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ASSESSING THE STABILITY OF LANDSLIDES - OVERVIEW OF LESSONS LEARNED FROM HISTORICAL LANDSLIDES IN UTAH

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ABSTRACT

As pressure to develop on hillsides underlain by landslides increases, detailed pre-development geological and geotechnical-engineering studies are needed to understand landslide stability. Research on historical landslides by the Utah Geological Survey (UGS) provides insights into landslide behavior, and the results of detailed pre-development landslide-stability studies should be consistent with these research results. Specifically, historical landslide behavior contradicts some geologic evidence commonly cited to demonstrate the stability of pre-existing landslides, such as subdued geomorphic expression and natural buttressing.

Similarly, although geotechnical-engineering analyses in Utah commonly indicate that Holocene-age landslides have adequate stability for development, historical landsliding indicates that Holocene landslides are commonly near a threshold of instability where slight increases in ground-water levels induce movement. Also, relative to determining minimum safe setback distances above and below landslides, historical landsliding has demonstrated that damaging deformation may occur downslope beyond the toe of the landslide, landslides may enlarge upslope beyond a setback based on main-scarp stability, and multiple failure types must generally be considered in estimating runout distances and setbacks from the base of slopes.

Stability analyses of landslides must objectively assess the likelihood of renewed movement, including relatively minor but still damaging movement. Also, all likely types of failure should be modeled based on historical occurrences and geologic conditions, and considered in stability analyses and mitigation recommendations.

INTRODUCTION

As residential development encroaches on geologically hazardous hillside areas in Utah, particularly along the east bench and foothills of the Wasatch Front and in Wasatch Range back valleys, pressure to develop on existing landslides increases. Before allowing such development, most local governments require developers and their consultants to assess landslide hazards and make recommendations to help ensure safe development. Existing landslides present a particular challenge, and stability analyses commonly involve considerable geologic and engineering judgment. Such judgment must be based on a thorough understanding of landslide behavior, including historical occurrences, and the uncertainties in stability analyses.

Northern Utah's hillsides are locally underlain by landslides and landslide-prone geologic materials, and pre-existing landslides have been the principal sites of historical landslide losses (Anderson and others, 1984; Ashland, 2003a). Although landslide losses occur on a continuing basis, including during drought years (Ashland, 2005a), Utah has recently experienced three periods of significantly above-normal precipitation and landslide losses: in 1983-84 and 1997-98 (Ashland, 2003a), and recently in 2005-06. Significant landslide losses occurred in the benchmark 1983-84 years, chiefly due to the Thistle landslide (over $200 million), the most expensive landslide in U.S. history (Anderson and others, 1984; Shuirman and Slosson, 1992). Estimated landslide losses in 2005 exceeded $10 million.

Landsliding in Utah over the past few decades (figure 1) gives clear examples of the issues to be considered when assessing slope stability and of the uncertainties in such assessments, particularly of pre-existing landslides. Some geologic observations used to infer adequate stability for development are often inconclusive and misleading, and do not reflect typical landslide behavior. The purpose of this paper is to outline the evidence from historical landslides that illustrate this typical landslide behavior and the uncertainties in landslide-stability analyses that are important in understanding the level of risk being accepted when building on landslides. The conclusions draw from the work of many UGS geologists and others in Utah over the past 25 years, particularly in responding to landslide occurrences and reviewing consultant's geologic-hazards reports submitted to cities and counties.

GEOMORPHOLOGY AND TIME SINCE MOST RECENT MOVEMENT

Various workers have noted a geomorphic sequence of weathering and erosion of landslides and defined various "Davisian" stages of development of landslide geomorphology, progressing qualitatively from active and youthful to inactive and old (Davis, 1899; Wieczorek, 1984; McCalpin, 1984, 1986). These classifications of geomorphic expression of a landslide are useful relative indicators of the time since the last major global movement, but care must be taken when inferring that a mature or old geomorphic expression implies adequate stability and suitability for development. Many historical landslides and landslide losses in Utah have involved partial reactivations of old landslides or relatively small but nevertheless damaging movements of large parts of old landslides. In particular, clay-rich landslides in Utah typically move at very slow rates for short periods of time and annual movement amounts may be less than a few centimeters. For such landslides, geomorphic expression may not be a reliable indicator of stability.

