resulting in a circular steep-sided, craterlike feature that has an inward drainage pattern. It is associated with roof collapse of mines that have total overburden (overlying unconsolidated material and rock) of less than 165 feet, weak roof rock of shale or mudstone, and a ratio of unconsolidated-material thickness to rock thickness of less than 1:2. Pit subsidence does not occur where the thickness of the unconsolidated overburden is more than 90 feet. Sag subsidence is a gentle, gradual settling of the surface. It is associated with pillar crushing or pillar punching (discussed below) of deeper mines (overburden of more than 75 feet). Sag-subsidence features may fill with water if the surface of the subsidence intersects the water table. Pit-subsidence features generally do not hold water because the pit drains into the underlying mine.



Diagrammatic cross section of typical subsidence resulting from mine-roof collapse. No scale implied.

Cross Section of Mine Roof Collapse (Crowell, 1995)

Mine subsidence is controlled by many factors, including height of mined-out area, width of unsupported mine roof, thickness of overburden, competency (strength) of bedrock, pillar dimensions, hydrology, fractures/joints, and time. The vertical component of subsidence is proportional to the height of the extraction area. Generally, the vertical component of subsidence does not exceed the height of the mine void. However, piping (subsurface erosion by water washing away fine-grained soil) of unconsolidated material can create a cavity deeper than the height of the mined area.

The area of mine subsidence increases proportionally with increasing width of unsupported roof rock. The potential area of subsidence is equal to the extraction area plus an area surrounding the extraction area measured by an angle up to 35 degrees, called the angle of draw, from the vertical at the edge of the extraction area. For example, roof collapse in a mine 160 feet deep could cause subsidence more than 75 feet beyond the edge of the mine. The deeper the mine, the larger the area potentially affected by mine subsidence at the surface.

The vertical component of subsidence decreases with increasing depth or thickness of overburden, especially bedrock. As the roof rock sags, ruptures, and eventually collapses into a mined-out area, the roof rock rotates, twists, splinters, or crumbles as it falls, resulting in incomplete compaction. In other words, the mine void is not completely filled during a mine-roof collapse. Because bedrock collapses with incomplete compaction, the deeper the extraction area, the smaller the vertical component is at the surface.

Mine subsidence is related to the strength or competency of bedrock, which is a measure of a rock's load-bearing capacity. Sandstones and limestones are capable of withstanding greater loads than are shales and mudstones. Therefore, sandstones and limestones can span larger unsupported distances or support thicker amounts of overburden before failing. (Jumikis, 1983.)

Mine subsidence increases as the size of the supporting pillars decreases. In room-and-pillar mining, about 50 percent of the seam is left in place as pillars for roof support. However, coal operators in the nineteenth and early twentieth centuries commonly mined the pillars, partially or wholly, as an area of the mine was abandoned. Complete mining of a pillar is called pillar robbing. Reducing the size of a pillar is called pillar slicing. Creating small, multiple pillars out of a single, large pillar is called pillar splicing. Mining the pillar increases the width of unsupported roof, which increases the likelihood of subsidence. Also, diminishing the size of a pillar increases the chance of pillar crushing or pillar punching and increases the chance of mine-roof collapse. Pillar crushing results when the weight of the overburden exceeds the load-bearing capacity of the pillar and it is crushed. Pillar punching results when the weight of the overburden exceeds the load-bearing capacity of the floor rock, and the pillar is pushed downward into the floor. In pillar punching, the floor rock is generally a soft, plastic clay that flows upward into the mine void, a phenomenon miners term a "squeeze."

Mine subsidence is affected by water circulation or the fluctuation of water level in a mine. Some underground mines remain dry after abandonment; many others fill with water. Circulating water in an underground mine can deteriorate roof support or the roof rock. Because of its incompressibility, water provides support to the roof of a mine that is filled with water. However, the likelihood of roof collapse may be enhanced or accelerated in mines where the roof rock is repeatedly saturated then left unsupported by fluctuating water levels (either by seasonal weather conditions or intentional pumping) and where the pillars of coal are eroded by flowing water.

The likelihood of subsidence increases where fractures (joints) intersect the mine roof. Fractures or joints are natural planes of weakness where collapse of the mine roof is likely to occur. Fractures also may allow the subsidence to extend beyond the limit of the mined area.

The length of time for mine subsidence to occur increases with increasing depth of mining and increasing competency of overburden. The type and amount of roof support in addition to pillars of coal left in the mine also affect subsidence. Most early underground mines in Washington used wooden timbers as additional roof support. By the mid-twentieth century, roof bolting was another type of roof support being used in the mines. With time following abandonment of an underground mine, these types of roof support eventually rot or deteriorate, allowing subsidence to occur. Because of the complexity of the variables which contribute to mine-related subsidence, no acceptable system exists which is capable of accurately predicting the time or amount of subsidence in a variety of geological settings, especially for mines that have an irregular pattern of room-and-pillar mining.

In addition to subsidence above a mine, the collapse of improperly stabilized mine openings presents a great risk to public property and safety. The collapse of an improperly sealed shaft may equal the original depth of the shaft. In 1977, an improperly stabilized shaft to a coal mine abandoned in 1884 collapsed underneath a garage in a residential neighborhood in Youngstown, Ohio, leaving a 115-foot-deep opening. This shaft was originally 230 feet deep. Fortunately, there was no loss of life or personal injury associated with this collapse, but this shaft collapse illustrates the potential for life-threatening situations due to collapse of mine openings.

Coal Mine Hazard Area Protection

Literature review indicates that these hazard areas should have protection boundaries applied to them that have the same effect and function as buffers. The boundaries should be established based on the known physical dimensions of the coal mine and on the stratigraphy of the beds in the area. As described above, the size of the boundary is directly related to the depth of the mine. The actual angle of draw that is applied will vary depending on the attitude of the underlying beds and on the surface (i.e., sloping vs. horizontal). The actual location of these boundaries must be established on a site-specific basis by a trained engineering geologist or geotechnical engineer.

In general, special studies can be used to determine whether coal mines exist in an area, and then design criteria for foundations and drainage systems can be applied. Repair work to ameliorate damage due to subsidence events should fill or block adits and airshafts as they are discovered.

5.2.6 Conclusion

A review of scientific literature about the five geologic hazard areas reveals that these areas pose potential physical hazards to life, limb, property, or the environment. There are specific soil types, slope gradients, climatic conditions, and many other factors that dictate the degree of hazard associated with any particular site. Best available science (BAS) indicates that site-specific review of these conditions is required to accurately evaluate the potential for development of a hazardous condition. In general, the site-specific review must be carried out by person(s) with technical knowledge related to the geologic or engineering subdiscipline in question e.g. slope stability or coal mine hazard potential. BAS also indicates that for certain types of geologic hazards, buffer zones of varying, but conservative widths may be substituted for site-specific evaluation. Among these are landslide hazard areas, volcanic hazard areas, and coal mine hazard areas. BAS also indicates that current science-based and fully implemented construction standards and Best Management Practices (BMPs) can be used to ameliorate the potential hazards.

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