GEOLOGIC CHARACTERISTICS AND MOVEMENT OF THE MEADOW CREEK LANDSLIDE, PART OF THE COAL HILL LANDSLIDE COMPLEX, WESTERN KANE COUNTY, UTAH

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ABSTRACT

The Meadow Creek landslide, part of the Coal Hill landslide complex in western Kane County, Utah, is about 1.7 miles (2.7 km) wide and 1.3 miles (2.1 km) long and contains six smaller historical slides. The upper part of the Meadow Creek landslide is gently sloping and consists of displaced and back-rotated blocks of Cretaceous Dakota and Cedar Mountain Formations that form northeast- to locally east-trending ridges that are separated by sediment-filled half-grabens. The lower part of the landslide is gently to moderately sloping, locally incised, and consists of heterogeneous debris that overrides the Jurassic Carmel Formation near Meadow Creek. Monitoring using a survey-grade Global Positioning System (GPS) instrument detected movement of the southern part of the Meadow Creek landslide between October 2005 and October 2008, including movement of two of the historical slides—landslides 1 and 2. The most movement during the measurement period occurred within the limits of persistently moving landslide 1 and ranged from about 24 to 64 inches (61-163 cm). Movement of the abutting southern part of the Meadow Creek landslide ranged from approximately 6 to 10 inches (15-25 cm). State Route 9 crosses over approximately a mile (1.6 km) of the southern part of the Meadow Creek landslide, including landslide 1. The highway and its predecessor (State Route 15) have been periodically displaced and damaged by persistent movement of landslide 1. Most of the landslide characteristics, particularly its size, probable depth, and the inferred weak strength and low permeability of clay-rich gouge derived from the Dakota and Cedar Mountain Formations, are adverse to and pose significant challenges to landslide stabilization. Secondary hazards include piping-induced sinkholes along scarps and ground cracks, and debris flows and rock falls from the main-scarp escarpment.

INTRODUCTION

The Coal Hill landslide complex (Doelling and Davis, 1989) consists of a cluster of mostly historical landslides in western Kane County, including the Coal Hill, Burning Coal, and Meadow Creek slides (figure 1) (Stouffer, 1964; Ashland and others, 2009). Several of these landslides have adversely impacted the highway between Mount Carmel Junction and Zion National Park (current State Route 9 [SR-9] and former State Route 15 [SR-15]) since the initial construction of SR-15 in 1928 (Gregory, 1950; Cashion, 1961; Stouffer, 1964; Doelling and Davis, 1989) (figure 2). The current alignment of SR-9 crosses over approximately a mile (1.6 km) of the southern part of the largest slide in the complex—the Meadow Creek landslide. Localized, recurrent damage to the highway resulting from persistent movement of a previously mapped historical slide in the Meadow

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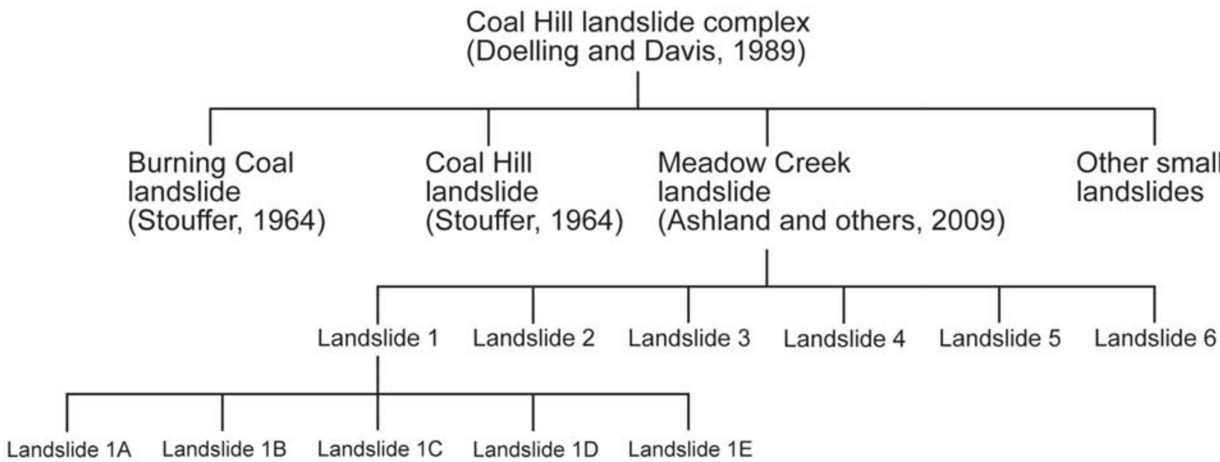


Figure 1. *Flow chart showing hierarchy of landslides in the Coal Hill landslide complex. See figure 3 for locations of Coal Hill, Meadow Creek, and Burning Coal landslides.*

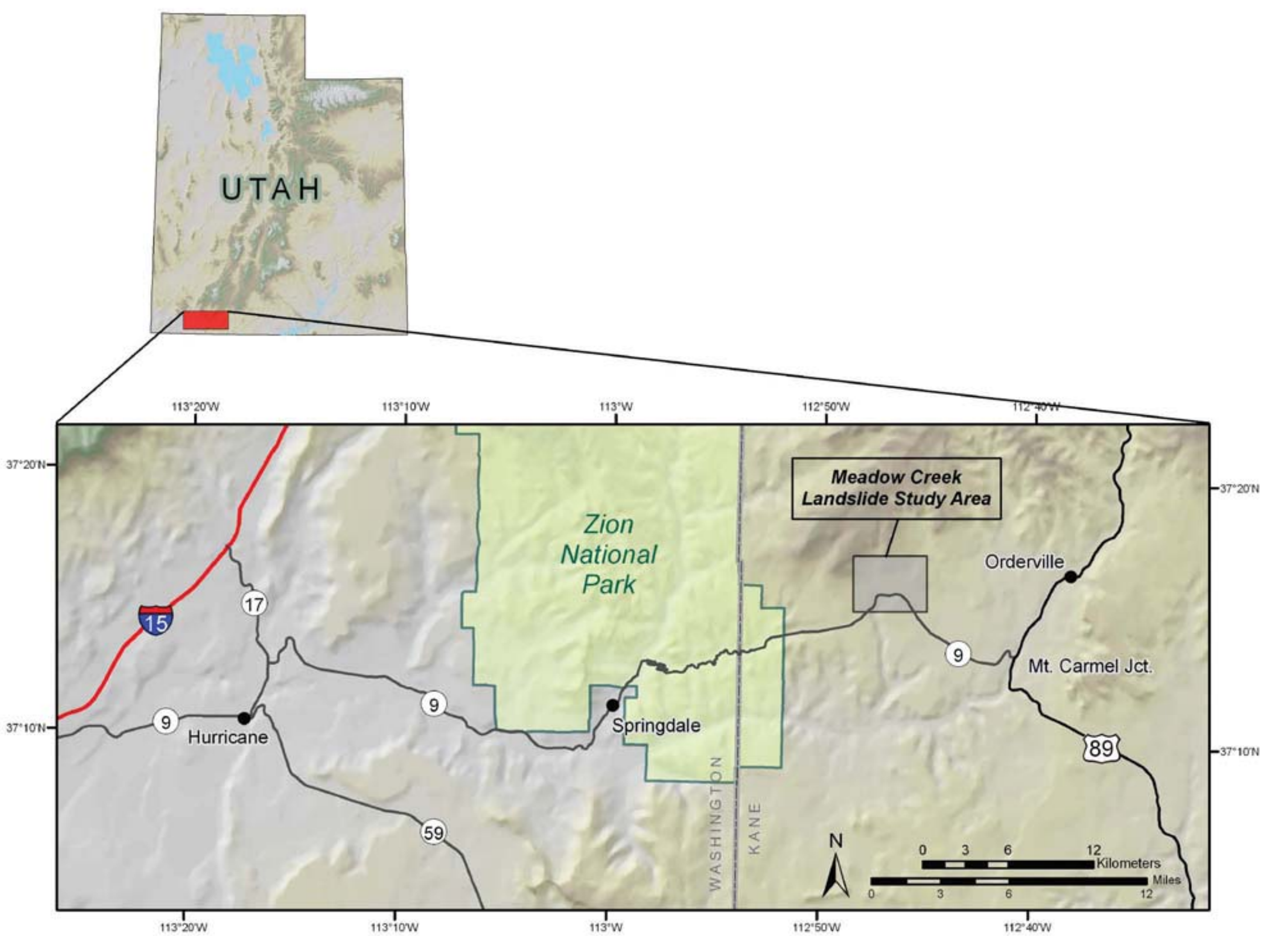


Figure 2. *Location of State Route 9 and Meadow Creek landslide study area (see figure 3) in Kane County, southwestern Utah.*

Creek landslide (landslide 1) requires frequent maintenance and repair, particularly during and immediately following wet years, such as the recent 2005 water year (October 2004-September 2005), the wettest on record at nearby Zion National Park, and hereafter referred to as the 2005 wet year. This paper summarizes the results of geologic investigations and movement monitoring conducted previously by Ashland and others (2009), presents the results of additional movement monitoring between June 2007 and October 2008, assesses the relationship between winter snowpack and average movement rates, and briefly discusses secondary hazards on the Meadow Creek landslide.

PHYSIOGRAPHY AND GENERAL GEOLOGY

The Coal Hill landslide complex is in the western Colorado Plateau province near the confluence of Meadow Creek and Little Meadow Creek, the former a generally south-flowing tributary of the East Fork of the Virgin River. The area ranges in elevation from about 5800 (1770 m) to locally over 7000 feet (2130 m). Parts of the Coal Hill ridgeline are over 6400 feet (1950 m) in elevation near SR-9.