Similarly, inferred stability, even when timing of the last movement is based on relative or numerical dating, may be misleading. Such determinations of timing may not capture the most recent movements, and may not document all episodes of movement that have occurred within a landslide deposit. Ashland (2002) documented the abandonment of internal deformation features in a recurrently active slide, suggesting that establishing a complete chronology of movement may require dating ground-deformation events in many parts of a slide.

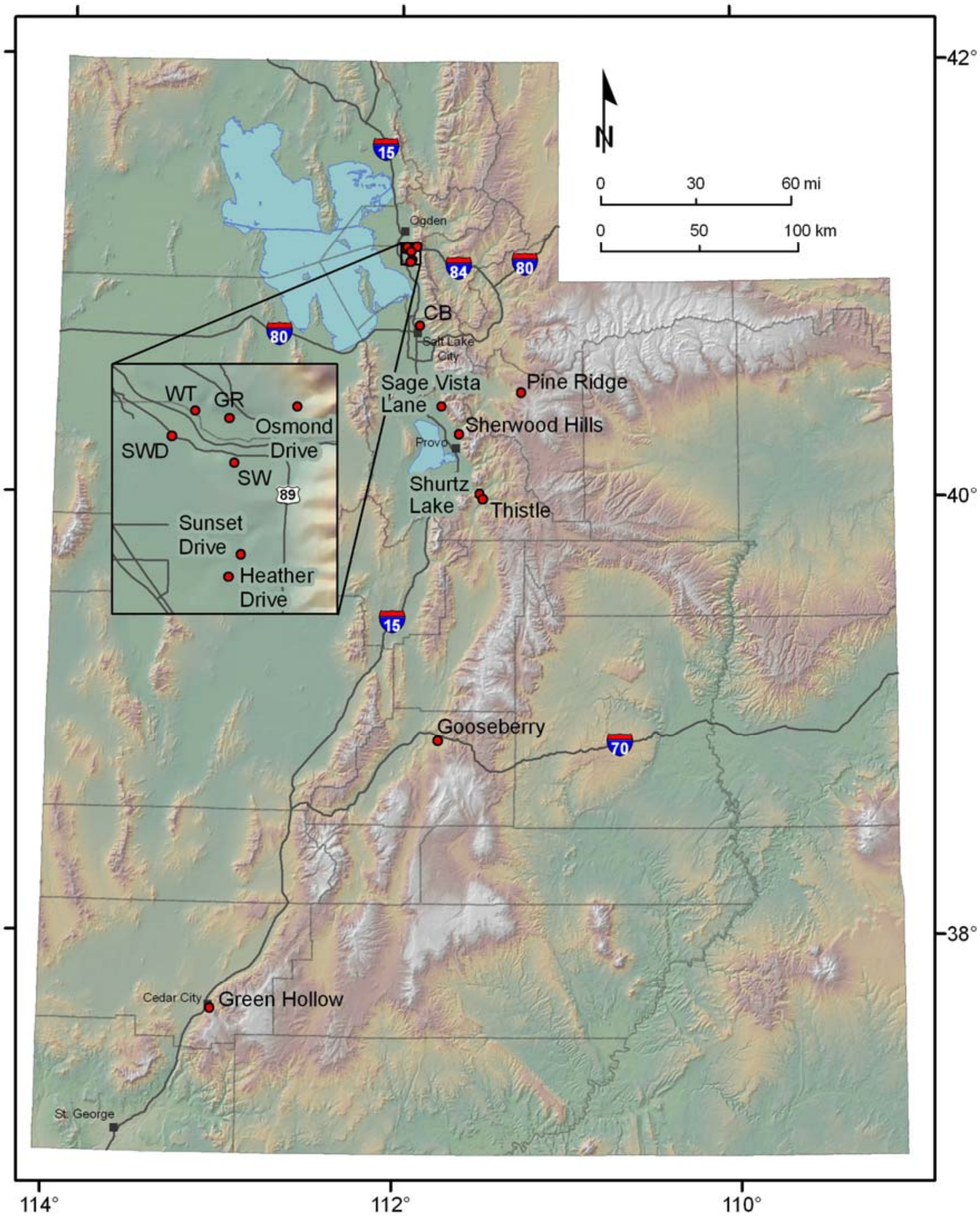

Figure 1. Locations of historical landslides discussed in the text (CB-East Capitol Blvd.-City Creek, GR-Gibbons and Reed, SWD-425 E. South Weber Drive, SW-1650 E. South Weber, WT-Washington Terrace).

Examples of partial reactivation of large, generally old landslide deposits include the 1983 movement and 2005 reactivation of a landslide in Cedar Hills (the Sage Vista

Lane landslide; figure 2; Ashland, 2005b), the 1985-86 movement of part of the Pine Ridge landslide in Timber Lakes Estates east of Heber City (figure 3; Ashland and Hylland, 1997; Biek and others, 2003), the 1997 Shurtz Lake landslide (figure 4; Ashland, 1997), a small 2001 slide within the Green Hollow landslide south of Cedar City, and the 2005 Horse Ranch landslide in the Sherwood Hills landslide complex in Provo (Ashland, 2006). Human modifications contributed to some of these localized reactivations, but all indicate the high susceptibility of landslides to renewed movement, even those mapped as older, Late Pleistocene landslides.

Probably the best example of damaging, global, but small-displacement movement of an old landslide is the continuous very slow movement of the Sherwood Hills landslide complex in Provo (Ashland, 2003b). Machette (1992) mapped it as an older landslide (Late Pleistocene to late Tertiary), and uncertainty exists whether modern movement was induced by grading and drainage modifications accompanying development, or if the landslide was moving prior to development. However, parts of the landslide complex are presently moving at average rates of a few centimeters per year, and the area of movement may be expanding as movement progresses.

