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## When hazard avoidance is not an option: lessons learned from monitoring the postdisaster Oso landslide, USA

**Abstract** On 22 March 2014, a massive, catastrophic landslide occurred near Oso, Washington, USA, sweeping more than 1 km across the adjacent valley flats and killing 43 people. For the following 5 weeks, hundreds of workers engaged in an exhaustive search, rescue, and recovery effort directly in the landslide runout path. These workers could not avoid the risks posed by additional large-scale slope collapses. In an effort to ensure worker safety, multiple agencies cooperated to swiftly deploy a monitoring and alerting system consisting of sensors, automated data processing and web-based display, along with defined communication protocols and clear calls to action for emergency management and search personnel. Guided by the principle that an accelerating landslide poses a greater threat than a steadily moving or stationary mass, the system was designed to detect ground motion and vibration using complementary monitoring techniques. Near real-time information was provided by continuous GPS, seismometers/geophones, and extensometers. This information was augmented by repeat-assessment techniques such as terrestrial and aerial laser scanning and time-lapse photography. Fortunately, no major additional landsliding occurred. However, we did detect small headscarp failures as well as slow movement of the remaining landslide mass with the monitoring system. This was an exceptional response situation and the lessons learned are applicable to other landslide disaster crises. They underscore the need for cogent landslide expertise and ready-to-deploy monitoring equipment, the value of using redundant monitoring techniques with distinct goals, the benefit of clearly defined communication protocols, and the importance of continued research into forecasting landslide behavior to allow timely warning.

**Keywords** Landslide · Monitoring · Debris avalanche · Emergency response · Crisis · Oso · GPS

### Introduction

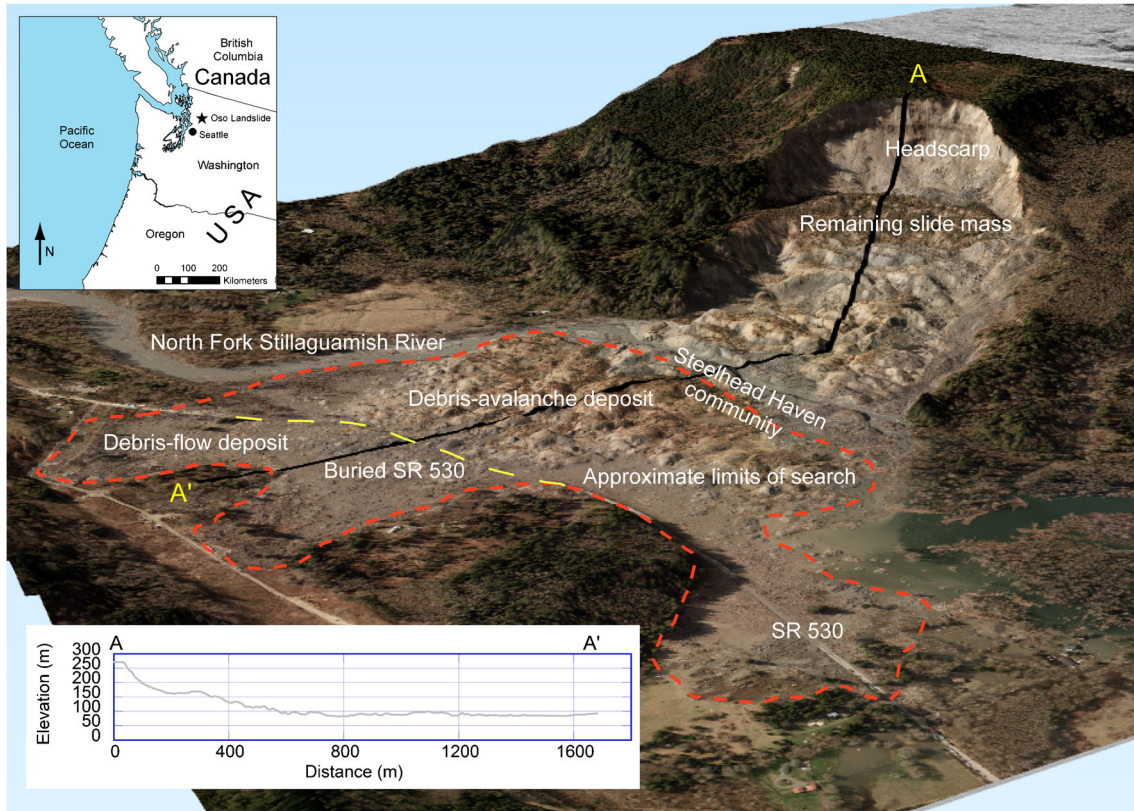
On the sunny Saturday morning of 22 March 2014, the Oso landslide (officially called the SR530 Landslide), in western Washington state, USA suddenly collapsed and swept away the Steelhead Haven community located on the adjacent flat alluvial valley floor, dammed the North Fork Stillaguamish River, and buried Washington State Highway SR530 in a debris avalanche and debris flow (Fig. 1). Eight people were rescued in the first 2 h following the slide, and more survivors were found over the course of the day. During the succeeding 5 weeks, as many as 900 workers toiled with hand tools and heavy excavation machinery under the shadow of the slide scar in an intense search, rescue, and recovery operation. Ultimately, the remains of 43 victims were located (SR530 Landslide Commission 2014), making this one of the most deadly

landslides in United States history. Only the 1985 Mameyes landslide in Puerto Rico (a US territory) was deadlier with at least 129 fatalities (Jibson 1992).

For many catastrophic landslides, once the rapid movement phase concludes, the overall hazard is reduced. Nevertheless, secondary slope failures may be a concern, and in these cases, expert advice typically calls for restricting access to the landslide area to allow ground conditions to stabilize, subsurface pore-water pressures to decrease, and/or dry weather to ensue. However, these actions are not always possible if rescue or recovery operations are required. At Oso, search and recovery operations began immediately following the landslide and continued for weeks. Because of the need for immediate operations, delay and complete hazard avoidance were not options here. This placed search and recovery workers at risk from additional potential landsliding for an extended period.

Importantly, three other landslide disasters that same year (2014) provide cautionary accounts of the threat to first responders entering areas where recent catastrophic landslides have occurred. On 2 May 2014 in Badakhshan Province, Afghanistan, fellow villagers attempting to rescue victims of a large mobile landslide were buried by a subsequent even larger slide. Hundreds were killed in the two events (Graham-Harrison 2014). In the United States, on 25 May 2014, the West Salt Creek landslide, a fast-moving, high-mobility slide near Collbran, Colorado, collapsed in several phases (White et al. 2015; Coe et al. 2016). Precursory slides occurred in the morning hours, and the apparent blockage of irrigation ditches by these small slides prompted three local residents to investigate. At 5:45 pm, a larger catastrophic rock avalanche/debris avalanche buried the men in a 4.5 km long deposit (White et al. 2015). Finally, in the predawn hours of 20 August 2014, torrential rains triggered landslides and debris flows in a residential area of Hiroshima, Japan killing 75 people (Asahi Shimbun 2014b; Asahi Shimbun 2015). A veteran firefighter responding to the scene was swept away by a subsequent debris flow while attempting to rescue a 3-year old boy; both were later found dead (Asahi Shimbun 2014a). These tragic examples illustrate that areas subject to catastrophic rapid landslides can pose continuing, sometimes deadly threats to first responders, as well as others in the immediate vicinity.