Subhorizontal Mesozoic sedimentary rocks underlie the landslide complex (Cashion, 1961; Doelling and Davis, 1989; Hylland, 2000; Sable and Hereford, 2004). The oldest rock unit in the vicinity of the landslide complex is the Jurassic Carmel Formation; its Crystal Creek Member, consisting mostly of reddish-brown sandstone and siltstone, crops out at the confluence of Meadow Creek and Little Meadow Creek. The overlying Paria River and Winsor Members of the Carmel Formation crop out along the two creeks and are locally overridden by landslide debris. The Paria River Member includes a prominent ledge- and cliff-forming alabaster gypsum bed, and the Winsor Member consists mostly of yellowish-gray sandstone. Sequentially overlying the Carmel Formation are three Cretaceous units: the Cedar Mountain and Dakota Formations, and the Tropic Shale. Hylland (2000) mapped conglomerate and mudstone formerly included in the Dakota Formation (Doelling and Davis, 1989) as the Cedar Mountain Formation (see Biek and others, 2003), which crops out around Coal Hill and locally along the slopes above the two creeks. The coal-bearing Dakota Formation, which consists mostly of mudstone and sandstone, underlies the upper part of Coal Hill, generally above elevation 6160 feet (1878 m), and crops out in slopes in the northern part of the landslide complex. Cashion (1961) had previously included the coal-bearing strata in the Tropic Shale, but these strata were later redefined as Dakota Formation (Lawrence, 1965; Elder and others, 1994). The Tropic Shale, consisting mostly of marine shale, crops out north and east of the landslide complex at elevations generally above 6600 feet (2012 m).

COAL HILL LANDSLIDE COMPLEX

The Coal Hill landslide complex includes three previously named landslides (the Meadow Creek, Coal Hill, Burning Coal slides) and several unnamed landslides (figure 3). The largest of these is the Meadow Creek landslide (Ashland and others, 2009) that is bound by Meadow Creek on the east and south, Little Meadow Creek on the west, and a large south-facing escarpment on the north. The Coal Hill and Burning Coal landslides (Stouffer, 1964) are two of a cluster of slides on the northwest-facing slope of Coal Hill southeast of Meadow Creek.

Landslides in the Coal Hill landslide complex are inferred to have formed due to failure in the weak, low-permeability mudstones in the Dakota and Cedar Mountain Formations. Geologic mapping (Hylland, 2000) and subsurface data (Stouffer, 1964) indicate that the surface of rupture of many of the complex's landslides may have formed in bentonitic mudstone included in the Cedar Mountain Formation (Biek and others, 2003). However, along Meadow Creek and Little Meadow Creek landsliding extends down into the underlying Carmel Formation where either landslide debris overrides erosional surfaces formed in the unit or as local creekside rotational land-

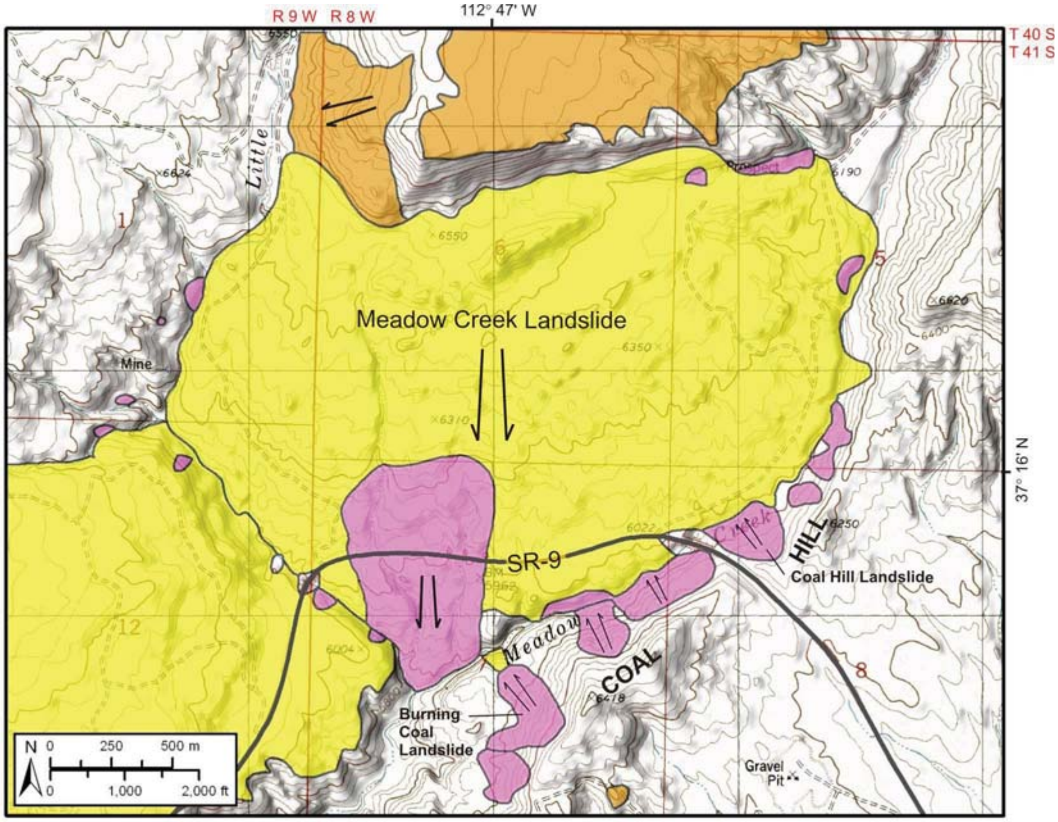


***Figure 3.** Simplified geologic map of the Coal Hill landslide complex, western Kane County, Utah. Older (orange), younger (yellow), and historical (pink) landslides shown. Historical slides include Coal Hill and Burning Coal landslides (Stouffer, 1964). Arrows show approximate movement directions of selected landslides. State Route 9 (SR-9) crosses the Meadow Creek landslide. Modified from Hylland (2000). Base map from USGS Clear Creek Mountain 7.5 minute quadrangle.*

slides that involve failure of members as low as the Crystal Creek Member.

Meadow Creek Landslide

The Meadow Creek landslide (figure 3) is about 1.7 miles (2.7 km) wide and 1.3 miles (2.1 km) long, and consists of two parts: an upper gently sloping extensional area and a lower gently to moderately sloping, and locally incised area. The upper member of the Dakota Formation and lower part of the Tropic Shale are exposed in the main-scarp escarpment that defines the northern boundary of the slide. The escarpment reaches a maximum height of about 400 feet (120 m). The Meadow Creek landslide contains six historically active landslides, of which four are in the lower part.

The upper part of the landslide consists of displaced and back-rotated blocks of Cretaceous Dakota Formation (and underlying Cedar Mountain Formation in the subsurface) that form narrow ridges separated by broad, sediment-filled flat areas or half-grabens. Figure 4 shows a conceptual model of the Meadow Creek landslide. The cross section assumes that the basal surface of rupture in the upper part of the landslide is gently sloping, roughly parallel to bedding, and in the Cedar Mountain Formation. The dip (about 25 degrees) of back-rotated blocks of Dakota Formation that form the prominent ridges in the upper part of the landslide are based on field measurements. White sandstone that caps the crest of the upper ridge is likely the “sugarledge sandstone” of the upper member of the Dakota Formation (Cashion, 1961; Hylland, 2000). Local dark gray soils suggest underlying coal, also indicative of the Dakota Formation. One area of septarian nodules in the upper part of the landslide suggests that it may lo-

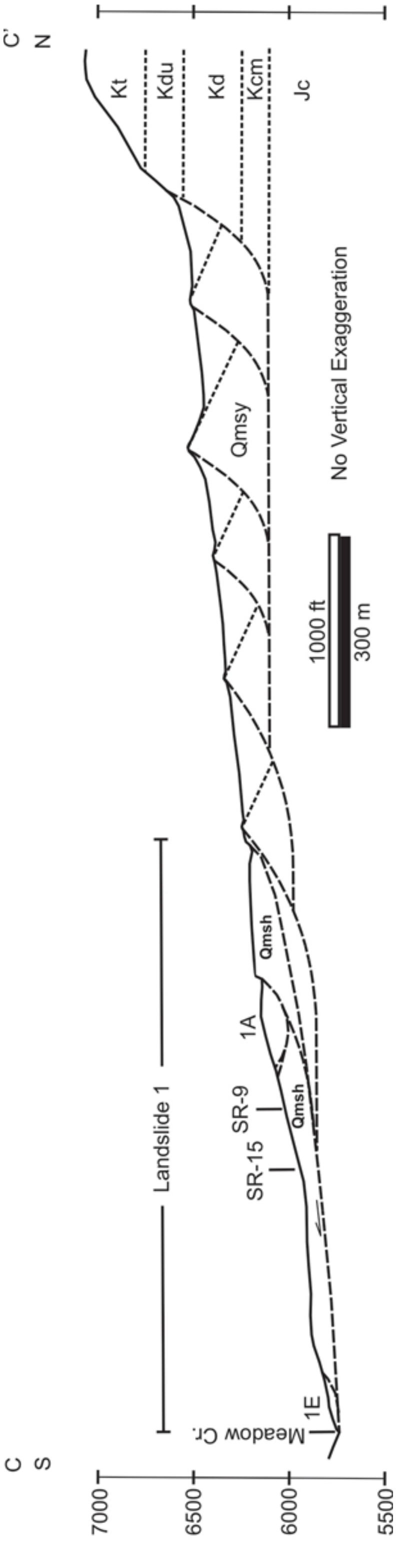


Figure 4. *Conceptual geologic cross section of the Meadow Creek landslide. See figure 5 for section line location. Geologic units: Qmsh – historical landslide 1 (including landslides 1A and 1E), Qmsy –Meadow Creek landslide, Kt – Tropic Shale, Kdu – upper member of Dakota Formation, Kd – main body of the Dakota Formation, Kcm – Cedar Mountain Formation, Jc – Carmel Formation. Bedrock unit thicknesses estimated from Hylland (2000).*

cally contain the lower part of the overlying Tropic Shale or debris derived from it; the lower part of the Tropic Shale is exposed in the upper part of the main-scarp escarpment. The upper extensional area extends downslope to about elevation 6200 feet (1890 m) where it transitions into an area that is generally sloping and incised.

The lower part of the landslide contains four of the six mapped historical landslides in the complex, the exceptions being two slides in the escarpment slope. Locally, the lower area is characterized by back-tilted surfaces with sag ponds indicating deep-seated rotational sliding. Local flat areas, particularly in the southeastern part of the landslide, may be the result of prehistoric stream terracing, deep-seated rotational sliding, or the near-horizontal attitude of underlying strata beneath the landslide debris near the crest of the Meadow Creek canyon slope. In the lower part of the landslide, particularly south of SR-9, surficial materials consist of heterogeneous unconsolidated debris, indicating a transition in the dominant material type from rock in the upper part of the slide to debris in the lower part. Stouffer (1964) recognized a similar transition in material type at both the Coal Hill and Burning Coal landslides.