Long periods may exist between climate- and/or earthquake-induced major global movements that rejuvenate landslide geomorphology. However, during these periods, partial failures and/or small displacements in significant parts of the landslide may occur. These movements may be insufficient to rejuvenate the “old” geomorphology of a landslide, but may still result in damage to structures.

Movement of some landslides may be periodic but relatively minor, and therefore preclude the development of a young, hummocky geomorphic expression. Some Holocene landslide complexes common in slopes in the Layton/northern Davis County and southern Weber County areas may result from a sequence of periodic minor movements, as occurred in the 1998 and 2006 movements of the Sunset Drive landslide in Layton (figure 5; Giraud, 1999) and 1999 Osmond Drive landslide in Uintah Highlands (figure 6). Recent trench exposures in Layton of highly deformed and tilted latest Pleistocene Lake Bonneville strata in areas lacking well-developed youthful, hummocky landslide geomorphology indicate that either Holocene erosional processes have subdued the geomorphology of large-displacement events, or that intermittent small-displacement or slow continuous movements allowed the relatively smooth slopes to be maintained.

Thus, an inactive, subdued geomorphic expression, even if constrained by a relative or numerical age, is generally not sufficient evidence to infer adequate stability for development. Historical landslides have shown that even old landslides may be at least partly reactivated under modern conditions, and that it is difficult to preclude recent movement of all parts of landslides. In many cases, damaging historical movements of older landslides have been relatively small, indicating that at least small periodic stability