Landslide monitoring, especially in near real-time, has the potential to provide timely notification of changes in slide motion during a landslide crisis when response actions must take place under hazardous conditions. Here, we use the term *near real-time* to indicate that data flow has some latency, but the delay is sufficiently short that the data essentially represent current field conditions. In several notable cases, monitoring has led to early



**Fig. 1** Oblique view of the 2014 Oso landslide portrayed in an orthophoto draped on postevent lidar-derived topography with inset location map. Bottom inset shows topographic profile with landslide deposit extending > 1 km across valley flats (no vertical exaggeration). Profile location designated by the black line on orthophoto. Approximate area of search operations outlined in dashed red. Lidar (6 April 2014) and orthophoto (14 April 2014) acquired by WSDOT

warning of imminent catastrophic failure and likely prevented loss of life (e.g., Rose and Hungr 2007; Keys and Green 2008; Pankow et al. 2014; Loew et al. 2016; Intrieri et al. 2019). Over the last several decades, near real-time monitoring systems have been increasingly deployed to provide situational awareness for both slow and rapid landslides (e.g., LaHusen 2005; Read et al. 2005; Yin et al. 2010; Intrieri et al. 2012; Malet et al. 2013; DeGraff et al. 2015). A wide variety of field instruments and techniques are available to monitor landslide deformation and movement (e.g., Dunnington 1993; Mikkelsen 1996; Angeli et al. 2000; Casagli et al. 2010; Jaboyedoff et al. 2012; Mazzanti 2012; Dick et al. 2015; Scaioni 2015). Yet more components are needed for these observations to be useful for emergency response decisions, such as issuing evacuation orders. Efficient data dissemination is required to transmit information about current conditions from the landslide site to users in a form that can be easily interpreted (e.g., Reid et al. 2008; Allasia et al. 2013; Intrieri et al. 2013; Froese and Moreno 2014; Pecoraro et al. 2019). Further, such information must be recorded, interpreted, and transmitted prior to catastrophic failure with detection thresholds capable of providing advance warning that allow sufficient time for evacuation of endangered personnel.

For landslides with the potential to fail catastrophically but having limited spatial and temporal monitoring, various methods based on observed changes in ground-surface displacements, velocities, and accelerations are typically used to evaluate activity and potentially estimate a time of rapid failure (Eberhardt et al.

2012; Intrieri et al. 2019). However, complexities and uncertainties in geologic settings, such as failure modes, material properties, failure geometries, kinematics, and variable driving forces, make definitive warning criteria elusive and have led to mixed forecasting success (e.g., Dick et al. 2015; Intrieri and Gigli 2016). Despite these uncertainties, some generalizations have emerged. One is that landslides controlled by reductions in strength or progressive failure typically do not instantly undergo rapid movement, as might occur during an earthquake-triggered event. Instead, they are in motion and usually accelerating prior to rapid failure. The time period of precursory acceleration can range between weeks or months for larger slides such as Vajont, Italy (Kilburn and Petley 2003) to hours for smaller slides (Fukuzono 1990; Dick et al. 2015). A related caveat is that some landslide acceleration, in itself, may be a false alarm and does not necessarily indicate that rapid failure is imminent (Eberhardt et al. 2012). The bottom line is that during a rapid response to a new landslide crisis, there are guides but no foolproof methods or algorithms to forecasting subsequent behavior.

Following the 2014 catastrophic Oso landslide, multiple government agencies (including Snohomish County, Washington State Department of Natural Resources (WADNR), Washington State Department of Transportation (WSDOT), and the U.S. Geological Survey (USGS)) cooperated to design and implement a multifaceted monitoring system aimed at detecting potential large-scale sliding that could threaten the on-going search and recovery

operations. We rapidly instituted diverse and redundant monitoring procedures, including the following: (1) continuous on-site observation by time-lapse camera and trained geologists; (2) periodic terrestrial laser scans and total station surveys; (3) repeat aerial photogrammetry and lidar scans; and (4) continuous near real-time data streams from extensometers, GPS receivers, and seismometers. Our effort is notable because it required continuously cataloging, evaluating, and interpreting incoming near real-time monitoring data over the weeks in which hundreds of recovery workers labored on the landslide deposit. In this situation, avoidance of the hazard was not an option. Here, we briefly describe the landslide event, review our landslide response efforts and monitoring techniques, and discuss the lessons we learned. Our intent is to provide a case study that illuminates the successes and challenges of using landslide science to support emergency management and search and recovery operations. Landslide crises are unfortunately inevitable, and lessons from our response could help guide preparation for future events.

### Landslide characteristics

Located about 100 km NNE of Seattle on the western edge of the Cascade Range, the Oso landslide initiated from a ~180-m high terrace of stratified glacial and proglacial deposits (Dragovich et al. 2003; Riemer et al. 2015) perched above the north bank of the North Fork of the Stillaguamish River (NFSR). Despite the relatively low relief of this terrace, the slide mass traveled rapidly ~1 km across the flat adjacent alluvial valley (Fig. 1). In places the leading edge of the slide (which had the character of a debris flow) reflected backwards when it encountered the opposite valley wall. The slide exhibited a high degree of mobility compared to other debris slides and avalanches, with a maximum height (H) to total travel distance (L) ratio of 0.105, and had a volume initially estimated at  $\sim 8 \times 10^6 \text{ m}^3$  covering an area of  $\sim 1.2 \text{ km}^2$  (Iverson et al. 2015). A subsequent analysis informed by exploratory drilling estimated a total slide volume of  $\sim 9 \times 10^6 \text{ m}^3$  (Collins and Reid 2020).