Significant uncertainty exists regarding the depth of the Meadow Creek landslide (as shown in figure 4) and the smaller slides within it. The dimensions of the Meadow Creek landslide, the main-scarp escarpment height, and the main-scarp heights of the smaller slides within it suggest a depth of 100 feet (30 m) or greater upslope of SR-9, likely increasing toward the escarpment where the relief locally exceeds 400 feet (120 m) (figure 4). South of SR-9 and along the perimeter of the Meadow Creek landslide, the depth of the landslide is likely less than 100 feet (30 m). Data from a geotechnical borehole and seismic refraction line (Stouffer, 1964) and more recent Spectral Analysis of Surface Waves (SASW) testing (Ashland and others, 2009) suggest that the Meadow Creek landslide may be about 40 feet (12 m) deep along its southeastern edge near where SR-9 crosses onto the slide. The subsurface geometries of landslides 1 and 1A shown in figure 4 are constrained by field mapping of the toe and main-scarp locations and, for landslide 1, the depth determined by SASW testing along former SR-15. The basal surface of rupture of landslide 1 is likely in or overrides an erosional surface on the Carmel Formation, although landslide debris at the surface appears to be mostly derived from overlying formations.

Historical Landslides

The Meadow Creek landslide contains six historical landslides (numbered 1 through 6) (figure 5), two in the escarpment slope and four in the lower part of the main slide. Hylland (2000) mapped four of these landslides, Stouffer (1964) mapped another, and Ashland and others (2009) identified the sixth. Reactivation of landslides 1, 2, 3, and 5 occurred in 2005, and some evidence, such as ground cracks and locally oversteepened slopes, suggests minor movement of the other two slides (landslides 4 and 6). Table 1 summarizes measured dimensions and average slopes of the historical landslides.

Landslide 1: Landslide 1 (figure 6) is the largest historical slide in the Meadow Creek landslide (table 1) and contains five smaller slides (landslides 1A through 1E) within its boundaries that were active in 2005. Movement of three of these (landslides 1A, 1D, and 1E) caused considerable local ground deformation. Road-damage inventories along SR-9 and former SR-15 conducted in 2005 (Ashland and others, 2009) indicate that most of the damage occurs within the boundaries of landslide 1.

Landslide 1 is characterized by two well-defined shear zones on its flanks, numerous internal shear zones, and a variety of ground-deformation features. The head of the landslide consists of a series of en echelon or stepping scarps that extend upslope into the upper extensional part of the Meadow Creek landslide. The uppermost scarps in landslide 1 consist of reactivated, downslope-side, ridge-bounding scarps. Sinkholes commonly form along these scarps, suggesting local soil piping at locations where snowmelt and rainwater collect and infiltrate along them. Seasonal seeps are commonly present at the base of steep, downslope-facing, internal scarps, and local back-tilted surfaces are present in the head of landslide 1.

The east- and west-flank shear zones are characterized by en echelon, right- and left-stepping ground cracks, respectively (figure 7). Movement in 2005 resulted in nearly continuous ground-crack zones along both flanks from the head to the toe of landslide 1. The east-flank shear zone intersects Meadow Creek where the toe of landslide 1E deflects the creek about 43 feet (13 m) (figure 8). The west-flank shear zone intersects Little Meadow Creek a short distance upstream from a sinkhole that captures the entire creek flow. From that point, the creek flows through a natural tunnel in landslide debris for about 210 feet (64 m). Doelling and Davis (1989) described this tunnel, suggesting that it has existed for at least 20 years (their field observations date from the mid-1980s).

The lower part of landslide 1 is locally intensely deformed, characterized by numerous ground cracks and fissures, minor scarps, pressure ridges (folds), and ground tilting. Along Meadow Creek, slickensided, carbonaceous (coal-bearing) gouge is locally exposed in the toe thrust system. This suggests that the basal surface of rupture of landslide 1 is at least in part formed in the Dakota Formation or that splays off the basal surface of rupture that form the toe thrust system cut through the unit.

We mapped five slides (landslides 1A through 1E) within landslide 1, but other small, shallow, unmapped slides exist, particularly on local steep slopes along incised drainages. Landslide 1A is the largest of these landslides and its toe is about 165 feet (50 m) upslope of SR-9. The landslide is characterized by a prominent main scarp zone that follows an irregular trace and locally exceeds 20 feet (6 m) in height; a back-tilted area with a sag pond at its head; and an irregular, discontinuous toe thrust system. Movement of the landslide has displaced power poles on the lower part of the slide about 21 feet (6 m) by 2005. Locally, the ground surface is intensely deformed and disrupted (figure 9).

The other four slides in landslide 1 are downslope of SR-9 and former SR-15, and abut either Little Meadow Creek (landslides 1B and 1C)

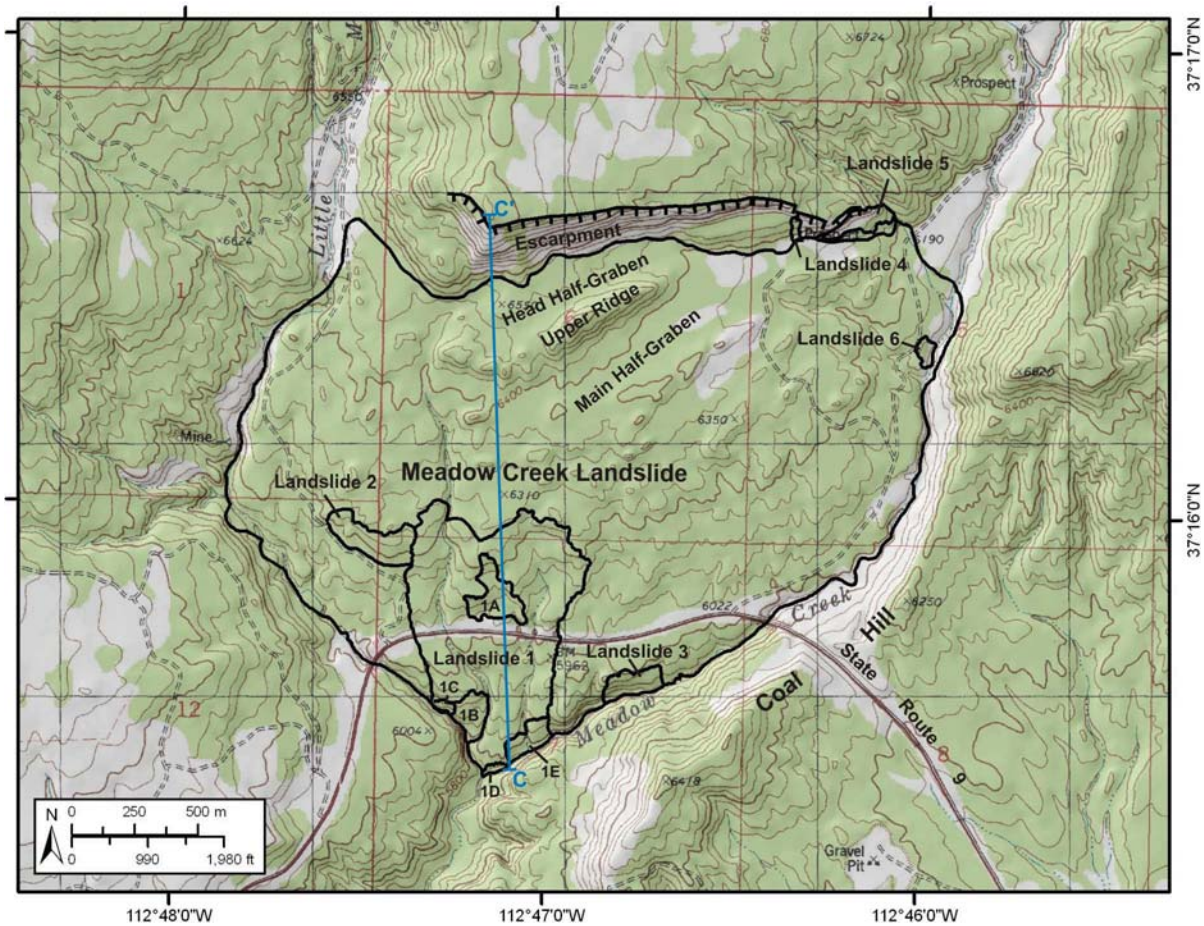


Figure 5. *Generalized map of the Meadow Creek landslide in western Kane County, Utah. Landslide perimeter modified from Hylland (2000). Boundaries of mapped landslides within Meadow Creek slide shown. Cross section shown on figure 4. Base from U.S. Geological Survey Clear Creek Mountain 7.5' quadrangle. Shaded relief from 10-meter Digital Elevation Model (DEM).*

Table 1. *Summary of approximate dimensions and average slopes of active slides in the Meadow Creek landslide as determined in 2005. Landslide locations shown on figure 5.*

Landslide	**Length** (feet)	**Width** (feet) **Toe**	**Upper**	**Other**	**Local Relief** (feet)	**Ave. Slope** (percent)
1	3200-3500	1630	---	1880[A]	500-510	15
1A	875	750	210	---	180	21
1B	650	---	310	---	170	26
1C	130	---	300	---	40	22
1D	110	---	350	---	40	36
1E	270-330	710	---	---	85	30
2	260	---	1070	---	60-100	23[B]
3	250	---	630	---	140	56
4	300	140	120	---	160	53
5	240	---	---	910[C]	140	56
6	230	---	420	---	65-80	28-34

Notes
[A] Width along SR-9.
[B] Western part.
[C] Middle slide.