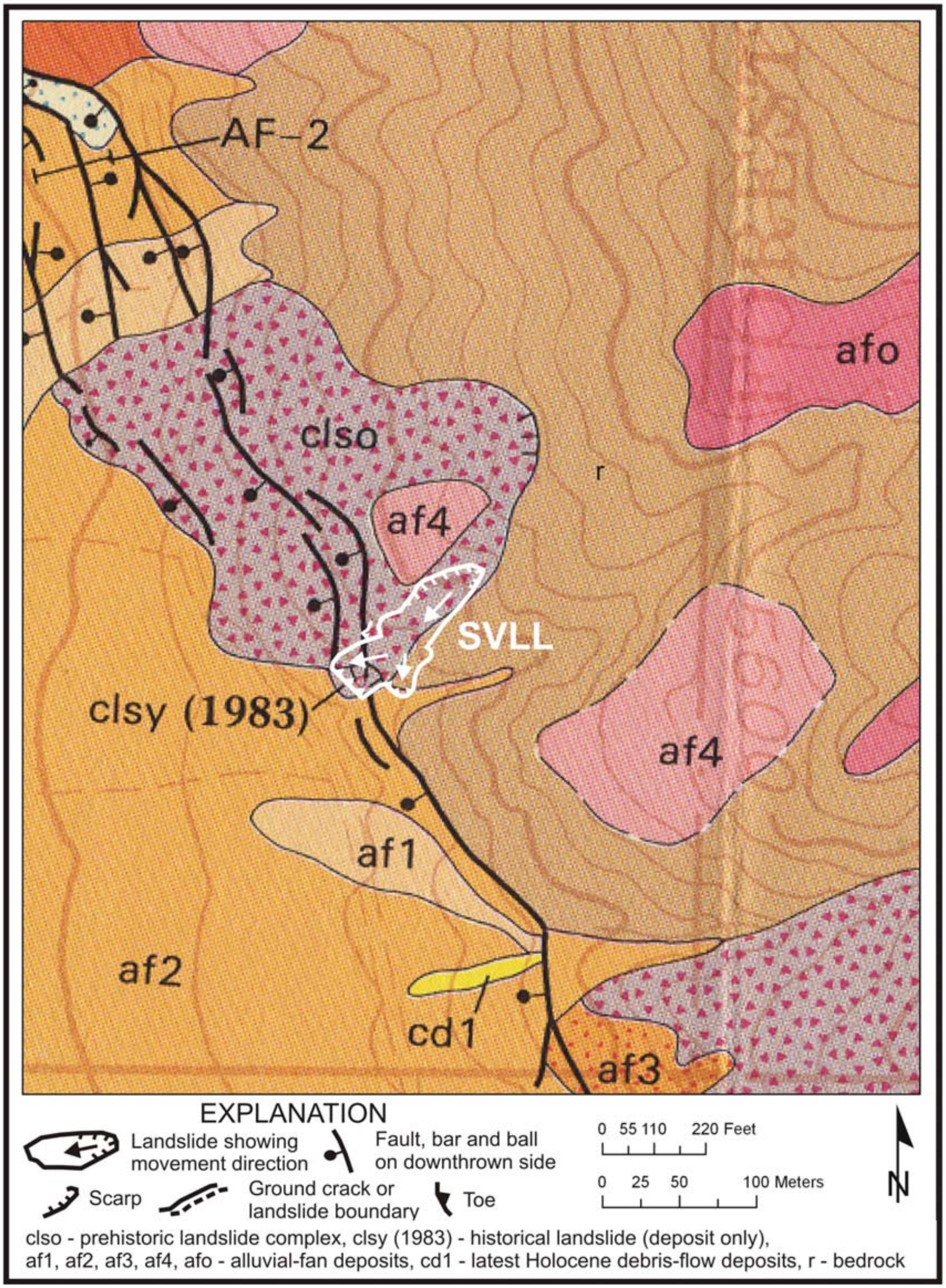

Figure 2. Geologic map of the 2005 Sage Vista Lane landslide (SVLL) in Cedar Hills showing reactivation of a 1983 slide within an older mapped landslide complex (from Ashland, 2005b). Geologic base map from Machette (1992).