The Oso slide deposits encompass a wide variety of morphological styles, as described elsewhere (Keaton et al. 2014; Iverson et al. 2015; Wartman et al. 2016; Aaron et al. 2017; Perkins et al. 2017; Stark et al. 2017), and explored further in a detailed field-based investigation into the causes of its mobility (Collins and Reid 2020). Here, we focus on aspects of the slide that directly affected the landslide crisis response during the 5 weeks following the event, rather than on details learned through later investigations. Overall, the deposits transition downslope from a rotational slump mass adjacent to the ~100 m high headscarp to extended coherent extensional slide blocks to debris-avalanche hummocks to a thin debris-flow deposit at the distal margin (Fig. 1). Most of the deposit covering the alluvial floodplain consists of debris-avalanche hummocks ranging up to ~10–20 m in height and decreasing in size away from the landslide source, with a thin veneer of debris-flow material in the southern distal regions. Nearly all the slide deposits exhibit signs of extension, including tension cracks, grabens, and hummocks. Although the overall slide displays a variety of movement styles, some researchers have termed it a debris avalanche-flow (Iverson et al. 2015), in part because avalanche and flow materials were the most mobile and now occupy large areas of the valley floor. The combined debris

avalanche-flow phenomena destroyed and buried the Steelhead Haven community previously situated on the valley flats.

The landslide area had experienced repeated episodic movements since at least the 1930s, with the most recent activity in 2006, referred to as the Hazel landslide (Thorsen 1969; Miller and Sias 1997; Miller and Sias 1998). These historical movement episodes primarily affected the terrace hillslope and the river at the base of the slope. None extended across the alluvial flats to the other side of the valley. Immediately following the 2014 event, mapping using preevent aerial lidar-derived topography from 2013 revealed the presence of multiple prehistoric landslides with deposits extending well across the valley flats (Haugerud 2014). A notable example, termed the Rowan debris avalanche-flow (Iverson et al. 2015), exists < 1 km downstream of the Oso landslide and had been identified in earlier regional geologic mapping (Dragovich et al. 2003).

Although the slide occurred on a sunny morning and precipitation over the prior several days was light, previous rainy periods likely contributed to failure and to the mobility of the landslide mass. The 21- to 42-day periods prior to the event had anomalously high precipitation; over the prior 21 days about 334 mm of precipitation was recorded near Oso (Henn et al. 2015). Previous years were wet as well and could have preconditioned the slope to failure; the previous 4-year period (ending on 31 March 2014) was the wettest on record (Iverson et al. 2015). However, the response between rainfall infiltration and increased groundwater pressures at depth can be delayed and nonlinear (e.g., Iverson 2000; Lu and Godt 2013), making it difficult to directly relate this failure to a specific wet period without measurements of pore-water pressures on, or in the vicinity of, the imminent landslide failure surface. Alternatively, progressive failure may have occurred in intact lacustrine sediments with negligible precipitation response on subsurface pore pressures (Badger and D'Ignazio 2018). Regardless of the initiation mechanism, wet materials can aid the transformation from slide into debris flow, and thereby enhance mobility and increase destruction in the runout path (e.g., Iverson et al. 1997).

Ground shaking records from the Pacific Northwest Seismic Network documented the timing of failure, commencing at about 10:37 am local time in an energetic burst with long-period motions that lasted about 2.5 min (Allstadt et al. 2014). A second high-frequency shaking event occurred about 4 min following the initial burst. Subsequent seismic analyses show that the vast majority of force associated with slide movement was exerted during the first seismic event, whereas movement of a smaller mass created the second period of shaking (Hibert et al. 2015; Iverson et al. 2015). From an immediate hazards-monitoring perspective, failure occurred rapidly with no obvious seismic precursors and could have potentially done so again, thereby threatening recovery workers.

### Response to the landslide crisis

As the landslide crisis evolved, so did emergency management goals and interpretations of landslide behavior. Fluctuating conditions necessitated adaptive strategies to help mitigate ongoing risks. This was particularly critical as search and recovery operations continued for about 5 weeks with hundreds of personnel working in the valley directly downslope from the landslide headscarp (Fig. 1). The pressure of a grim search situation, the uncertainty of additional massive landsliding, and the lack of avoidance options to ensure worker safety generated a stressful and challenging environment for geologists responding to the crisis.



Immediately following the catastrophic collapse on March 22, search and rescue units from county, state and federal agencies responded, with multiple helicopters airlifting a total of 11 survivors that day. The scale of the disaster prompted a declaration of a state of emergency by the governor of Washington State. The Incident Command System (ICS), used worldwide for disaster management, was implemented to manage the massive landslide crisis. Within this system, landslide experts from a consortium of government agencies were requested to provide technical assistance to an Incident Management Team (IMT). The IMT, with both liability and chain-of-command issues in mind, controlled who provided technical assistance. The IMT, in turn, was responsible for directing search, rescue, and recovery operations.

The day following the collapse, geologists from the WADNR performed the first of several reconnaissance overflights to assess the extent of damage and the potential for future movement. Initial concerns focused on flooding, as the landslide dammed the NFSR (Fig. 2a) and a lake formed upstream and flooded homes that were not impacted by the landslide itself. In addition, catastrophic failure of the landslide dam could potentially have caused downstream flooding. Fortunately, the landslide dam did not fail rapidly. Rather the river overtopped the debris and incised a narrow channel into the hummock field on March 24 (Fig. 2b). Although an elevated water pool behind the landslide dam remained for the next month, subsequent excavation operations enlarged the existing channel through the slide debris allowing lake drainage and increasing the flow of the NFSR. Further details of postevent NFSR behavior can be found elsewhere (Anderson et al. 2017).

Preliminary geologic reconnaissance conducted by WSDOT, WADNR, Snohomish County, and the USGS immediately after the catastrophic landsliding concentrated on event characterization to inform response efforts. On March 24, 2 days after the occurrence of the main slide, the first postslide aerial lidar and orthophotographs of the site were acquired by WSDOT. That same day a small slope failure on the main headscarp, as noted by on-site workers, prompted temporary evacuation of rescue workers from the slide area. Clearing the entire area was not rapid; it required several hours and reflected the difficulties of working in partially liquefied slide debris. Also on that day, United States President Obama issued a Federal Emergency Declaration which enabled the Federal Emergency Management Agency (FEMA) to bring additional resources and federal personnel to the emergency operations. During these early times, a tactical science team covering both flooding and landslide hazards was formed and information relayed through a liaison geologist to the Incident Management Team (IMT).

