Landslides
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Ferguson rock slide buries California State Highway near Yosemite National Park

Abstract During spring 2006, talus from the toe area of a rock-block slide of about 800,000 m^3 buried California State Highway 140, one of the main routes into heavily-visited Yosemite National Park, USA. Closure of the highway for 92 days caused business losses of about 4.8 million USD. The rock slide, composed of slate and phyllite, moved slowly downslope from April to June 2006, creating a fresh head scarp with 9–12 m of displacement. Movement of the main rock slide, a re-activation of an older slide, was triggered by an exceptionally wet spring 2006, following a very wet spring 2005. As of autumn 2006, most of the main slide appeared to be at rest, although rocks occasionally continued to fall from steep, fractured rock masses at the toe area of the slide. Future behavior of the slide is difficult to predict, but possible scenarios range from continued scattered rock fall to complete rapid failure of the entire mass. Although unlikely except under very destabilizing circumstances, a worst-case, rapid failure of the entire rock slide could extend across the Merced River, damming the river and creating a reservoir. As a temporary measure, traffic has been rerouted to the opposite side of the Merced River at about the same elevation as the buried section of Highway 140. A state-of-the-art monitoring system has been installed to detect movement in the steep talus slope, movement of the main slide mass, local strong ground motion from regional earthquakes, and sudden changes in stream levels, possibly indicating damming of the river by slide material.

Keywords Rock slide · Yosemite National Park · Monitoring · GPS data · Hazard

Introduction

A wide range of rock falls and rock slides, originating in both plutonic and metamorphic rocks, sculpt the Sierra Nevada Mountains of California, USA. Massive slope movements have been triggered by rainfall, increased groundwater levels, and earthquake shaking (Harp et al. 1984; Wieczorek 2002). Yosemite National Park, a UNESCO (United Nations Educational Scientific and Cultural Organization) World Heritage Site of immense granitic cliffs visited by about 4 million people each year, has been the location of numerous rock falls and slides. Some of these have resulted in fatalities, damage to property, and road closures (Wieczorek et. al. 1992, 2000). During the wet spring of 2006, a large rock slide reactivated the upslope of California Highway 140, about 10 km west of Yosemite National Park (Fig. 1). Talus from the toe of the slide, locally known as the Ferguson Rock Slide, completely buried the highway, necessitating temporary rerouting of the roadway to the opposite side of the steep-walled Merced River Canyon. The talus also encroached about 10 m into the river channel.

Because Highway 140 is one of three year-round routes into Yosemite National Park and the only one without tunnels that is not significantly affected by winter snow, there is widespread concern about future movement of the approximately 800,000-m^3 slide mass. Normally, the highway accommodates about 800,000 vehicles per year. During the 92 days in 2006 when the highway was completely closed, the nearby city of Mariposa sustained losses in tax and business community revenue of about 4.8 million USD (Rick Benson, Mariposa County Administrator, personal communication, 2007), traffic congestion increased on other routes to Yosemite National Park, and local residents and school children endured greatly lengthened commutes. Moreover, future downslope movement of a large part of the slide mass could potentially impact the highway realignment and dam or alter the Merced River, a designated National Wild and Scenic River. A potential rock-slide dam could pose additional hazards from inundation of upstream infrastructure, homes, and businesses and downstream flooding of campgrounds, roads, and other facilities should such a dam breach rapidly. Here, we review documented nearby large slides in the Sierra Nevada Mountains, describe the Ferguson Rock Slide reactivated in the spring of 2006, discuss the continuing hazards posed by this slide, and present a brief overview of mitigation and monitoring efforts.

Nearby large slides in the Sierra Nevada Mountains

Compared to some mountain ranges elsewhere in the world, such as the European Alps or the Himalayas, the Sierra Nevada Mountains generate relatively infrequent massive rock slides. Nevertheless, there have been a number of recent large slides in and near Yosemite (Fig. 1), similar in size to the Ferguson Rock Slide. These slides have had severe impacts on people, communities, and infrastructure (Table 1). Some large failures, both historic and prehistoric, have created landslide dams in adjoining steep river canyons. Some of these dams failed rapidly and catastrophically, others created long-lived impoundments.