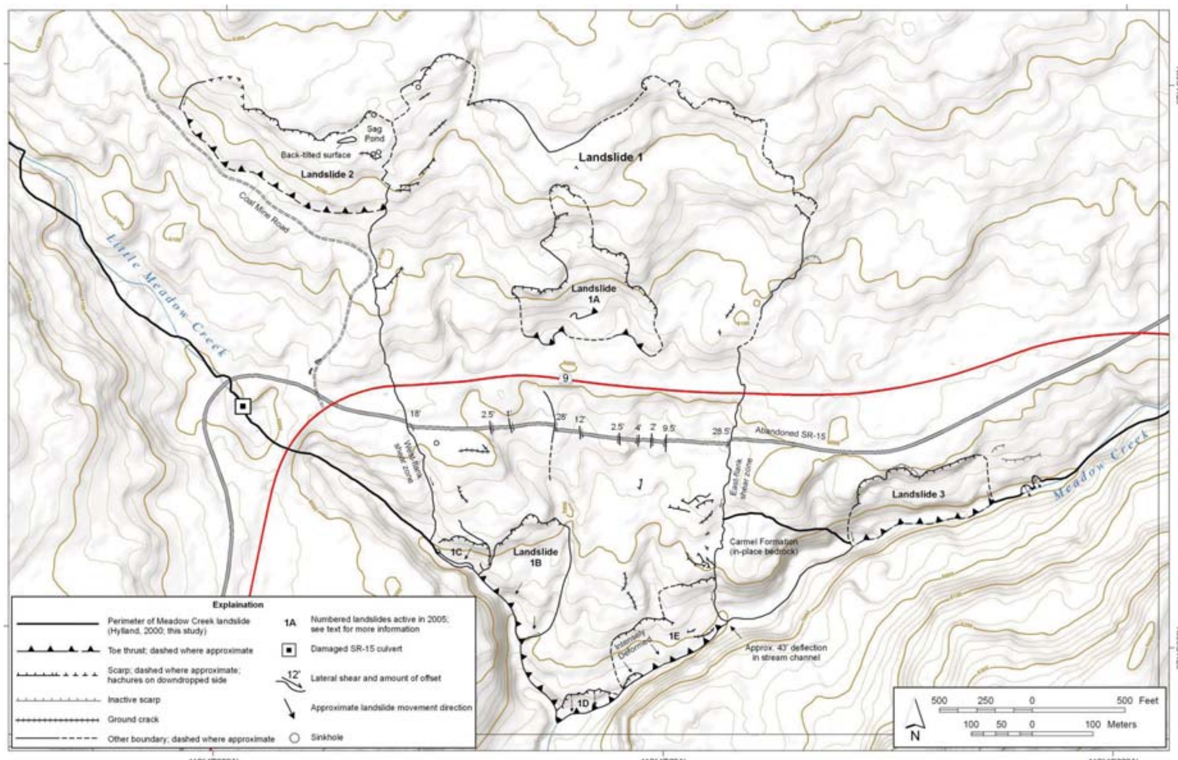


Figure 6. *Detailed map of the southwestern part of the Meadow Creek landslide and landslides 1, 2, and 3.*

Figure 7. *Right-stepping ground cracks along the left-flank shear zone of landslide 1.*

Figure 8. *View downstream of southeast corner of landslides 1 and 1E where Meadow Creek is deflected about 43 feet (13 m).*

Figure 9. *Local intense ground deformation along east flank of landslide 1A.*

or Meadow Creek (landslides 1D and 1E). Landslide 1B is directly west of an incised drainage that crosses the western part of landslide 1 and flows into Little Meadow Creek. The landslide is characterized by a main scarp that locally exceeds 10 feet (3 m) in height. Landslide 1C is upslope of the natural tunnel along Little Meadow Creek. Movement in 2005 resulted in offset and ground cracking along the main scarp of the slide. Landslide 1D is near the confluence of Little Meadow Creek and Meadow Creek and is characterized by intense ground deformation (figure 10). Landslide 1E is in the southeastern toe of landslide 1 and is characterized by locally intense ground deformation and a zone of scarps in its upper part. The 43-foot (13-m) deflection of Meadow Creek occurs at landslide 1E, and some, if not most, of the deflection is likely the result of local movement of this smaller slide rather than global movement of landslide 1. Stouffer (1964) documented deflection of Meadow Creek by landslide 1E, but did not quantify it.

A comparison of previous landslide mapping (Cashion, 1961; Stouffer, 1964; Doelling and Davis, 1989; Hylland, 2000), aerial photographs, topographic maps of the complex, and road-damage accounts suggests most of the historical movement of landslide 1 likely occurred between 1964 and 2004. Stouffer (1964) mapped small slides near our landslides 1B and 1C along Little Meadow Creek and landslide 1E along Meadow Creek, but did not show a large slide equivalent to landslide 1 in the "creep zone." In addition, accounts of road damage in Stouffer (1964) indicated several inches of downslope movement per year in the "creep zone," and more significant movement in wet years. Stouffer (1964) did not describe the movement and road damage as being localized in the vicinity of our landslide 1, but our review of aerial photographs, dated 1960 and hence predating his study, identified damage to former SR-15 localized to the shear zones on the east and west flanks and a major internal shear zone of landslide 1. However, the 1960 aerial photographs do not

Figure 10. *Local intense ground deformation in landslide 1D along Meadow Creek.*

show any significant offset in the former SR-15 alignment, consistent with Stouffer's (1964) road movement description. Doelling and Davis (1989) mapped the flanks of landslide 1, but showed the east-flank shear zone farther to the east than that later mapped by Hylland (2000) and Ashland and others (2009). Doelling and Davis (1989) also documented offset of abandoned SR-15 by 1985. Aerial photographs dated 1994 clearly show offset in the former SR-15 alignment at the boundaries and internal shear zones in landslide 1. Thus, we conclude that movement of landslide 1 has been more significant subsequent to Stouffer's (1964) investigation than in the period prior to his study (1928-1964).

Landslide 2: Landslide 2 abuts landslide 1 on the west above Coal Mine Road on the west side of the Meadow Creek landslide. Landslide 2 is characterized by a well-defined main scarp zone that was active in 2005, but a poorly defined toe. In the eastern part of the head of the landslide is a back-tilted surface with a sag pond on its northern edge, suggesting deep-seated rotational sliding. Numerous east-trending ground fissures with local sinkholes are also present in the eastern head of the slide. To the west, ground-deformation patterns suggest shallower landsliding than in the east. We initially inferred that an oversteepened slope north of Coal Mine Road is the probable toe of the landslide (figure 6), but some movement was detected directly downslope of this feature. Whereas offset on the main scarp occurred in 2005, translation of landslide debris at the toe appears to have been minimal. Instead, movement of the upslope part of the landslide may have resulted in ground tilting and folding at the toe with little, if any, translation. A reconnaissance downslope of the jeep road revealed no evidence of ground deformation indicative of deep-seated landsliding in 2005. However, damage to the former SR-15 culvert (figure 11) across Little Meadow Creek suggests historical movement in this area, either

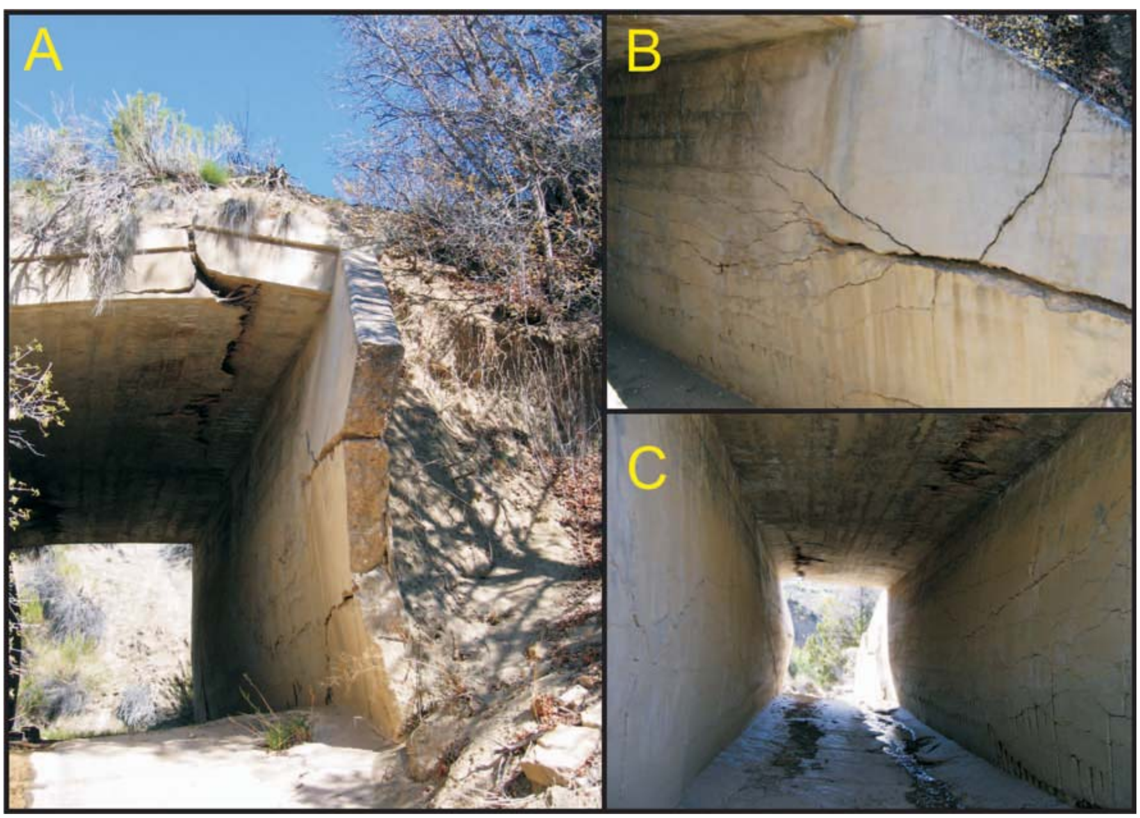


***Figure 11.** Damage to box culvert at abandoned SR-15 crossing of Little Meadow Creek. Damage suggests historical movement downslope of landslide 2. A) View upstream showing damage to northeast wall of box culvert and upper deck. B) Damage to northeast wall of box culvert. C) View downstream of interior of culvert showing hourglass distortion of originally rectangular box culvert.*

of the southwestern part of the Meadow Creek landslide (the western part of the "creep zone") or an as-yet unmapped slide that includes landslide 2. If the latter is true, this suggests that landslide 2 is a partial reactivation of a larger pre-existing slide that extends downslope to Little Meadow Creek.