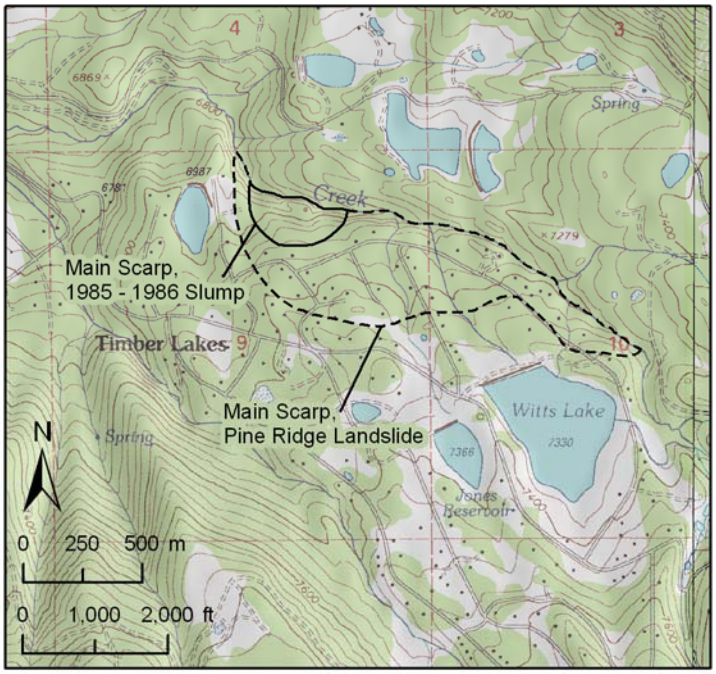

Figure 3. Map of the Pine Ridge landslide in Timber Lakes showing the part that reactivated in 1985-86 (modified from Ashland and Hylland, 1997; Biek and others, 2003).

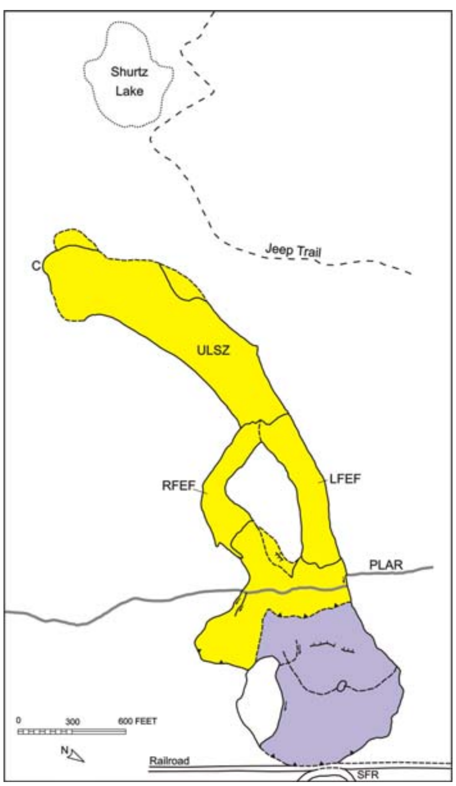

Figure 4. Map of the 1997 Shurtz Lake landslide showing upper earth flows (yellow) and lower older landslide deposits (blue) that reactivated in 1998 (modified from Ashland, 2003b) (C-crown, ULSZ-upper lateral spread zone, RFEF-right-flank earth flow, LFEF-left-lank earth flow, PLAR-power-line access road, SFR-Spanish Fork River).

Figure 5. Main scarp of the 2006 Sunset Drive landslide showing small displacement main scarp in the crown of prehistoric landslide. Photo by Ashley Elliott, UGS.

Figure 6. Scarps in the 1999 Osmond Drive landslide showing small displacements within the older landslide complex.

adjustments may occur regularly in these landslides in response to normal climate variability.

STABILITY OF HOLOCENE LANDSLIDES

Maximum limits on the timing of movement for many landslides along the Wasatch Front are relatively well constrained where the landslides are developed in slopes cut into Lake Bonneville deposits or where landslides override Lake Bonneville deposits. Such landslides postdate the affected Lake Bonneville deposits (generally post-16,000-18,000 years ago) and subsequent regression of the lake and incision and widening of drainages to produce slopes. Landslides on these slopes can therefore be considered to be of Holocene (post-glacial) age and to have moved under essentially modern climatic conditions. Recent reactivations of these Holocene landslides include the 1998 and 2006 Sunset Drive landslide (Giraud, 1999), 2001 Heather Drive landslide (Giraud, 2002), and many other 1983-84 and 1997-98 landslides (Lowe, 1988a; Ashland, 2003b).