As the response unfolded, the enormity of assessing ongoing multiple hazards prompted a separation of the tactical science team into two teams, with one focusing on landslide issues and the other on flooding. Beginning on March 26, the Landslide Monitoring Team (with members from Snohomish County, WADNR, WSDOT, and USGS) began holding daily landslide coordination calls among county, state, and federal geologists and engineers on site and those located in their respective regional offices. Geologists on site examined continuing landslide hazards posed from slopes adjacent to the search area, with daily on-the-ground field reconnaissance of the landslide margins and the headscarp region. Based on these observations, geologists initially

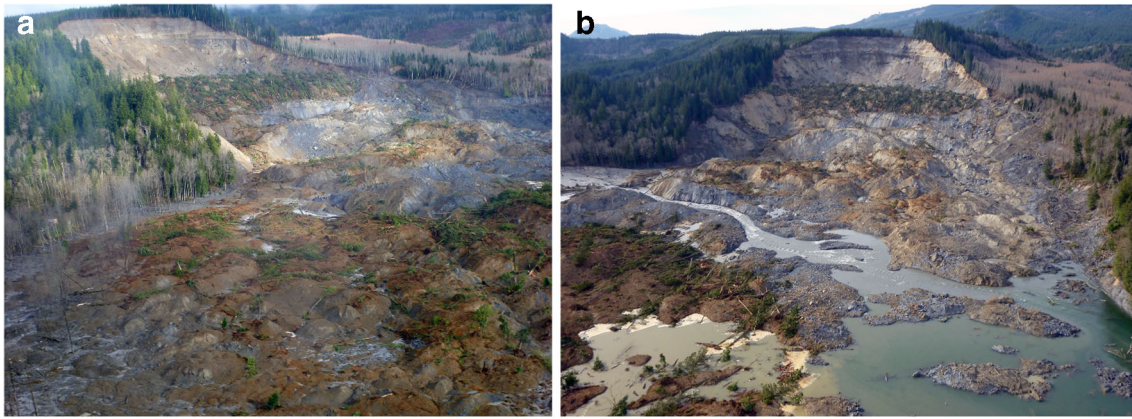
identified four slope-failure scenarios that could generate far-traveled slides with the potential to impact search operations: additional failure of the headscarp area; additional failure of the slope adjacent to the western landslide flank; continued, possibly rapid reactivation of the remaining landslide mass on the slope; and possible generation of smaller debris flows from the upper eastern flank. Early in the response, these smaller debris flows could have generated waves in the lake formed by damming of the NFSR and thereby impacted rescuers searching for victims. Moreover, concerns about the potential for additional large failures were heightened with the publication of the lidar-derived map of nearby prehistoric landslides available 5 days after the Oso event (Haugerud, 2014), and with preliminary assessment of nearby landslide hazards as presented by Badger (2015). These assessments indicated that multiple past failures in this region had been highly mobile and suggested that subsequent failure of the Oso headscarp or adjacent areas might produce failures capable of reaching recovery workers.

Crucial questions involved the deployment of search and rescue efforts: both where to focus search energies and where to avoid continuing hazards. Geologists, using field observations and interpretations of aerial imagery and high-resolution topography, provided information about both of these issues to guide decisions by emergency managers. On March 29, geologists established a “no-go” management line (Fig. 3) to delineate areas directly beneath the landslide headscarp at the greatest risk from further large-scale landsliding. This line was located south of both the new river channel and high hummock deposits, about 1000 m from the headscarp. During search operations, ground access upslope of the no-go line, as well as airspace access to the landslide area, was severely restricted for safety reasons. Geologists were granted access above the main headscarp, with additional protocols such as safety ropes, to visually monitor the slide and to install monitoring devices. Geologic investigations during this time were limited to those that contributed directly to the missions of the tactical science teams and emergency managers.

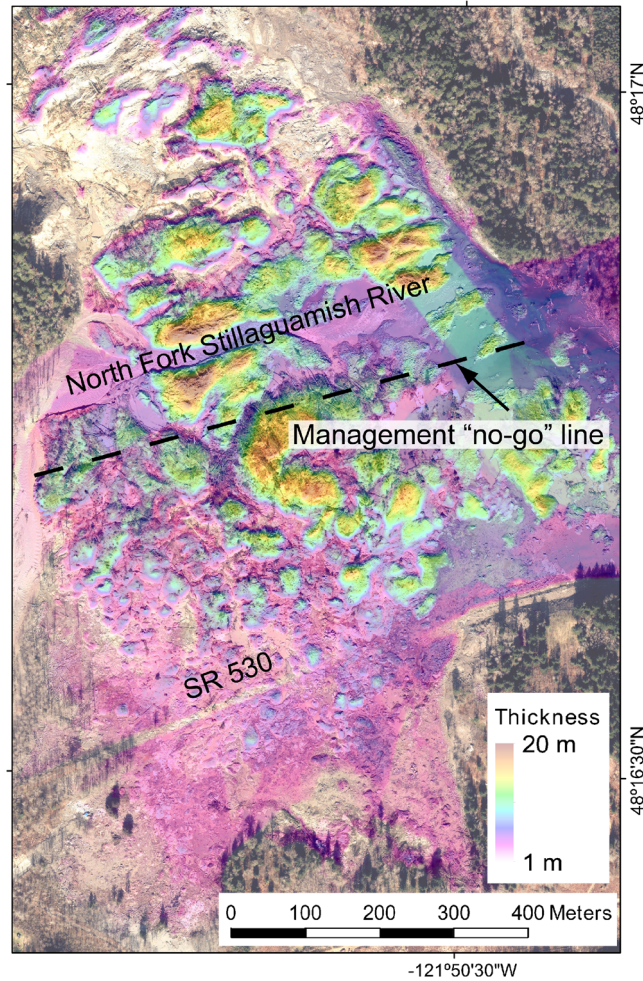
The Oso landslide event swept homes, vehicles, and their contents across the valley floor and away from the steep slope on the northern slide of the NFSR. Geologists advised search and rescue workers to focus their pursuit of buried victims on distal debris fields near the landslide deposit margins. Maps and GPS-enabled locator systems installed in search helicopters that identified original home locations were less useful, as most victims had been swept to the deposit margins by the debris-flow front. Moreover, landslide deposit thickness maps created using pre- and postevent lidar elevation differences showed that the former locations of homes were buried under more than 10 m of slide debris, more than could be quickly and safely excavated given the unstable conditions of the deposit (Fig. 3). To help identify search targets, USGS researchers used the D-Claw model to simulate the dynamics of the landslide (Iverson et al. 2015; Iverson and George 2016). On April 4, animations of preliminary simulations were shown to search personnel in the field and these animations were soon available on the internet (<https://www.youtube.com/watch?v=2NzHCOhKr7g> and <https://www.youtube.com/watch?v=Gj-7AyVwqZo>).

Recovery efforts progressed for weeks following the initial landslide event. The landslide disaster's status was elevated by a Presidential Major Disaster Declaration on April 2, allowing





**Fig. 2** Photographs taken 1 day apart showing (a) before and (b) after the North Fork Stillaguamish River incised through the Oso landslide deposit. Photos by S. Slaughter (WADNR) taken on 23 March (a) and 24 March 2014 (b), from slightly different view angles



**Fig. 3** Topographic elevation difference image of the Oso landslide deposit created using pre- and postevent lidar-derived digital elevation models. The management “no-go” line was defined to limit search and recovery operations to an area beyond the estimated reach of additional large-scale landsliding. Original figure cautioned against using thicknesses north of the river to estimate deposit thickness, as this area contained remaining landslide mass. This image was available to emergency managers several days after the event

additional FEMA funds to aid recovery efforts. Official efforts to recover the remains of landslide victims continued on-site until April 28, when all but one of the 43 victims had been located. On June 20, highway SR530 reopened and on July 14, continued local recovery efforts found remains of the last victim (SR530 Landslide Commission 2014).