Landslide 3: Landslide 3 is north of Meadow Creek in the southern part of the Meadow Creek landslide. Stouffer (1964) mapped a landslide in what is now the western part of landslide 3 and Hylland (2000) mapped landslide 3 as a historical landslide. Most of landslide 3 reactivated in 2005, locally causing considerable ground deformation (figure 12). Our mapping of the 2005 landslide boundary suggests that the landslide likely enlarged to the north and west since it was mapped by Hylland (2000) using 1994 aerial photographs. Some or all of this enlargement probably occurred in 2005. The eastern part of the landslide did not reactivate in 2005, but at least two small, shallow landslides occurred in 2005 to the east of the active part of the slide and within the eastern limits of the landside as mapped by Hylland (2000).

Landslide 4: Landslide 4 is directly west of an abandoned coal mine adit (Meeks-Carrol mine of Cashion, 1961) in the eastern part of the large escarpment that bounds the Meadow Creek landslide on the north (figure 5). The small landslide abuts the ruins of the abandoned coal mine and overthrusts a jeep road to the mine adit, indicating historical movement. Observations including the fresh appearance of the landslide perimeter, wet soils in the upper slide, and a 15-foot-wide (5 m) shallow landslide in the main scarp slope suggest some minor movement of the slide in 2005. Seeps and abundant phreatophytes exist in the upper part of the landslide.

Landslide 5: Landslide 5 is the larger and easternmost of two historical landslides mapped by Hylland (2000) in the eastern part of the large escarpment. In 2005, landslide 5 partially reactivated and enlarged in an upslope direction. The toe of the active part of the landslide is in the middle of the deposit mapped by Hylland (2000). A series of scarps and ground fissures occur in the upper part of the active slide. Along the eastern part of the main scarp zone, a narrow horst separates landslide 5 from an active, shallow debris slide to the north. Ground deformation features suggest landslide 5 becomes shallower to the west, similar to landslide 2. In the early part of 2005, local shallow debris flows originated from the toe area of the active part of the slide. One flow traveled downslope of the historical toe mapped by Hylland (2000). During our fieldwork in November 2005, audible rock falls originated from the upper part of the landslide, suggesting the slide remained active in the latter part of 2005 (assuming the rock falls were triggered by movement of the slide).

Landslide 6: Stouffer (1964) mapped a small rotational slide abutting Meadow Creek along the east edge of the Meadow Creek landslide. Our mapping indicates a northward enlargement of the landslide since the early 1960s. The toe of the landslide deflects Meadow Creek to the east near the central part of the slide. Local cracks along the base of the main-scarp colluvium and near the crest of the main scarp suggest minor movement of the landslide in 2005. White precipitate deposits (efflorescence) in the lower part of the landslide indicate local seasonal seeps that likely flow in the early part of the year.

LANDSLIDE MOVEMENT

We performed landslide movement monitoring between October 2005 and October 2008 using a Trimble 5800 survey-grade Global Positioning System (GPS) instrument. The initial surveying was conducted in October 2005, with subsequent measurements taken in November 2005, June 2006, June 2007, July 2008, and October 2008. Additional survey points were installed in the upper, central, and western parts of the Meadow Creek landslide in November 2005 and June 2007, respectively (figure 13).

The initial objective of the landslide movement monitoring was to assess the state of activity of landslides crossed by SR-9 (the southern Meadow Creek landslide and landslide 1). Therefore, many of the survey points were installed along

Figure 12. *Local ground deformation caused by movement of landslide 3.*

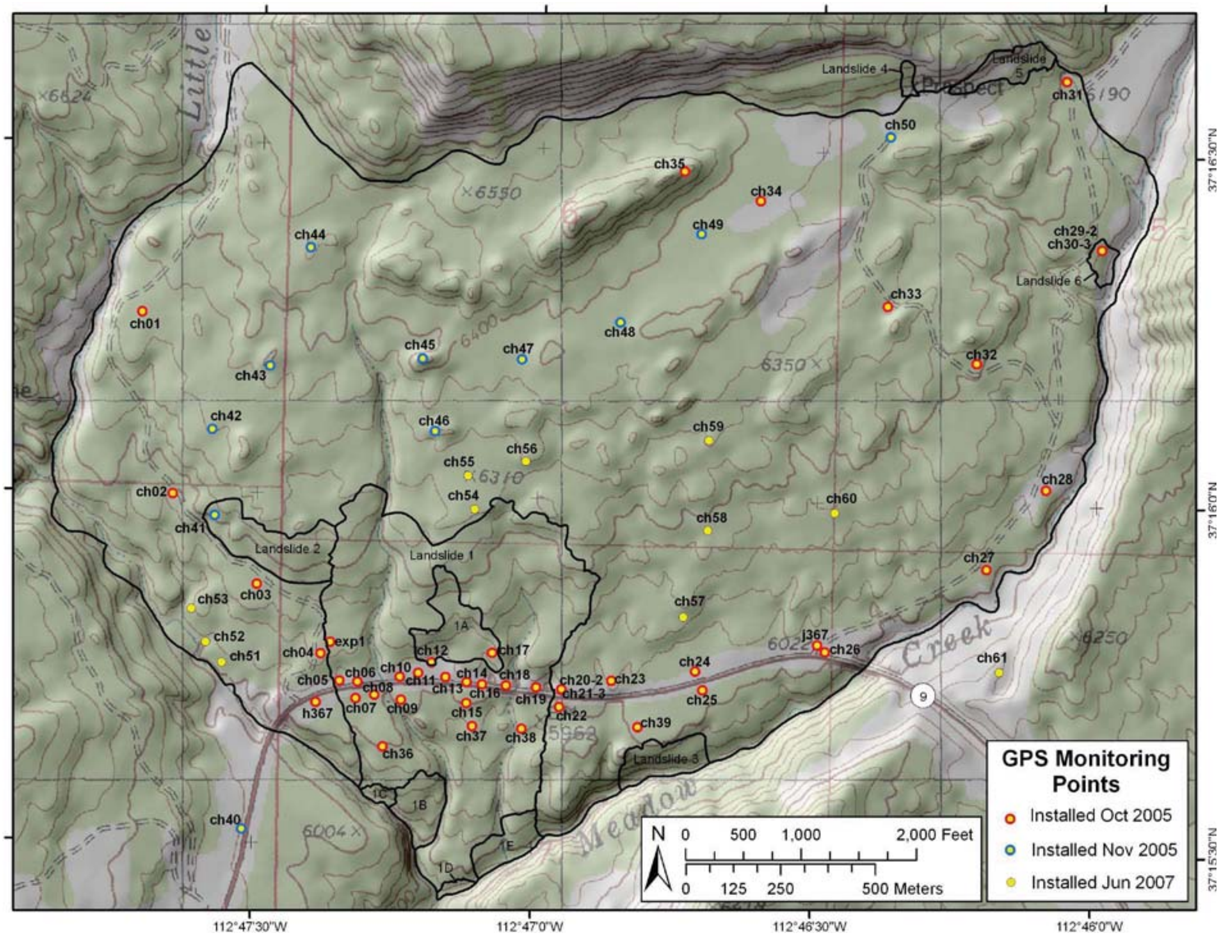


***Figure 13.** Locations and installation dates of survey points used to monitor movement of the Meadow Creek landslide using a survey-grade Global Positioning System (GPS) instrument. Survey point ch40 is an off-slide survey point. Survey point ch61 was installed in June 2007 to monitor movement of the Coal Hill landslide, which was inactive between June 2007 and October 2008.*

the SR-9 alignment. A second objective was to assess the state of activity of the entire Meadow Creek landslide, in part to evaluate the feasibility of an alternate highway route around landslide 1. In addition, we monitored movement of two other mapped historical slides (landslides 2 and 6) in the Meadow Creek landslide; these landslides were selected primarily based on easy access along graded roads. Movement of landslides 3, 4, and 5 was not monitored due to access difficulty and safety concerns for the survey crew related to slope steepness and intense ground deformation.

Documented Historical Movement

Previous researchers have documented episodic movement of several of the landslides in the Coal Hill landslide complex, and provided descriptions suggesting possible continuous movement of parts of two slides. Stouffer (1964) inferred intermittent (or episodic) movement of the Coal Hill landslide and upper Burning Coal landslide based on historical accounts, review of aerial photographs, limited fieldwork, and a short period of monitoring of the toe of the Coal Hill slide that showed no movement between September 1962 and April 1963. Stouffer's (1964) use of the term "creep" to describe movement of the lower parts of the Burning Coal and Meadow Creek landslides suggests very slow, continuous movement. This inference is supported by reports by State Road Commission (the predecessor to the Utah Department of Transportation) staff (Stouffer, 1964) of a few inches of creeping movement per year in the Meadow Creek landslide where crossed by former SR-15. One shortcoming in Stouffer's (1964) assessment of the nature of movement of the Coal Hill landslide is his reliance on reports of "no significant movement," which do not preclude very slow, continuous movement. A review of aerial photographs dated 1960 and 1967, a time period spanning Stouffer's fieldwork in 1962-63, shows movement of landslide 1 and the Coal Hill and Burning Coal landslides sometime during those seven years. Doelling and Davis (1989) also documented movement of landslide 1 between 1983 and 1986, but did not specifically describe the nature of the movement. A photograph in Heppler (2004) shows recent road repair near the east-flank shear zone of landslide 1 in 2004, suggesting at least minor recent movement during the dry period prior to the 2005 wet year. Thus, seasonal movement (coincident with or immediately following each year's snowmelt) may have been occurring even in the dry years of the early 2000s.