Ferguson Rock Slide

During the wetter-than-average spring of 2006, talus from the toe of the Ferguson Rock Slide, located in the central Sierra Nevada foothills, completely blocked California State Highway 140 (Figs. 1 and 2). The activity of the slide was first noticed on April 25, 2006, as a few scattered rocks rolled onto Highway 140. At that time, surficial displacement of soil and rock produced a distinct track extending from the road to its origin 60 to 70 m upslope. This initial surficial sliding announced the eventual reactivation, over the next few months, of the entire rock-slide complex, having a volume of about 800,000 m^3. Rock-fall activity from the toe of the slide accelerated in late May 2006, destroying recently emplaced road barriers and rock-fall protection fencing, burying the entire roadway, and extending about 10 m into the Merced River. Rock-fall activity was greatest during late May and early June; it then decreased substantially over the summer. The main slide mass appears to be a reactivation of an older rock slide; the older

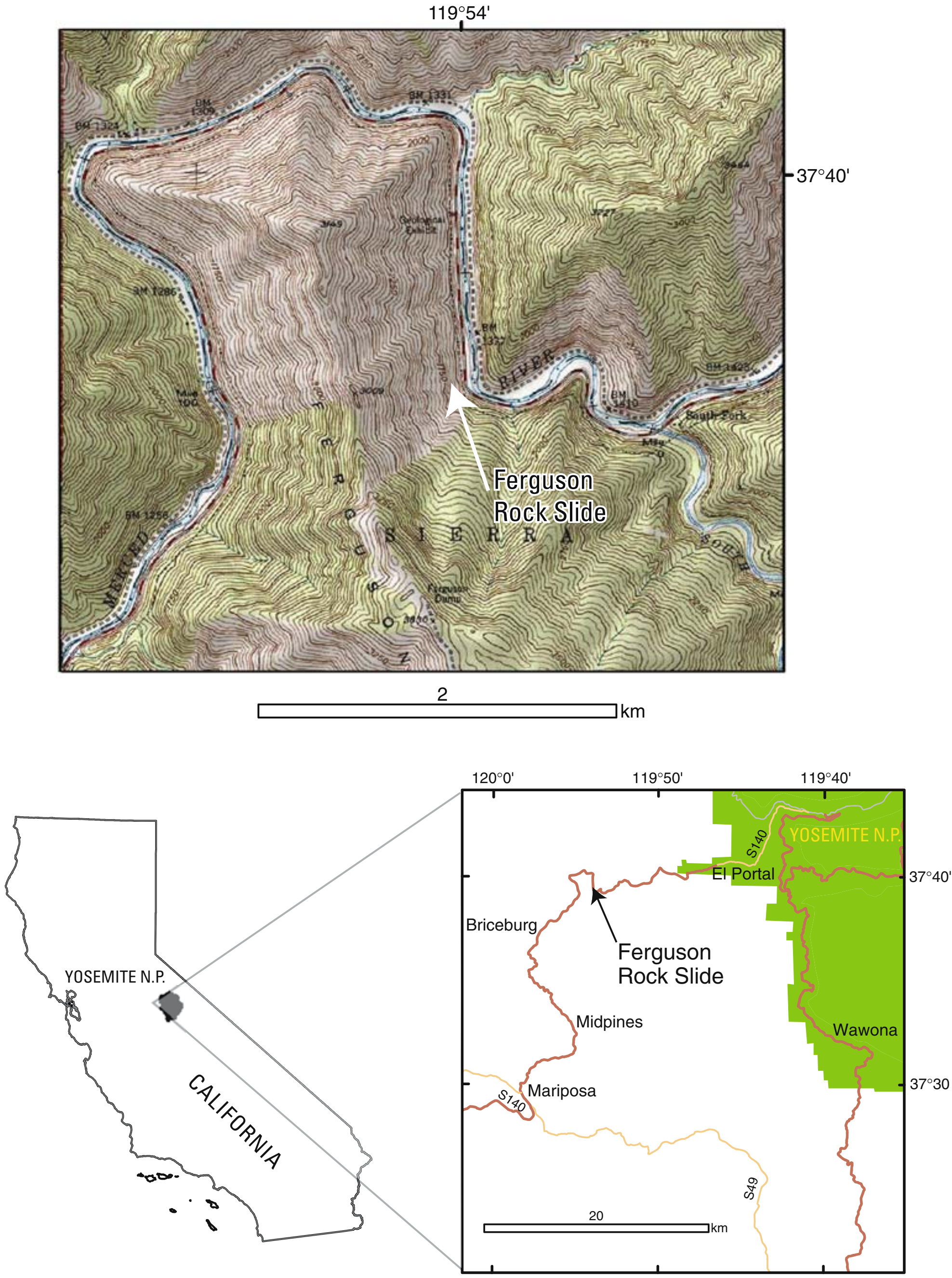

Fig. 1 Location maps showing the position of the Ferguson Rock Slide at regional and local scales