A fundamental change in landslide response strategy occurred over the first few weeks following catastrophic sliding. Although survivors were found on the day of the event, within a few days the initial search and rescue operations morphed into a massive recovery operation with hundreds of workers striving to exhume victim remains using hand tools and dozens of mechanical excavators (Fig. 4). This transition accelerated when Washington State Governor Inslee, in a meeting with local residents on March 30, supported a goal of recovering all victims. This goal extended recovery work and precluded simple avoidance of the continuing landslide hazard.

### Landslide monitoring

#### Purpose

Our overall goal was to provide as much reliable information about landslide behavior as possible to inform decisions being made by *others*, namely, emergency managers overseeing search and recovery operations. The objective was not reconnaissance or exploratory science but rather science to support decision making, similar to that used during volcano eruptions (e.g., Williams et al. 2020). This differed from typical postevent fact-finding missions. Within a week of the Oso landslide event, concerted efforts began to continuously monitor both postevent landslide movement and precursory signs of movement on adjacent hillslopes. Monitoring was crucial to detect and track changes in landslide behavior. Several intertwined issues prompted calls for continuous monitoring of the Oso landslide activity, including (1) uncertainty about slope instability potentially affecting the disaster site; (2) new landslide mapping that indicated the potential for other large failures (Haugerud, 2014); (3) an increase in field personnel and their exposure time to meet recovery commitments; and (4) the extended time needed to potentially evacuate recovery personnel if precursory landslide activity was detected. This latter point emphasized the need to analyze longer-term movement trends to aid advance notification.

Because recovery operations began immediately following the initial collapse, a landslide monitoring/warning system needed to be quickly operational to provide information in a timely manner. Multiple agencies involved in the postslide assessment activities (Snohomish County, WADNR, WSDOT, and USGS) had previous experience utilizing different techniques to monitor ground deformation. Because of these established capabilities, each agency could rapidly bring different dedicated monitoring abilities to a joint multiagency monitoring effort. Moreover, both the USGS and WSDOT had previous experience providing near real-time monitoring data from active landslides and large excavations (Reid and LaHusen 1998; Harp et al. 2008; Reid et al. 2008; Badger et al. 2011; Norrish et al. 2011; Reid et al. 2012). However, questions remained about how long such monitoring operations would continue. Initial estimates were for “about 2 weeks” and this time frame affected decisions about which techniques could be rapidly

deployed and implemented. Official recovery operations, however, lasted considerably longer—more than 5 weeks (Fig. 5).

#### Monitoring design

Although a variety of field monitoring techniques formed the backbone of the monitoring effort at Oso, development of a complete alert system required several key components to provide reliable information for decision making and subsequent actions. A complete, end-to-end early warning system should include the following: (1) knowledge of specific hazards and risks; (2) the ability to detect, monitor, assess, and forecast hazards; (3) procedures to disseminate timely, authoritative knowledge with actionable warnings; and (4) preparedness at all levels (UN Working Group 2016). At Oso, despite our imperfect knowledge of potential slide behavior, we needed to quickly deploy monitoring utilizing readily available monitoring and forecasting capabilities. Our primary monitoring objectives were to identify precursory indications of large-scale upslope movement that might portend a subsequent failure large enough to reach recovery operations in the NFSR valley. Monitoring to detect lower-threat, smaller potential failures from the recent headscarp or slide margins was less of a priority. As such, our techniques relied on detecting ground-surface displacement or acceleration over time that might reveal changes in velocity or acceleration in regions upslope or adjacent to the March 22 failure. An immediate collapse, such as that triggered by strong earthquake ground shaking, would not have such precursory signals. To reveal evolving spatial patterns, as well as longer-term temporal trends in movement, we opted for a variety of redundant techniques to detect displacement, in the event that a specific technique provided spurious or incomplete information. Because time scales for changes in motion can vary from weeks to hours, we implemented both near real-time and repeat assessment monitoring methods spanning a range of update frequencies from seconds to days (Figs. 5 and 6).

Providing timely notification of landslide activity in this ongoing emergency situation required actionable communication and notification protocols. The basic chain of communication began with the Landslide Monitoring Team, with members from Snohomish County, WADNR, WSDOT, and the USGS, communicating through a defined geologist liaison (from WADNR) to the Incident Management Team. Once near real-time data flows were established, USGS personnel took the lead on continuously monitoring these data during the working daylight hours of the recovery operation every day of the week. We defined four levels for notification of landslide activity, with communication protocols varying depending on landslide activity tailored to the specific Oso situation (Table 1). Protocols ranged from daily summaries for the Incident Commander if there had been no slide activity of concern, to immediate direct communication with field commanders if large-scale activity was noted and evacuation of field personnel was warranted. Recovery operation personnel had defined procedures for emergency evacuation from the site that could be triggered by radio communications or on-site audible sirens for notification of impending additional landslide movement.

Continuous near real-time data streams were aggregated onto a web-based dashboard that summarized and displayed current conditions in synch with the near real-time data feeds; this information was available over the internet to all members of the Landslide Monitoring Team. Teams of two USGS geologists, which





**Fig. 4** Photographs of recovery operations on distal part of landslide deposit. Photos by M. Reid (USGS) taken on 30 March 2014