Movement of the Meadow Creek Landslide

Movement of the southern half of the Meadow Creek landslide, including the part crossed by SR-9, was detected during the measurement period (October 2005 through October 2008), and the most movement occurred within the boundaries of landslide 1, where we measured a maximum horizontal displacement of about 64 inches (163 cm) (figure 14). Outside of the mapped boundaries of landslide 1, movement along SR-9 ranged from 6 to 10 inches (15-25 cm) during the same period. Interestingly, the most movement (greater than 9 inches [>23 cm] at four survey points) along the highway outside of landslide 1 occurred upslope of landslide 3. Stouffer (1964) mapped this active part of the slide, including part of landslide 1, as the "creep zone" and reported minor displacement, typically a few inches per year, of former SR-15. We detected no movement along the eastern and western edges of the Meadow Creek landslide, upslope of the intersection of SR-9 and Meadow Creek and along Coal Mine Road north of landslide 2, respectively. However, we measured between about 3 to 7 inches (8-18 cm) of movement (over a 16-month measurement period between June 2007 and October 2008), directly upslope of the mapped boundaries of landslide 1 in the upper part of the Meadow Creek slide. At a survey point about 750 feet (230 m) upslope of the main scarp of landslide 1, installed in November 2005, we measured about 6 inches (15 cm) of movement. The amount of movement between June 2007 and October 2008 along a general longitudinal and south-southeast trend, directly upslope of the main scarp of landslide 1, increased in a downslope direction, from about 2 to 7 inches (5-18 cm). The data suggest either that landslide 1 is contained in the slower moving active part of the Meadow Creek landslide, the possibility of incipient upslope enlargement of landslide 1, or both. The western boundary of the upslope active area appears to be the unnamed, ephemeral, south-flowing drainage that transects the western part of the Meadow Creek landslide and landslide 1. No movement was detected elsewhere in the upper part of the Meadow Creek landslide. We measured about 3.5 inches (9 cm) of movement of landslide 2 between November 2005 and October 2008, but landslide 6 was inactive during the entire measurement period.

State of Activity of the Entire Meadow Creek Landslide

Our movement monitoring results through October 2008 (a measurement period spanning a maximum of three years) did not detect movement of the entire Meadow Creek landslide, but such movement cannot be entirely ruled out. Based on the spatial distribution of our survey points, we estimate that the active part of the slide extends upslope to approximately elevation 6360 feet. The eastern and western boundaries of the active part of the landslide are somewhat uncertain. The eastern boundary is possibly an unnamed drainage between survey points ch27 and ch60 (figure 13) and the western boundary extends to the westernmost limit of landslide 2, but does not include the lowermost slope directly below landslide 2 along Little Meadow Creek (in the vicinity of survey points ch51 through ch53). An unnamed tributary drainage directly west of Coal Mine Road, and south of landslide 2 may define the southwestern boundary of the active slide as indicated by active lateral shear cracks in a ridge along the east side of the drainage.

Movement in the apparently inactive part of the landslide may be occurring at an extremely slow rate (Cruden and Varnes, 1996) not possible to detect over the measurement period. If the average movement rate in the upper part of the Meadow Creek landslide was less than 0.6 inch per year (<1.6 cm/yr) (the upper limit of an extremely slow rate of movement) then the total maximum movement during the three-year measurement period would have been about 1.8 inches (5 cm) and slightly above the detection threshold of the movement monitoring technique. Future landslide movement monitoring will eventually better define the state of activity of the upper part of the landslide.

Movement of Landslide 1

During the measurement period, the largest and most damaging movement occurred in landslide 1. The maximum total movement of landslide 1 was over six times greater than the maximum total movement in the southern part of the Meadow Creek landslide. However, the relative changes in the rate of movement over the measurement period were generally similar in both landslides.

The total movement of landslide 1 between October 2005 and October 2008 ranged from about 24 to 64 inches (61-163 cm), varying incrementally across the width of the slide (figure 14) with the largest movement in the east-central part. The total movement decreases toward the flanks of the landslide resulting in a generally bow-shaped pattern of movement across the width of the slide. Figure 15 shows the displacement pattern across the width of landslide 1 for the period between October 2005 and June 2007. Both figures 14 and 15 show that the largest movement was in the area directly downslope of landslide 1A between the major internal right-lateral shear zone and the east-flank shear zone. The movement vectors of points in the western part of landslide 1 converge slightly with those in the central and eastern part. The major internal right-lateral shear zone appears to be the boundary between these two movement areas. West of the internal right-lateral shear zone the movement amounts are more uniform, decreasing slightly toward the west-flank shear zone. Movement amounts appear to be relatively uniform upslope and downslope of SR-9 within the slide, but the maximum distance between survey points bracketing the highway corridor that includes SR-9 and abandoned SR-15 is only about 1000 feet (300 m). Thus, the apparent relatively uniform movement along the length of the landslide may be due to the short distances between survey points that span, at a maximum, less than a third of the total length of the slide.

Changes in Average Movement Rates

The average movement rates of survey points in the Meadow Creek landslide and landslides 1 and 2 gradually decreased during the first two years of the measurement period likely as a result of declining ground-water levels with a return of dry conditions in the two years following the 2005 wet year (figure 16). At the Harris Flat and Long Valley Junction SNOTEL sites north of the landslide, the snow water equivalent of the winter snowpack was significantly below normal in the 2006 and 2007 water years, ranging from 24 to 52 percent of normal. Figure 17 shows an increase in the average rate of movement subsequent to the wet winter during the 2008 water year. Interestingly, in the shallow western part of landslide 2, the average rate of movement increased only in the second half of the year, possibly after a period during which movement had suspended or dropped to an extremely slow rate between June 2007 and July 2008.

Persistent Movement of Landslides in the Complex

Our movement monitoring results and field observations, in addition to historical accounts of landslide movement (Stouffer, 1964; Doelling and Davis, 1989), indicate that most of the landslides in the Coal Hill landslide complex have at least a decades-long history of persistent movement. Stouffer (1964) described minor displacement of

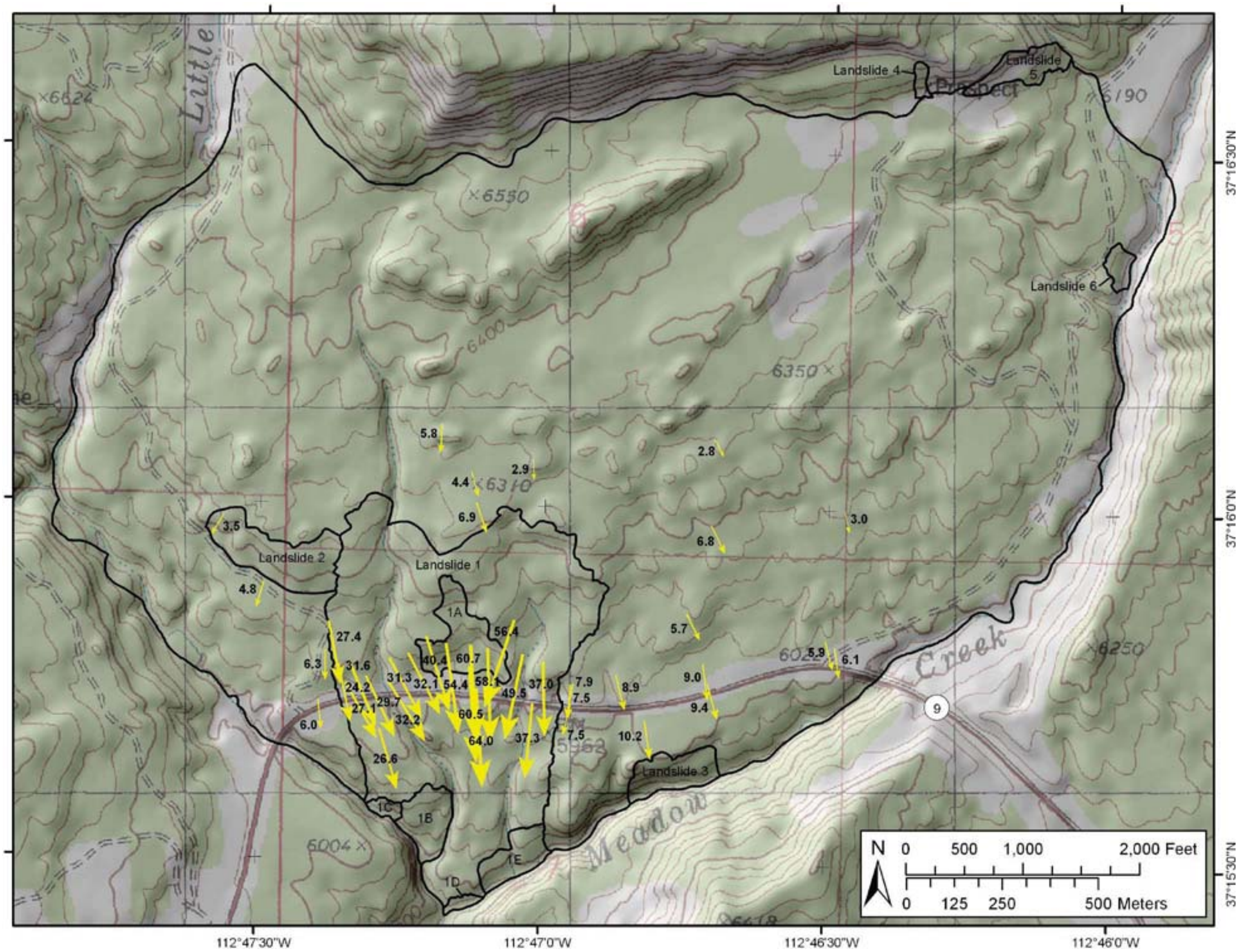


Figure 14. *Movement of the Meadow Creek landslide between the initial survey date (see figure 13) and October 2008. Most of the survey points along State Route 9 were installed in October 2005. Arrows show movement direction. Movement amounts in inches.*

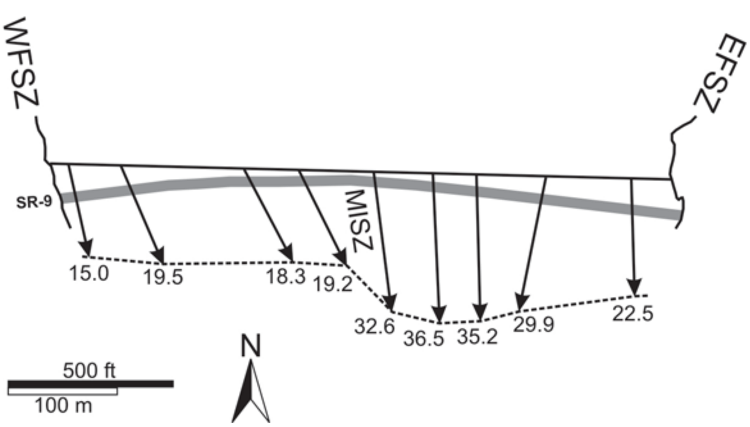


Figure 15. *Variation in displacement across landslide 1. Figure shows the horizontal displacement (inches) of a hypothetical straight line across the slide during the measurement period (October 2005 to June 2007). Displacement has a generally bow-shaped pattern (in plan view) increasing toward the right center of the slide from both flanks. A significant step in displacement occurs across the main internal shear zone (MISZ). Parts of east- and west-flank shear zones (EFSZ, WFSZ) and SR-9 shown.*