Recent reactivations of Holocene landslides indicate that these slides remain at threshold stability levels. Case histories have demonstrated that the ground-water conditions necessary to reactivate Holocene landslides are possible under the present climate, and are even more likely given development-induced rises in ground-water levels due to lawn watering, redirected runoff, and other hillside modifications. Therefore, if significant geomorphic changes have not occurred to increase stability since the landslide last became dormant, recovery of adequate stability for development is unlikely. The reactivation of numerous Holocene landslides in northern Utah suggests little justification for inferring adequate stability in their natural state or subsequent to hillside modifications typical in development.

NATURAL BUTTRESSING

Some landslides are naturally buttressed against an opposite canyon wall or may otherwise have movement restricted naturally at the toe. However, care must be taken when using such natural buttressing to infer sufficient stability for development in any part of the landslide.

Probably the best example of the potential for continued movement in both the upper and lower parts of a naturally buttressed landslide is the 1983 Thistle landslide. In 1983 the landslide blocked Spanish Fork Canyon and became buttressed against rock in the opposite canyon wall. Heavy equipment was used to mechanically compact and flatten the local slopes of the lowermost part of the deposit mainly to reduce the likelihood of failure of the landslide dam (Shuirman and Slosson, 1992), but also to improve the material to act as a buttress. However, in 1983 during the last stages of movement, the lower part of the landslide overthrust the buttress. Movement continued upslope through 1985 (Duncan and others, 1986). Again in 1998, a significant failure in the head caused up to 7 meters of movement just above the buttress as the lower part of the landslide overthrust the buttress (figure 7; Ashland, 2003b). Movement farther upslope was estimated to be as much as 48 meters (Ashland, 2003b). Both failures would have severely damaged anything built on the landslide in the area. Therefore, natural buttressing does not guarantee stability of upslope parts of a landslide, and should not be used to imply adequate stability for development.

Figure 7. Toe thrust just above natural buttress in the Thistle landslide caused by 1998 failure in head area.

DOWNSLOPE EFFECTS, SETBACKS, AND RUNOUT

Landslide stability analyses and decisions on safe setback distances should consider the downslope effects of landsliding, including the potential for shortening deformation and landslide enlargement below the toe, and increased runout where the slide type has the potential to change from sliding to flow. Setbacks and other hazard-reduction measures for rapid flow-type failures are different from those for coherent, slow-moving rotational slides. In addition, setbacks from the main scarp of the landslide should be based not only on scarp height, but the potential for upslope enlargement of the landslide.

The 1997 Shurtz Lake landslide demonstrated how movement in the upper part of a prehistoric landslide complex can induce movement in the lower part. In 1997, several earth flows in the landslide complex were deposited at the base of a bluff (figure 4) atop the lower part of the complex. The lowermost part of the complex showed signs of incipient reactivation by late May 1997 (Ashland, 1997), and in 1998 nearly the entire lower part reactivated, forming a zone of uphill-facing minor scarps, lateral strike-slip shear zones, and a toe thrust system (figure 8). The total amount of movement of the lower landslide locally exceeded 3 meters (Ashland, 2003b) and would have caused extensive damage to any structures built on the lower landslide deposits.

Figure 8. Deformation in 1998 in lower landslide deposits caused by the 1997 Shurtz Lake landslide.

Shortening deformation may occur beyond the toe of a landslide due to subhorizontal forces caused by the upslope moving debris. The effects are illustrated in the Sherwood Hills landslide where possible deformation is occurring in Lake Bonneville deposits beyond the toe, as indicated by pavement and building distress. Shortening deformation and ground tilting may be a precursor to or accompanied by downslope enlargement of a landslide and propagation of toe thrusts. The toe of the Salt Lake City East Capitol Boulevard-City Creek landslide consists of a stacked system of thrusts (figure 9), the youngest and most active being the lowermost frontal thrust (Ashland, 2003b).