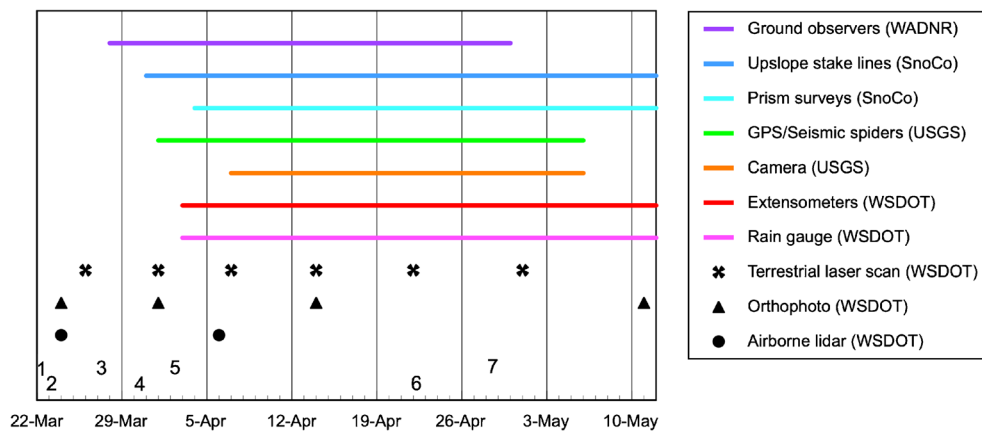
rotated on an overlapping 2-week schedule, conducted continuous surveillance of the data and activities – initially at the nearby Incident Command Post and later remotely via the internet. Overlapping schedules allowed for cross training on instrument setups and on-going landslide behaviors. Operational roles and responsibility checklists for these observers were clearly defined. Also during the recovery working hours, another rotating geologist from WADNR was stationed at the Engineering Observation Lookout (Fig. 6) for continuous visual observation of on-site conditions. This geologist had direct radio links to both the Landslide Monitoring Team and field operation commanders and could request immediate evacuations. In addition, this geologist would issue short descriptions via radio immediately following any debris falls from the main headscarp. These statements served to reassure first responders that someone was watching and aware of slide activity. Both of these observational activities continued until official recovery operations ended on 28 April 2014.

#### Near real-time monitoring methods

We implemented several near real-time systems to monitor postevent landslide movement. One system, deployed by WSDOT, relayed surface extensometer and precipitation data from the area

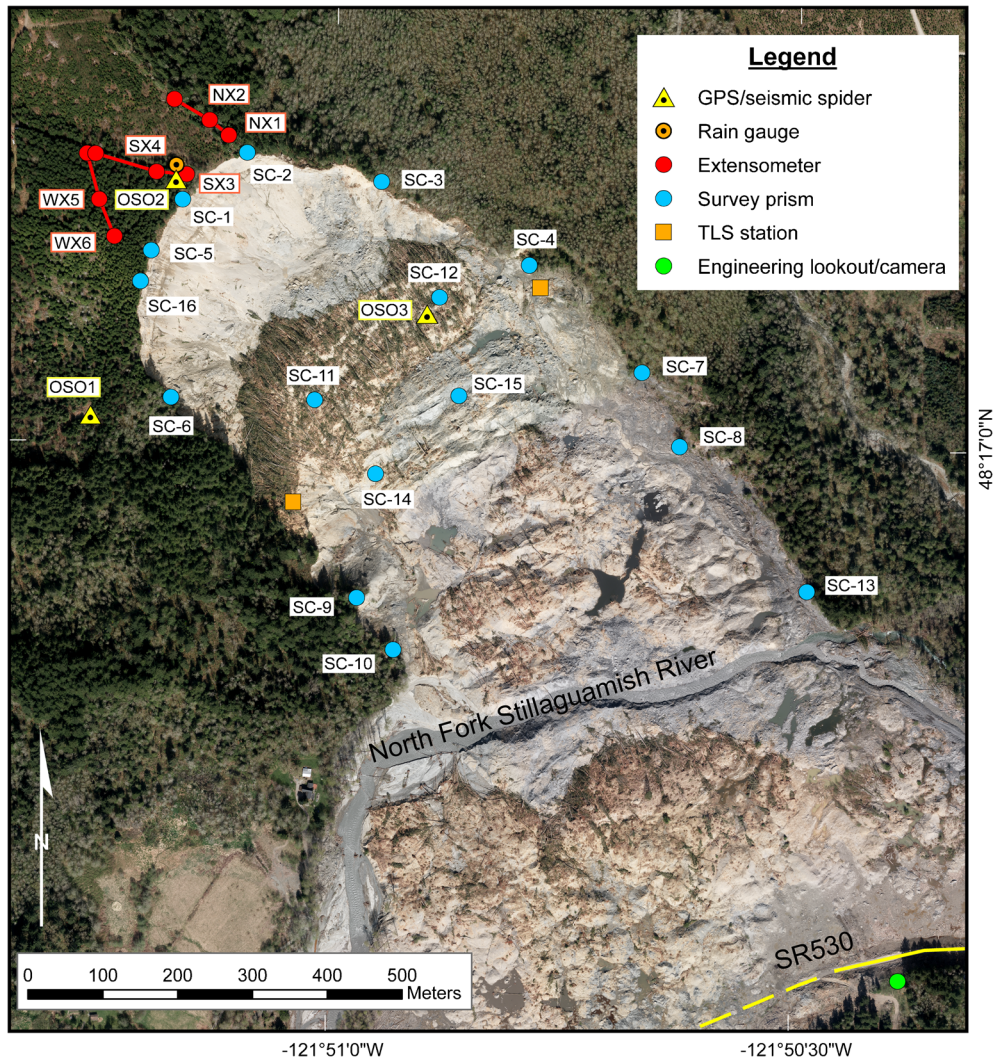
above the main headscarp every 5 min (see Fig. 6 for locations). Ground displacement (extension) or acceleration of this region might have indicated the start of a large retrogressive failure. This system utilized six UniMeasure JX-PA extensometers (50-cm range) with steel cables protected by PVC pipe and installed in three transects, a NovaLynx tipping bucket rain gauge (0.01-inch resolution), a Campbell Scientific CR1000 data logging system, and cellular telemetry. Automated data collection was performed in LoggerNet software (Campbell Scientific), with data processed, stored, and web-accessible via server-based ARGUS Monitoring Software (Interfels).

A second near real-time system, installed by the USGS, used three GPS-seismometer “spider” units to monitor the area above the headscarp, to the west of the slide (to detect any impending adjacent activity that could reach recovery operations), and the failed remaining main slide mass (see Fig. 6). We remotely deployed the spider units using helicopter sling load techniques. The battery powered spider units consisted of self-contained tripod-mounted instrumentation vaults with on-board L1-only GPS receivers, external seismometers/geophones, and dedicated spread-spectrum radio telemetry (Fig. 7). The data acquisition system and seismic waveform digitizer for the spiders were designed and



**Fig. 5** Timeline of near real-time and repeat-assessment monitoring activities during the 2014 Oso landslide response. Bottom row of numbers indicate select events described in text: (1) landslide occurrence; (2) North Fork Stillaguamish River incises through landslide deposit and Federal Emergency Declaration; (3) release of landslide lidar mapping (Haugerud 2014); (4) Washington State Governor Inslee meets with local residents; (5) Federal Major Disaster Declaration; (6) U.S. President Obama visits landslide; and (7) end of official recovery efforts. SnoCo is Snohomish County Public Works