headscarp varies from 45 to 75 m in height. Review of available aerial photography from 1944 to the present shows no evidence of significant pre-2006 movement on this feature.

The main slide complex emanates from a steep slope (38°–45°) in metamorphic slate, phyllite, and chert of the Phyllite and Chert of Hite Cove (Bateman and Krauskopf 1987). The overall dimensions are approximately 244 m in length at its midsection, 187 m wide at its widest extent, and 30–40 m deep (Gallegos and DeGraff 2006), although the depth to the failure surface is not well-known and may be highly variable. The main mass is a rock-block slide with numerous internal slumps below the headscarp. Movement of the main body of the slide mass appears to be primarily translational. Recent motion on the older main head-scarp (Fig. 3) is about 9–12 m. Approximately 50 m downslope from the reactivated headscarp is an area of multiple internal scarps (Fig. 2). Immediately downslope of this area, the surface steepens from approximately 35°–40° to greater than 50°. This area is the source of most of the rock fall that forms the talus slope that has buried the highway and extended into the river. This steep rock-fall source area may reflect a local steepening of the basal failure surface. The distal portion of the landslide is a steep (~42°) talus slope of about 100 m length (Fig. 2). Talus fragments are coarse and range between gravel and pebble sizes to boulders larger than cars. Fragment shape is typically bladed prismatic and highly angular.

The basal shear surface of the rock slide appears to toe out below the steep, disrupted rocks at the head of the talus slope but also appears to extend farther downslope to near the bottom of the slope as if its dip steepens in the direction of the toe (see Fig. 2). The right side (looking downslope) of the slide toe has shed enough rock debris recently to exhume what appears to be a shear surface in this area.

Table 1 Other large slides in the Sierra Nevada Range

Landslide	Location and date	Size and material	Impact
Sourgrass Debris Flow (DeGraff 2001)	Stanislaus National Forest North Fork Stanislaus River; Jan. 1, 1997	190,000 m^3, glacial till overlying volcanic mudflow breccia	Destroyed electric transmission line, bridge, and telephone cable; dammed Stanislaus River for several hours; deposit reduced capacity of McKay reservoir
Glacier Point Rock Fall (Morrisey et al. 1999)	Yosemite National Park, Glacier Point, July 10, 1996	23,000–38,000 m^3, granitic intrusive	Air blast destroyed 1,000 trees, one fatality, several injuries
Mill Creek Landslide (Sydnor 1997)	Village of White Hall in El Dorado County., California, near US Highway 50; Jan. 24, 1997	1.5×106 m^3; colluvium overlying mafic plutonic rocks	Destroyed three cabins and dammed the South Fork American river for 17 h; closed US Highway 50 for 27 days.
US Highway 50 Landslide (Kuehn and Bedrossian 1987)	White Hall in El Dorado County, California, near US Highway 50; April 9, 1983	765,000 m^3; granitic rocks	Dammed the South Fork American River for 6 h and closed Highway 50 for 75 days; canal for irrigation and electric power disrupted; several houses submerged by lake
Slide Mountain Rock Slide (Bronson and Watters 1987; Huber et al. 1989)	Yosemite National Park, Piute Creek; prehistoric	1.9×10^6 m^3; quartz monzonite	Dammed Piute Creek in northern Yosemite National Park, marshy meadow remains
Tiltill Creek Rock Slide (Wieczorek 2002)	Yosemite National Park; prehistoric	1.9×10^6 m^3; granitic intrusive rocks	Dammed Tiltill Creek in northern Yosemite National Park; small lake remains
Mirror Lake Rock Fall (Wieczorek and Jager 1996)	Yosemite National Park; prehistoric	11.4×10^6 m^3; granodiorite	Dammed Tenaya Creek forming a lake, marshy meadow remains
Kaweah River Rock Avalanche (Costa and Schuster 1991)	Kings Canyon National Park, South Fork of Kaweah River; December 1867	445,000 m^3; granitic rock and sandy loam	Dammed Kaweah River for 25 h, dam failed sending water, timber, and rocky debris 68 km downstream into town of Visalia, California