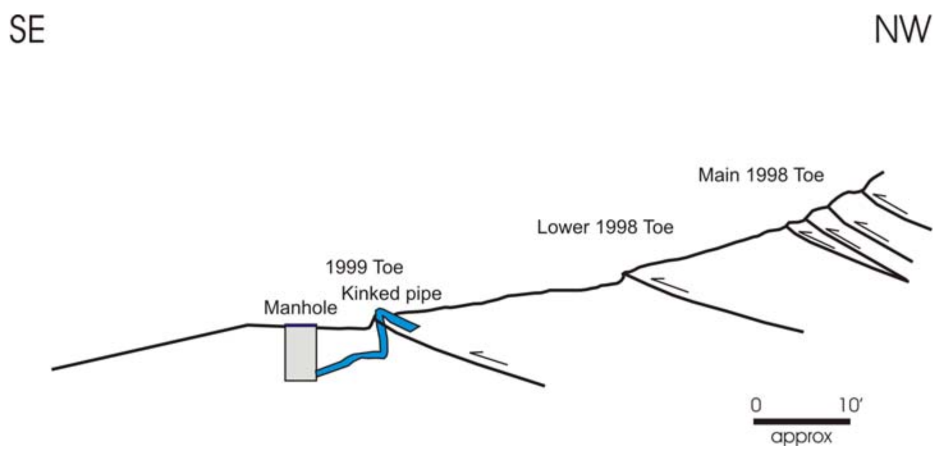

Figure 9. Schematic cross section showing downslope-progressing stacked thrusts at the toe of the East Capitol Boulevard-City Creek landslide.

Building on or at the base of slopes characterized by landslides also involves predicting future landslide types and runout distances, particularly if rapid flow-type failures are possible. This is especially important because rapid-runout landslides have implications for life safety as well as property damage. Several recent landslides in areas characterized by both slow-moving rotational landslides and rapid, long-runout flow-type movements have demonstrated the importance of considering all likely types of landslides. The bluffs on the north side of the Weber River in the Washington Terrace area of southern Weber County are typically characterized by large, presumably slow-moving coherent rotational slides (Pashley and Wiggins, 1972), but a 1981 landslide in Washington Terrace (Gill, 1981) was a large, rapid, disrupted complex earth slide-earth flow that ran out a sufficient distance to knock a Union Pacific train off the tracks below the landslide and into the Weber River. Likewise, in the bluffs on the south side of the Weber River in South Weber, the 425 East South Weber Drive landslide in 2005 (figure 10; Giraud, 2005) and the 1650 East South Weber landslide in 2006 failed as rapid, shallow, long-runout slides and flows.

Figure 10. Toe of the 2005 425 East South Weber landslide that ran out over 50 meters from the base of the slope. Photo by Richard Giraud, UGS.

Setbacks are also commonly used upslope from main scarps to define safe buildable areas in the crown. These setbacks must account for potential upslope enlargement of the main landslide mass, as well as local stability of the main scarp based on its height and geology. The location of the main scarp of the 2001 Heather Drive landslide was as much as 20 meters upslope from its prehistoric position (AGEC, 2002). The estimated additional setback distance from the 2001 main scarp to achieve a 1.3 factor of safety is as much as 40 meters (AGEC, 2002), well beyond the distance needed to account for natural degradation of the 3-meter-high main scarp to a stable slope angle.

In summary, building in sloping terrain both above and below landslides presents unique challenges, and the potential for enlargement and long runout of landslides must be respected when determining how close one can safely build. Also, setbacks must consider the potential for shortening below the toe.

FLOWS AND SLIDES ON LOW-GRADIENT SLOPES

A critical element of any slope-stability analysis is slope angle. Commonly, slope angles are an initial screening criterion used to determine if a stability analysis is necessary. However, historical landslides have shown that Utah has materials that are prone to flow-type failures on low-gradient slopes when saturated, including non-earthquake-induced liquefaction. Also, Utah has many weak, low-strength slide-prone materials that fail on gentle slopes.

The upper part of the 1997 Shurtz Lake landslide, which consisted principally of saturated clayey landslide deposits along a stream channel, failed by lateral spreading in low-gradient slopes (figure 4; Ashland, 1997). The average pre-failure slope angle of the upper Shurtz Lake landslide was about 11 degrees (20%).