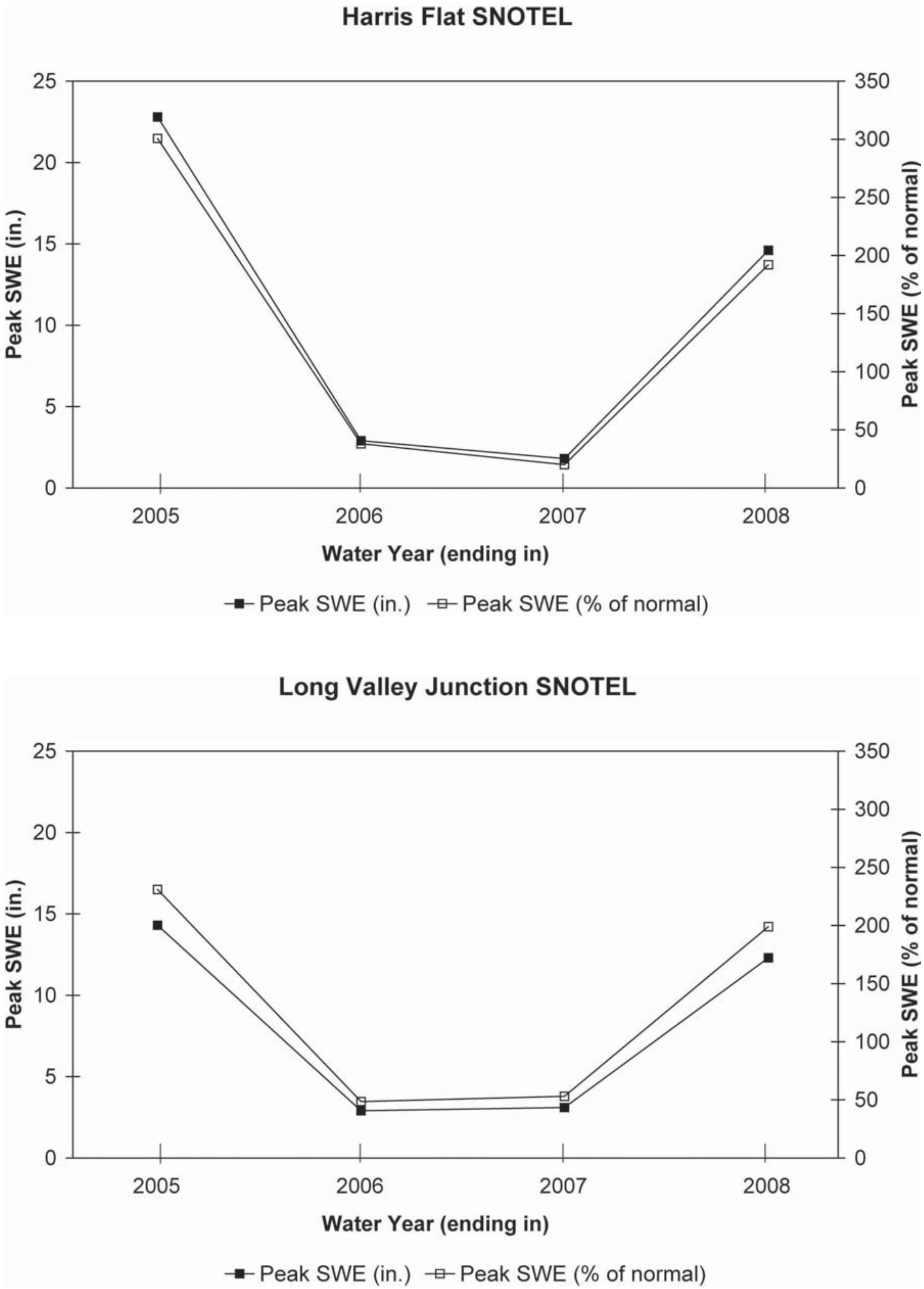
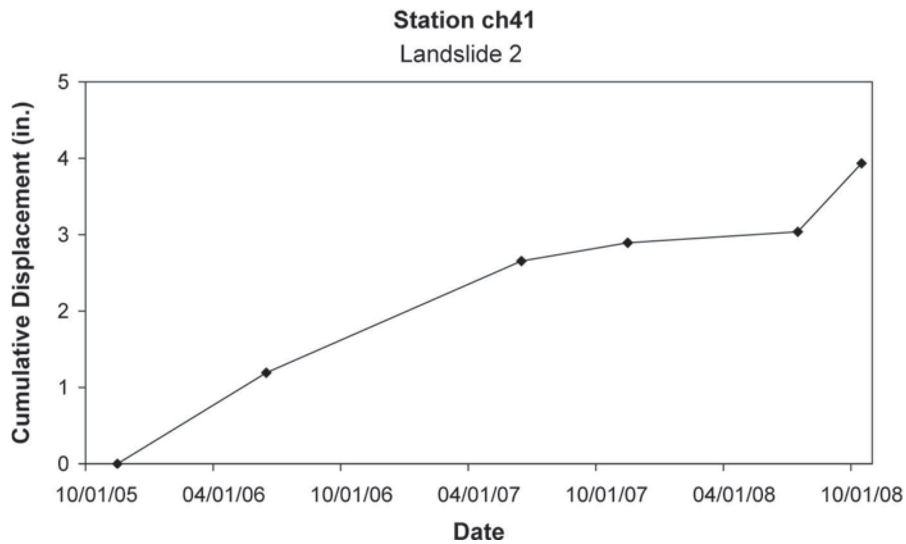
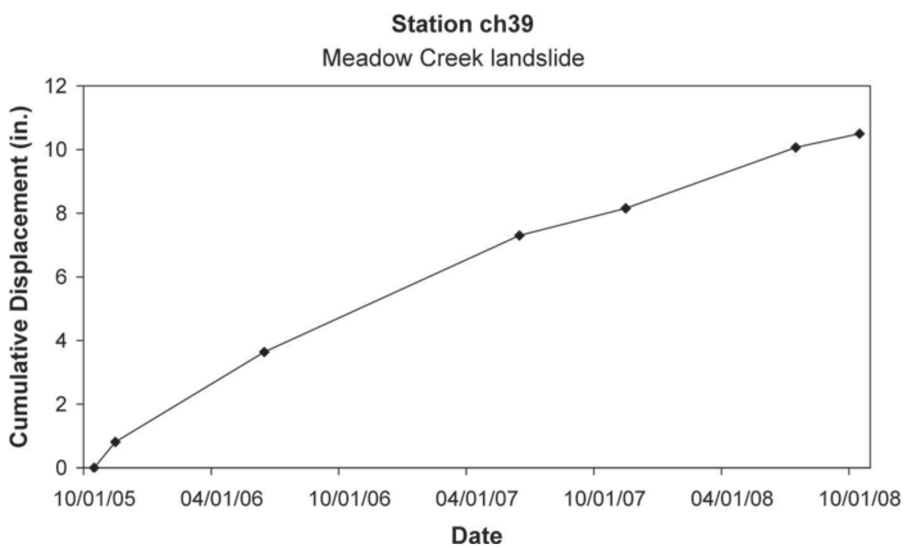


Figure 16. *Comparison of peak snow water equivalent (SWE) of snowpack at two nearest SNOTEL stations to the Meadow Creek landslide for the 2005 through 2008 water years.*





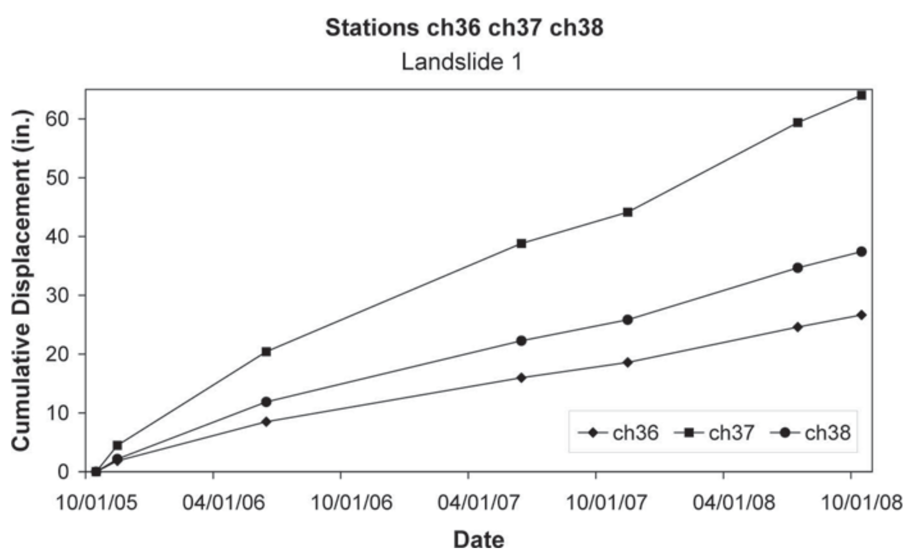


Figure 17. *Plots showing cumulative movement of selected survey points on the Meadow Creek landslide and landslides 1 and 2. The average rate of movement of all three landslides decreased in the dry years of 2006 and 2007, but increased following the wet winter in the 2008 water year (see figure 16).*

former SR-15 in the "creep zone" portion of the Meadow Creek landslide, where our monitoring detected movement at a very slow rate between October 2005 and October 2008. Thus, movement of the southern part of the landslide has persisted, at least episodically, over the past four decades. The activity of smaller landslides along Meadow Creek, including landslide 1B, 1E, and 3, which Stouffer (1964) identified as active in the early 1960s, has also spanned over four decades. Our review of aerial photographs dating from the 1960s showed damage to former SR-15 along the flanks of landslide 1. This, in addition to the similar damage in the early 1980s (Doelling and Davis, 1989) and the movement and resulting damage between 2005 and 2007 (Ashland and others, 2009), identifies landslide 1 as being persistently active for over four decades. Reconnaissance in May 2007 of the Burning Coal landslide, a landslide that may have originated in the past 70 years (post-1938; Stouffer, 1964), also showed evidence for recent activity. In contrast, our field observations and movement monitoring results indicated that landslides 4 and 6 are examples of currently dormant slides.