Sheared slide material resting over intact bedrock is clearly visible on the lower right margin of the slide (Fig. 4). Where the basal failure surface is exposed in the lower right section of the rock-slide toe (Fig. 4), it is parallel to an intact rock-bedding or joint surface dipping at approximately 50° toward the Merced River. The left side of the slide toe is the area where rock fall was first noticed in April 2006. This part of the slide mass may be a separate rock slide as evidenced by the scarp at its head (Fig. 2).

Fig. 2 Oblique aerial photograph of Ferguson Rock Slide. *Dashed yellow lines* indicate extent of the rock slide based on visual inspection. Rock-fall source area, talus, new scarps, and locations of GPS instruments are indicated. Photo taken on June 13th, 2006

The main rock slide was likely reactivated by elevated pore-water pressures due to a very wet 2006 spring in the central Sierra Nevada foothills, following a wet 2005 spring. Precipitation in this area typically occurs in the winter and spring months (from October through May) with relatively dry summer and fall seasons. The nearest rain gauge to the slide is located about 7 km downstream at Briceburg. At this gauge, 1,246 mm of precipitation fell during the 2004/2005 season and 985 mm fell in the 2005/2006 season (California Water Resources Data Exchange Center). Because the Briceburg rain gauge has only existed since 1999, no long-term monthly or annual mean precipitation amounts are available for this station. The rain gauge at Mariposa, California, 19.5 km from the rock slide and 12.5 km from the Briceburg site has similar precipitation levels as the Briceburg site for the two seasons mentioned above. The Mariposa gauge has existed since 1931, and monthly mean precipitation levels for this station are shown for comparison with the two wet seasons at the Briceburg gauge (Fig. 5a). Yearly totals for the Mariposa gauge, using a water year (WY) of May 1–April 30, are shown in Fig. 3b, the long-term mean annual precipitation is about 760 mm. We use this water year because slide movement began near the end of April. As shown in Fig. 3a, monthly precipitation for March and April 2006, just prior to rock-slide movement, was well above the long-term mean. Both 2005 and 2006 were wet years, although other years were wetter. The two-year moving average for WY 2005–2006 is near, but slightly below, the maximum on record (Fig. 5b).

Continuing hazard

By autumn 2006, the main body of the rock-slide mass was essentially stationary, based on observations from helicopter and on foot, repeat surveying of temporary monuments on the slide, and high-precision Global Positioning System (GPS) measurements on the slide (see following section). However, some large blocks downslope of the main mass, in the rock-fall source area, continued to move downslope at about 1.5 cm/day into the winter of 2006–2007. Occasional rock fall from the toe continued to build the extensive talus slope.

Fig. 3 Fresh displacement on older headscarp of Ferguson Rock Slide (*arrows*)

Future behavior of the slide is difficult to predict. Past movement patterns provide some insight. Because the slide appears to be a reactivation of a pre-existing older rock slide, there is evidence for past movement without complete, rapid movement of the entire mass. The Merced River channel downslope of the slide has abundant rapids and boulders, indicating past rock fall into the river. However, there is no obvious evidence that past rock fall has reached the opposite bank of the river. This may or may not be a good predictor of future movement. The original landslide resulted from conditions that caused movement in a previously stable rock slope. The current movement is on a pre-existing, now weakened, failure surface within the rock slope. Moreover, the time between the original failure and the current activity may have permitted weathering or other changes on the failure surface resulting in additional lowering of strength. Consequently, additional movement may act in a manner different from past movement. Another unknown is the degree to which the rockslide mass remained intact during the original movement. The current movement has created obvious differentiation within the rock-slide mass. Cronin (1992) describes how smaller secondary landslides can behave differently from an original large landslide. A variety of future slide movement scenarios is possible, depending on driving forces; these range from occasional rock fall from the oversteepened toe to rapid failure of a large block at the toe to complete, rapid failure of the entire slide mass. The uncertainty associated with these scenarios is a major reason for the concerted effort to monitor movement on the Ferguson Rock Slide.