Liquefaction is suspected in failures along the bluffs of the Weber River near the mouth of Weber Canyon, creating landslide hazards on adjacent low-gradient slopes where the liquefied material runs out. Non-earthquake-induced liquefaction, likely caused in part by a drain-pipe-break-induced increase in pore pressures on the Gibbons and Reed property (figure 1) (Lowe, 1988b), caused sliding and liquefaction of sandy hillside deposits that flowed onto the flood plain of the Weber River. The resulting deposits are on a low-gradient alluvial fan at the base of the bluff. Geologic investigations have identified similar types of flow deposits on Weber River terraces in South Weber on the opposite side of the canyon (Nelson and Personius, 1993; Western GeoLogic, 2004; Solomon, in press). It is not known whether these prehistoric landslides were earthquake-induced or not, but historical occurrences indicate that earthquake ground shaking is not necessary to cause these types of failures.

Similar flow-type failures have occurred due to non-earthquake-induced liquefaction in granular alluvial-fan deposits at very low slope angles of less than 4 degrees (7%) (Larrabee, 1984). During the record spring snowmelt in 1983, a flow failure in alluvial-fan deposits along Gooseberry Creek, a southern tributary to Salina Creek in Sevier County east of Salina, likely resulted from liquefaction caused by high pore pressures which were heightened by infiltration from an unlined canal above the failure (figure 11).

Figure 11. Evacuated area in alluvial-fan deposits along Gooseberry Creek in 1983 resulting from non-earthquake-induced liquefaction.

Utah also has many landslide-prone geologic units and related landslide deposits (Harty, 1991) with very low strengths. Measured and back-calculated strengths in landslides, stated as angles of internal friction assuming no cohesion, are as low as 7 degrees in the Triassic Petrified Forest Member of the Chinle Formation (Jibson and Harp, 1996), 8 degrees in the Mississippian Manning Canyon Shale (AMEC, Inc., 2005), 7 degrees in the Tertiary North Horn Formation (Duncan and others, 1986), and 16-21 degrees in some Late Pleistocene Lake Bonneville clays (AGEC, 2002; Nordquist, 2003). Because of these low strengths, landslides in these units occur on relatively gentle slopes. The average slope angle of the 1998 reactivated landslide deposits at the toe of the 1997 Shurtz Lake earth flows, derived mostly from the North Horn Formation, is less than 11 degrees (20%). The overall gradient of the 2001 Heather Drive landslide in Lake Bonneville Weber River delta clays ranged from 11-16 degrees (20-28%; Giraud, 2002). Although such slopes are not typically considered to be potentially unstable, care must be taken to recognize geologic units that are prone to such low-gradient failures.

Thus, when assessing slope stability, consideration must be given to the potential for low-gradient flow-type landslides and for high pore pressures in granular, generally non-slide-prone units that may fail by liquefaction. Similarly, slope-stability analyses in areas of characteristically low-strength material should recognize that higher measured shear strengths from site-specific studies may not adequately characterize material strengths.

CONCLUSIONS AND RECOMMENDATIONS

Landslide-stability assessments for development on hillsides underlain by landslide deposits involve considerable professional judgment and high levels of uncertainty. Investigations for slope-stability analyses should attempt to reduce these uncertainties, and final development recommendations must address remaining uncertainties. Studies should also consider the conditions under which both neighboring and on-site landslides failed and their implications to site development.

Historical landslides provide important lessons to be considered when assessing landslide stability. Historical landslide movement in areas with subdued geomorphic expression and natural buttressing contradicts some geologic evidence commonly cited as demonstrating stability. Similarly, the accuracy of calculated factors of safety indicating adequate natural stability of Holocene landslides and minimum setback distances above and below landslides must be carefully evaluated in light of historical landslides. Finally, determining possible failure types is necessary to adequately assess the hazard and risk. Pressure to build on landslides will continue, so we must improve our assessments to adequately consider landslide behavior and uncertainty, and reflect these in mitigation recommendations.

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