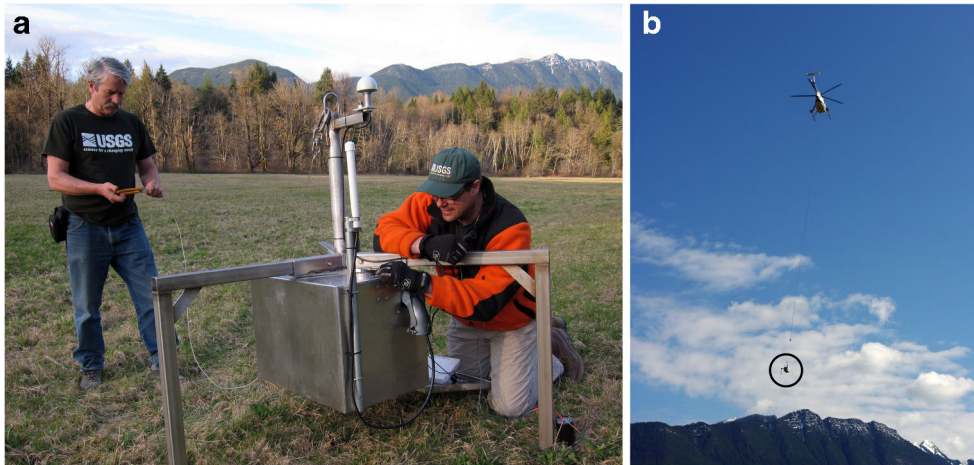
**Fig. 6** Locations of monitoring instrumentation during the 2014 Oso (SR530) landslide response, as of 19 April 2014. TLS station denotes terrestrial laser scanning setup locations. Orthophoto base acquired by WSDOT (14 April 2014)

developed by the USGS. Spiders were initially designed to monitor active volcanoes such as Mount St. Helens (LaHusen et al. 2008), but have also been used to monitor active landslides (Harp et al. 2008; Reid et al. 2012). At Oso, GPS data received by the spiders were collected every 15 s using u-blox T4 GPS receivers with Trimble Bullet antennas. These data were continuously transmitted by cellular telemetry to an offsite USGS server. Static, fixed ambiguity positions for each 15-s epoch were automatically computed (using Waypoint GrafNav software, version 8.1) nominally

every 10 min. Each computed position used GPS satellite observations from the previous 3-h period. Computed differential positions (est. accuracy < 2 cm) were relative to a stable GPS base station installed by the USGS less than 2 km from the slide. Compared with GPS receivers using multiples frequencies (e.g., L1–L2), L1-only receivers typically are less expensive, have lower power requirements, and introduce less noise when satellite observables are processed using very short baselines (LaHusen et al. 2008). Processed differences in position at Oso were available to

**Table 1** Notification/warning levels used during the 2014 Oso landslide monitoring period. Each level also included information about specific responsibilities and what actions should be taken (not shown here)

Level 1	Daily briefing
Level 2	Small changes in monitoring trends
Level 3	Large or accelerated changes in monitoring trends observed
Level 4	Immediate action is necessary to evacuate one or more search and recovery divisions



**Fig. 7** Photographs showing (a) close-up and (b) helicopter deployment of USGS spider monitoring unit. Each spider unit contains an onboard GPS receiver, seismometer, and radio telemetry. Photos by M. Reid (USGS) taken on 31 March 2014 (a) and J. Godt (USGS) 1 April 2014 (b)

the Landslide Monitoring Team via a secure, nonpublic USGS website and summarized on the web-accessible near real-time dashboard.

Spider units also collected seismic data using external, single-axis Sercel seismometer/geophones (model L-10 AR) with a natural frequency of 10 Hz. These instruments were vertically buried to a depth of ~0.5 m adjacent to the spiders, thus enabling direct contact with surficial materials. They could sense strong ground vibrations associated with any additional large upslope or adjacent slope failure. We collected seismic data at 100 Hz; the Landslide Monitoring Team could view these data as waveforms, spectrograms, helicorder representations, and processed RSAM (Real-time Seismic Amplitude Measurement) data in close to real time over the internet. RSAM data are commonly used during volcanic eruptions as a predictive tool to track overall levels of seismicity (Endo and Murray 1991). At Oso, we used RSAM data (integrated over 10-s intervals) to potentially detect any increases in seismic activity resulting from increases in the frequency of smaller slides originating from the main Oso headscarp that might herald a larger retrogressive slope failure.

In addition to these two automated systems, WADNR geologists stationed at the Engineering Observation Lookout acted as real-time human spotters. These observers had an additional task to identify the timing and relative size of notable small failures from the main Oso headscarp – information used to help correlate these small failures with seismic records from the spider units and thus build on-site knowledge of how to interpret seismic signals. These size-to-seismic correlations were also aided by images taken every hour by a USGS time-lapse camera (Nikon D90 in a housing) positioned near the Engineering Observation Lookout.

#### Repeat-assessment monitoring methods

We also monitored ground-surface displacements using periodic surveying techniques on both regular and irregular intervals. Although these observations did not provide near real-time information, much of this surveying covered large areas and provided episodic time-series trends. The methods used at the Oso site

included the following: stake-line surveying upslope of the main headscarp, total-station surveying of reflectors placed around the edge of that headscarp and on the slide mass, terrestrial laser scanning, repeat aerial lidar scans, and repeat aerial orthophotography (Figs. 5 and 6).

Snohomish County engineers used conventional surveying methods twice a day to measure three stake lines placed upslope of and perpendicular to the main head scarp. Survey observations from these lines were assessed daily to detect ground extension that might precede retrogressive failure above the main headscarp. Snohomish County also used total station survey methods to track the motion of prism reflectors placed at multiple locations (typically attached to large trees) around the upslope edge of the main headscarp and later on the slide mass itself. The total station instrument was located at the Engineering Observation Lookout across the valley from the slide (Fig. 6). Measurements of the reflectors were typically taken hourly and trends assessed daily. Survey data were provided to the Landslide Monitoring Team on a daily basis; however, information regarding any substantial changes were transmitted immediately via radio.

A series of repeat terrestrial laser scans (TLS), performed by WSDOT, helped us monitor both small (centimeter-scale) and large (meter-scale) topographic changes in the remaining main slide and headscarp areas, and to place other point surveying measurements into a spatial context. These oblique scans were collected on a weekly basis (Fig. 5) using an Optech ILRIS HD scanner from two ground locations on the east and west edges of the main slide (Fig. 6); data were processed using PolyWorks software. Due to limited scan locations, the resulting point cloud coverage typically included some areas with no laser returns, i.e., no data. Average laser point spacing was about 18 cm. Elevation differences between the point clouds obtained from these repeat TLS surveys were computed and available to the Landslide Monitoring Team, typically within 1–2 days following the most recent TLS survey.