In dry summer and autumn months, occasional rock fall from the oversteepened toe onto the talus slope is likely, whereas significant movement of the main mass is unlikely. Relatively dry winters may only result in continued rock fall. However, given a relatively wet winter and spring, increases in groundwater levels may induce renewed movement of the main slide mass. Slow movement of the slide will likely spawn abundant rock fall from the toe, as was observed in 2006. A surge in movement, due to transient elevated groundwater pressure, might precipitate failure of a large block from the steep toe upslope of the talus. Such a block might also fail without movement of the main mass, owing to locally elevated groundwater pressures. A worst-case scenario would be complete, rapid failure of the entire mass. Although this scenario appears unlikely based on past behavior, several exceptionally destabilizing conditions might provoke rapid movement in the future. Failure of a large block from the toe while the entire mass was slowly moving might debutress the main mass and lead to rapid retrogressive failure of the remainder of the slide mass. Alternatively, if the main mass was already moving, a moderate to large regional earthquake might trigger rapid movement.

The continuing hazards posed by these different movement scenarios also vary. Continued rock-fall activity onto the angle-of-repose talus slope would make removal of the talus from the buried Highway 140 roadway hazardous. The portion of the talus slope that extends into the Merced River has not been eroded by the river even though the flow was relatively high when the talus was first emplaced and flow is relatively rapid in this area because it is on the outside edge of a bend in the river. Failure of a large block from the toe would deposit additional rock in the river channel and might reach the opposite bank, depending on the volume of the rock mass, its degree of saturation, and the river level. Such rock emplaced in the river would modify local flow hydraulics and could locally increase bank erosion.

In the unlikely, worst-case scenario involving complete, rapid failure of most or all of rock-slide mass, it is possible that the Merced River would be dammed and the road grade on the opposite side of the Merced River (Incline Road) buried. This grade is a temporary alternate route for California State Highway 140. The rate of water-level rise in a reservoir upstream from the dam would depend on the flow of the river at that time. The size and shape of talus deposited from 2006 activity suggests that a blockage of the Merced River due to a rapid failure of the rock slide might result in an impounded reservoir which could remain for some time, even though some erosion would take place. Also, a rock-slide dam composed of slate and phyllite cobbles and boulders would be relatively permeable and would likely allow significant flow through the dam as well as over it. Because the rock slide generates large sizes of boulders, as observed in its talus slope, a catastrophic breach of a rapidly emplaced rock-slide dam would not be likely. Instead, an elevated pool of water upstream from such a dam might remain for a period of time, possibly years. Inhabitants living upstream from the rock-slide area are not numerous, but a few residents live close enough to the area that an inundation hazard exists for them depending on the water impoundment height of a rock-slide dam. Below the rock-slide area, there is only one residence along the river for 30 km downstream. At 30 km downstream, the river flows into Lake McClure reservoir.

Fig. 4 Basal shear surface of Ferguson Rock Slide underlying fractured and sheared rock and talus. Note electrical transmission tower in *upper left corner* of photo for scale