RECURRENT HIGHWAY DAMAGE

Recurrent, but localized, road damage has occurred along SR-9 and abandoned SR-15 where the highways cross the southern part of the Meadow Creek landslide. Stouffer (1964) documented that SR-15 moved several inches per year toward Meadow Creek and noted that most of the movement occurred during the spring following snowmelt. Doelling and Davis (1989) measured 16-foot and 20-foot (5-m and 6-m) total offsets of abandoned SR-15 along the shear faults bounding landslide 1 on July 23, 1985. These measurements indicate an average annual rate of movement of between 9.1 and 11.4 inches per year (23-29 cm/yr). However, Doelling and Davis (1989) also indicated that movement amounts and road damage were greater during wet years such as 1983, when landslide 1 moved several feet. Doelling and Davis (1989) also documented that SR-9 was regraded and resurfaced in the spring of 1985, at a cost of about $150,000, but by September 10, 1985, the road was offset 1 inch and 1/2 inch (2 and 1 cm) on the west and east boundaries of landslide 1, respectively. By the summer of 1986, offset of the highway exceeded 1 foot (30 cm). Damage to the abandoned SR-15 box culvert in Little Meadow Creek resulted from historical movement downslope of landslide 2 along the southwest edge of the Meadow Creek landslide.

During our investigation, SR-9 was repeatedly repaired only to be recurrently damaged by persistent landslide movement between October 2005 and October 2008. The most severe damage to the highway occurred along longitudinal lateral shear zones that either bound or are internal to landslide 1 (figure 18). These structures accommodate differential rates of movement up to a factor of five. Damage to SR-9 along the west-flank shear zone of landslide 1 results from mostly ground-parallel right-lateral shear that forms left-stepping road cracks and discontinuous, zone-parallel, through-going shear fractures (figure 18A). Most of the damage between the west-flank shear zone and a major internal right-lateral shear zone results from similar ground-parallel right-lateral and locally left-lateral shear on discrete structures. Damage along the east-flank shear zone results from a combination of left-lateral shear and vertical movement (figure 18B).

FUTURE HAZARD TO STATE ROUTE 9

To date, the most movement in a single year has only been "several feet" (Doelling and Davis, 1989) consistent with the average maximum annual movement of landslide 1 of about 22.5 inches (57 cm) (this study); and has been dealt with primarily by frequent road repair (patching) of the highway surface. However, future, large-displacement movement of landslide 1 cannot be ruled out. Such large-displacement movement of large, clay-rich landslides has occurred elsewhere in central and northern Utah (Fleming and others, 1978; Duncan and others, 1986; Ashland, 2003). In southern Utah, earthquake-induced historical landsliding has resulted in moderate movement

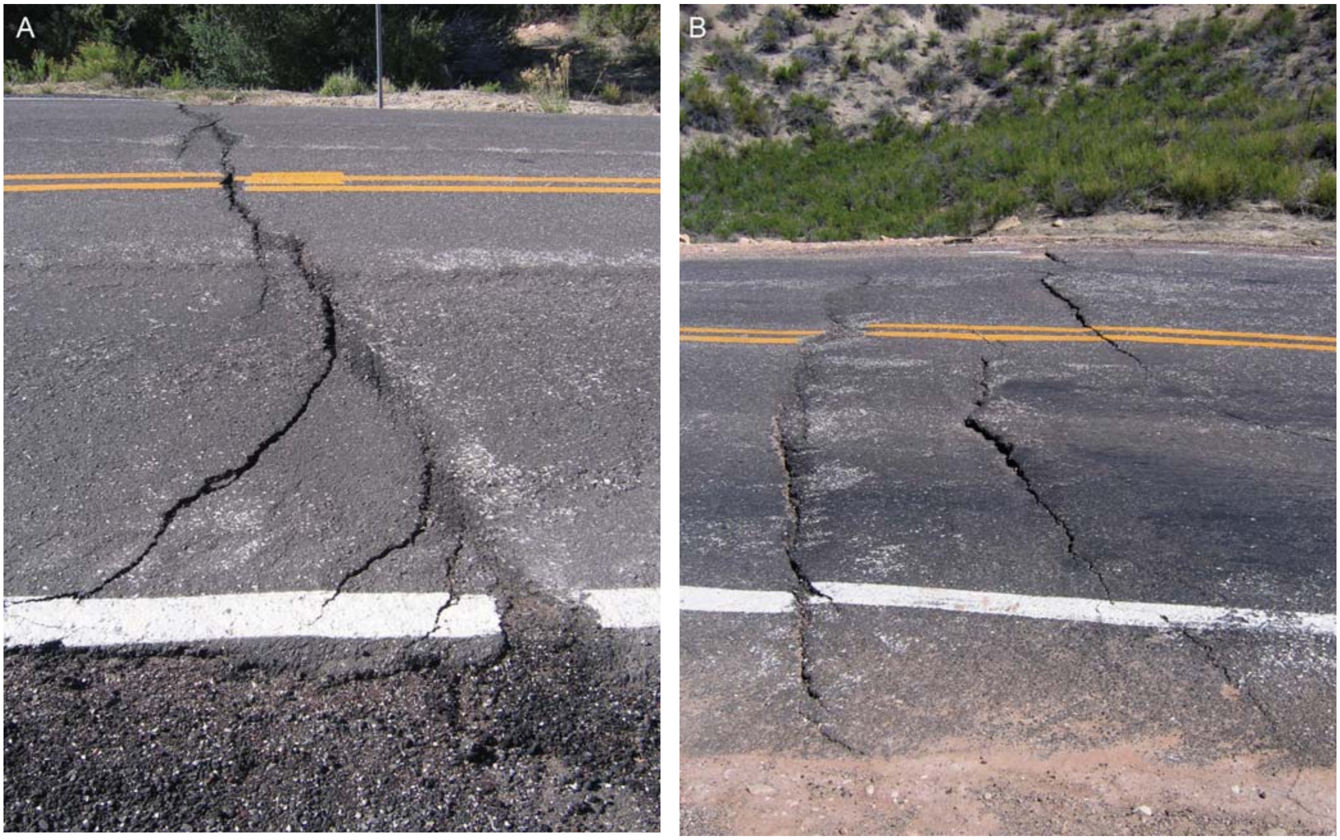


Figure 18. *Examples of damage to State Route 9 localized to shear zones that bound landslide 1. A) Left-stepping (diagonal cracks) merging into a nearly continuous right-lateral shear fracture along the west-flank shear zone. B) View upslope of parallel road cracks along the east-flank shear zone. Vertical offset accompanies left-lateral movement. Both photographs taken in May 2007.*

(tens of feet), which initiated in a matter of minutes, and that caused intense ground deformation (Jibson and Harp, 1996). The encroachment of landslide 1A onto the highway may result from future large-displacement movement. Whereas the absence of large-displacement movement during the nearly 80-year record of the two highways (SR-9 and SR-15) may suggest a low probability for such movement, some case histories indicate otherwise. In 1997, the reactivation of the Shurtz Lake landslide resulted in tens of feet of displacement of power-line transmission poles that had not moved, at least significantly, in the previous 70 years (Ashland, 2003).

SECONDARY HAZARDS

Secondary hazards on the Meadow Creek landslide fall into two categories: hazards related to the main-scarp escarpment or to piping. Escarpment related hazards include rock falls and debris flows. During our fieldwork in the fall of 2005, we observed ongoing rock fall and recent debris-flow deposits associated with active landslide 5 in the eastern part of the escarpment. Piping has resulted in numerous sinkholes particularly along minor scarps and transverse ground cracks. Seepage points at the base of minor scarps directly downslope of sinkholes, suggest that piping results from local, steep ground-water gradients and concentrated infiltration of runoff and snowmelt along scarps and ground cracks.

SUMMARY

Field investigations and movement monitoring using a survey-grade GPS instrument revealed persistent movement of the southern part of the Meadow Creek landslide. The active part of the landslide is gently to moderately sloping, and underlain by heterogeneous debris derived from the Cretaceous Dakota and Cedar Mountain Formations, but extends upslope into the mostly inactive, gently sloping upper part of the slide underlain by displaced and back-rotated rock blocks. Field observations and mapping suggest that the basal surface of rupture and thrusts in the lowermost slide are likely formed in bentonitic mudstone in the Cedar Mountain Formation and mudstone in the Dakota Formation and consist of weak, low permeability clay gouge. The results of movement monitoring between October 2005 and October 2008, indicate the maximum total movement of historical landslide 1 in the southwestern part of the Meadow Creek landslide ranged from about 24 to 64 inches (61-163 cm) and was greatest in the center of the slide east of a major internal right-lateral shear zone. Movement of the adjacent southern part of the Meadow Creek landslide ranged from about 6 to 10 inches (15-26 cm) and was greatest directly upslope of historical landslide 3. Movement continued in 2006 and 2007 despite a return to dry conditions, during which the average movement rates decreased. A wet winter in the 2008 water year resulted in an increase in the average rate of movement in 2008. Persistent movement of the landslide has resulted in recurrent damage to SR-9, requiring continual repair. Most of the damage is localized to the lateral shear zones that bound or are internal to landslide 1, and limited damage to the highway has occurred in the slower, more uniformly moving adjacent part of the Meadow Creek landslide. Historically, highway damage has been limited to annual movement amounts of only several feet or less, but larger movement amounts cannot be ruled out, based on case histories of other landslides in Utah. Secondary hazards on the Meadow Creek landslide are related to either the main-scarp escarpment or to piping, and include rock falls, debris flows, and sinkholes.

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