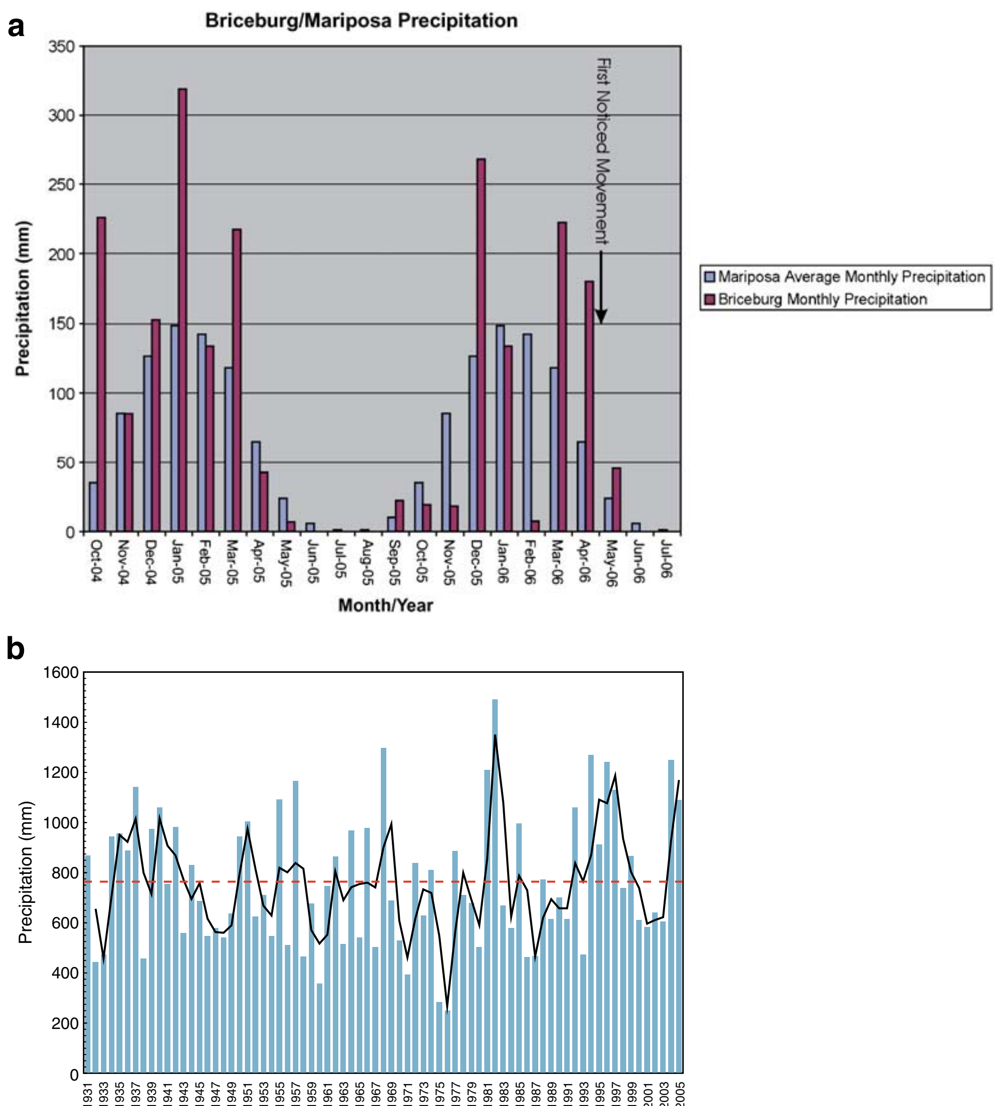

Fig. 5 **a** Rainfall at Briceburg rain gauge near Ferguson Rock Slide and comparison of monthly mean rainfall from Mariposa rain gauge, **b** Water-year (May 1–April 30) precipitation (*blue bars*) and two-year moving average (*black line*) for the Ferguson Rock Slide area. The mean WY precipitation for the 1931–2005 period is 760 m (*dashed horizontal line*)

Because of the uncertainty of the effects of a complete rapid failure of the entire slide mass or portions of the slide mass, numerical simulations of various scenarios in which all, or portions, of the slide fail were conducted (Denlinger 2007). These simulations, using granular flow mechanics, show that a weak failure mass can reach the opposite side of the Merced River and dam the river, in some scenarios. Simulated failure masses with stronger rocks modify the canyon geometry but do not completely dam the river.

Mitigation and monitoring efforts

Following the initial rock-fall activity in April 2006, a combination of concrete barriers and chain-link fence was deployed along the section of highway affected by rock fall. However, it soon became obvious that the rock fall was not just from scattered rock cliffs upslope of the highway, but was caused by a large rock-slide mass that threatened the entire width of the roadway. When the rock-fall activity accelerated on May 26, the barriers, fence, and the entire roadway were buried by the talus which eventually extended into the Merced River. After visits to the rock-slide site by geologists and engineers from the U.S. Forest Service (USFS), U.S. Geological Survey (USGS), California Department of Transportation (Caltrans), and private consultants, recommendations for a variety of monitoring instruments and systems were proposed for monitoring continued activity of the rock slide. In August 2006, Caltrans opened a temporary rerouting of Highway 140, pending further design of a more permanent solution. The detour involves two temporary bridges across the Merced River and a one-lane bypass, using the existing Incline Road on the opposite side of the river. This bypass is located at an elevation above the river similar to buried Highway 140. In a cooperative effort between the USFS, Caltrans, and the USGS, additional monitoring has been established at the rock-slide site to detect: (1) changes in the talus slope and rock-fall source area, (2) movement and potential acceleration of the main slide mass, (3) regional seismicity that might trigger accelerated movement, and (4) stream-level changes in the Merced River that might accompany rock fall into the river channel.

Rock-fall monitoring

Rock fall from the toe of the slide buries Highway 140, encroaches into the Merced River, and poses an on-going hazard. Initial monitoring of this activity was conducted by on-site geologists recording visual estimates of rock-fall volume. Visual observation was supplanted by a Slope Stability Radar (SSR) system, operated by GroundProbe, a firm based in Queensland, Australia, under contract with Caltrans. Located on the opposite side of the river, the SSR system scans the talus slope and rock-fall source area about every 10 min and compares the ground surface image with earlier images, thereby detecting changes in the talus slope. This system has several advantages, it can operate day and night, rain or shine, and it provides a complete survey of the entire talus slope area. A displacement value that may represent an adverse amount of change in rock-fall activity can be set. If the SSR system detects this threshold level at the Ferguson rock slide, it causes the lights controlling traffic to remain red to prevent vehicles from entering the potentially unsafe road segment.

Displacement monitoring of main slide mass

Movement of the main slide mass drives much of the rock-fall activity at the toe. Studies have shown that rapid landslide movement may be preceded by gradually accelerating movement (Terzaghi 1950; Varnes 1983; Voight 1989; Fukuzono 1990), and that repeat surveying can detect this acceleration. Displacement of the Ferguson Rock Slide is monitored by monthly total station surveys of monuments located on the slide by Caltrans. Changes in the rate of movement, including acceleration, are monitored by three Global Positioning System (GPS), single frequency (L1) receivers packaged into tripod-like spider units initially placed on the slide mass by helicopter (Fig. 6). This monitoring system, developed by the USGS, (LaHusen and Reid 2000), can detect sub-centimeter displacements by differentially processing GPS satellite observations against those from a nearby USGS-installed reference station. GPS spider units have been used successfully at Mount St. Helens to monitor lava-dome growth. At the Ferguson Rock Slide, data from the GPS receivers are usually transmitted hourly via radio telemetry; location solutions are automatically computed in near real time and available to USFS, Caltrans, and USGS personnel via the Internet. In addition, each

Fig. 6 GPS spider monitoring device with accompanying unidirectional geophone to measure displacements of the main slide mass and vibrations due to rock-slide movement

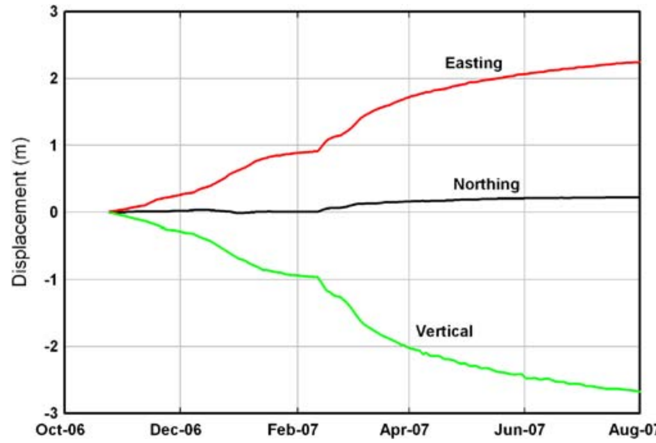

Fig. 7 Displacement components (*eastings*, *northings*, *vertical*) over time computed for GPS spider unit A, located on an outer block of the slide (see Fig 2). High-precision, differential GPS solutions are automatically computed relative to a nearby USGS-installed reference station

spider unit has a uni-directional geophone buried 20–30 cm in the slide. These geophones can detect strong ground vibrations associated with rapid slide movement (LaHusen 2005). The availability of near-real-time displacement data can enable rapid response to slide changes (Reid et al. 1999). During the relatively dry winter/spring of 2007, most of the slide mass showed little movement. However, GPS spider unit A, located on an outer slide block, showed continued slow displacement. Three-dimensional components of displacement from this unit are shown in Fig. 7. Here, the mass moved more than 2 m eastward and about 2.5 m downward between October 2006 and August 2007.

Seismic shaking

Moderate to large earthquakes could trigger movement or acceleration of the Ferguson Rock Slide or its talus slope. For the slide area, the USGS National Strong-Motion Maps predict a 10% chance in 50 years of exceeding a shaking level of 12.02% g (http://earthquake.usgs.gov/hazmaps). To better detect potentially destabilizing strong ground motion associated with an earthquake, a USGS strong-motion accelerometer is deployed near the rock slide. This instrument is linked to the California Integrated Seismic Network (CISN), the primary source for information about the occurrence, location, and magnitude of earthquakes in the rock-slide region. This system provides a notification service for earthquakes exceeding set magnitude levels. CISN also operates ShakeMap, an analysis package that integrates strong-motion data into a map-based product of shaking effects (http://earthquake.usgs.gov/shakemap). This additional strong-motion station near the slide will improve the accuracy of ShakeMap portrayals, especially for earthquake shaking of possible significance to slide stability (magnitude 3.5 to 4 and larger).

Stream-level monitoring

In the event of rapid failure of a large part of the rock slide with subsequent damming of the Merced River, normal stream flow would be disrupted. To detect changes in river water level, two stream gauges were installed in late September 2006, one near the temporary bridge at the detour about 150 m upstream and one near the temporary bridge about 500 m downstream from the rock-slide location. Data from these gauges are recorded every 15 min and transmitted hourly via GOES satellite and are accessible on the internet (http://cdec4gov.

water.ca.gov/cgi-progs/queryF?s=fsu, http://cdec4gov.water.ca.gov/cgi-progs/queryF?s=fsd). Sudden differences in stream stage measured between these gauges might indicate damming of the river.

These monitoring efforts have been undertaken to satisfy three goals. During the initial emergency, a U.S. Federal Incident Management Team developed a plan to coordinate the resources and roles of various local emergency-response agencies. The first goal is to ensure that timely warning is given of rock-slide activity requiring implementation of these actions. The traffic detour on California State Highway 140 is in close proximity to the rock slide on the opposite side of the Merced River. The distance from the distal edge of the rock-fall talus that buries the highway to the detour roadway is about 65 m. Due to this close proximity, the second goal is to protect the safety of the public traveling this road. Consequently, monitoring is designed to detect small changes in the talus slope, acceleration of the main slide, earthquake shaking, and sudden changes in Merced River levels. An emphasis is placed on utilizing systems that can report in "real time" via satellite and radio links. Future behavior of the rock slide is uncertain. The third monitoring goal is to document the slide's behavior. Data from these efforts can be used to better forecast future movement patterns and to enable better management of the hazards posed by the rock slide.

Summary and conclusions

During the spring of 2006, an 800,000 m^3 rock-block slide of slate and phyllite occurred west of Yosemite National Park. The talus emanating from the toe of the slide buried California State Highway 140, one of the main highways providing access to the park. Businesses in the area lost about 4.8 million USD due to the 92-day closure of the highway. Traffic was eventually rerouted to the opposite side of the Merced River across from the rock slide. To address concerns for public safety should the landslide become reactivated partially or fully, a number of measures were undertaken to monitor the rock slide and to evaluate its behavior should movement reoccur.

A Slope Stability Radar System scans the talus slope and rock-fall source area at 10-min intervals to detect movement within the talus and toe area of the rock slide.

Three Global Positioning System spiders are located on the main part of the rock-slide mass to detect movement within this area of the slide.

A strong-motion accelerometer has been deployed near the rock slide to detect and record any destabilizing shaking associated with an earthquake.

Two stream gauges were installed upstream and downstream from the rock slide to monitor any sudden changes in river water level that might indicate damming of the river by movement of the slide.

Numerical simulations of different scenarios of partial and complete failure of the rock-slide mass were performed to assess the slide travel distance and its potential to dam the Merced River.

These monitoring systems have detected small movements of parts of the slide mass, and data indicate relatively rapid response to rainfall. Numerical simulations of slide failure show that the mass can reach the opposite side of the Merced River Canyon and dam the river under some scenarios.

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