In addition to on-the-ground measurements, WSDOT obtained two aerial lidar-based digital elevation models (DEMs), one from



data acquired 2 days after the slide event and the other from data acquired in early April. WSDOT also acquired multiple orthomosaics from vertical digital aerial photogrammetry (with ~8 cm ground sampling distance) of the site (Fig. 5). Both lidar DEMs and orthomosaics were highly valuable for overall site characterization, localized assessments, and operational planning.

### Monitoring observations

Although no additional large catastrophic slope failures occurred during the 5-week monitoring period, nor in the ensuing seven years, several other styles of failure did occur during our monitoring. Our methods implemented to detect precursors of large retrogressive failure upslope of the main headscarp, such as repeat surveys of stake lines and near real-time recording from extensometers (Fig. 6), revealed no trends in or significant amounts of ground displacement that would have caused recovery effort work stoppage. However, both our near real-time and repeat-assessment techniques detected smaller retrogressive, rapid debris falls from the headscarp and slow movement of the rotational slide block remaining downslope of the headscarp. These events were not threatening to recovery efforts. Here we present some of these monitoring observations, both to demonstrate the efficacy of these techniques in capturing smaller, potentially precursory events and to illustrate some typical failure behaviors we recorded. Graphs and images presented in the following sections serve to illustrate the data available during the actual response period and have not been modified other than the addition of some labels.

### Headscarp failures

During our monitoring, relatively small (~100 to 3000 m<sup>3</sup>), retrogressive, rapid failures and small-scale sloughing typically occurred daily or multiple times a day on the ~50° headscarp of the main Oso landslide. Most of these shallow (~1–3 m thick) landslides initiated in the recently exposed glacial outwash sands in the upper third of the scarp and deposited material at the base of the scarp into a graben formed by the downdropped upper block of the landslide. Some of these headscarp failures also contained more coherent glacial till that was exposed midway down the scarp face. Redundant and complementary monitoring techniques were effective in recording these small failures, including repeat terrestrial laser scans, time-lapse photography, repeat surveying of monuments placed at the top of the scarp, and continuous 100 Hz seismic monitoring. In addition, some of the headscarp failure events were witnessed by ground observers.

Elevation changes revealed by differencing DEMs acquired through repeat TLS scans clearly illustrate the locations and sizes of some of these small failures. Figure 8 shows the vertical elevation differences over a 2-week period, with pockets of erosion near the top of the scarp and corresponding deposition near the base of the scarp. The regions showing elevation differences on the scarp were likely the foci of one or several small failures. In addition, a few of the prism reflectors mounted on trees around the top of the headscarp showed slow displacement over the weeks of monitoring, although most were relatively stable. Some of these reflectors were eventually lost over the headscarp edge due to small retrogressive slope failures on the headscarp.

The timing of small-scale slope failures and sloughing on the headscarp was captured by seismometer/geophones on the spider

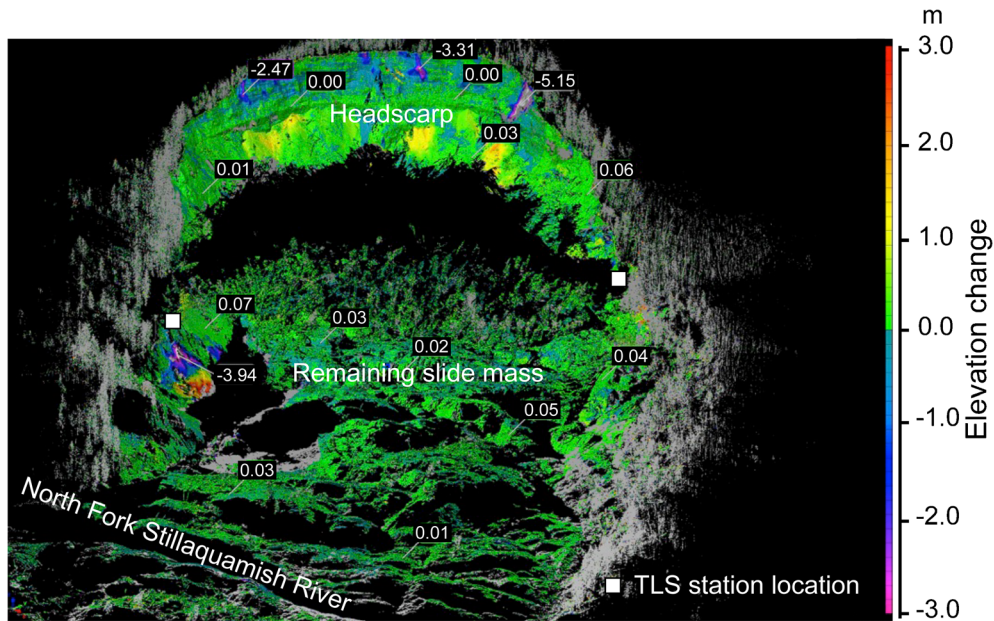
units and later correlated with time-lapse photographs. RSAM measurements, which integrated seismic activity, provided a more unified method to monitor overall site activity, as illustrated in Fig. 9, and they also detected increases in headscarp failure activity. Overall site activity noise during daylight hours (Fig. 9) may have swamped signals generated by minor sloughing from the steep headscarp, but small retrogressive failures from the headscarp produced emergent seismic signals exceeding the background seismicity generated from recovery operations during daylight hours. Waveforms from geophones on the three spider units for one such event, on April 25, are shown in Fig. 10 (data available through IRIS). The event, documented in a video recorded by a nearby on-site geologist, consisted of a small headscarp failure in the upper outwash sands and underlying more coherent glacial till that slid, impacted, and travelled across the downslope remaining landslide deposit. About 15 s later (time 22:41:16 in Fig. 10), a larger topple composed of similar materials occurred; it also impacted, disaggregated the till into smaller blocks, and slid across the downslope main slide mass. These two small failures and transport of their deposits occurred over about 25 s. Impacts from the two failures and subsequent shaking from debris disaggregation and sliding are clearly seen in the waveforms in Fig. 10. Interestingly, seismic responses from this small event helped characterize travel times from the landslide to nearby seismic stations and thus aided seismic analysis of the March 22 catastrophic failure (Iverson et al. 2015).

### Motion of the remaining landslide block

Over the approximately 5 weeks of intensive monitoring, the large rotational mass remaining upslope of the recovery operations continued to displace slowly. Several techniques were used to document this slow motion, including periodic repeat TLS scans and near real-time L1 GPS positions obtained from the spider unit placed on this mass (OSO3). Elevation differences in sequential DEMs constructed from repeat TLS scans (Fig. 8) indicated small displacements of the order of centimeters per week.

Using near real-time GPS positional data (Reid et al. 2021), we tracked the time history of landslide displacement. Figure 11 shows the 3D displacement over time from a spider located on the remaining landslide mass (OSO3) and a curve fit to the data using locally weighted smoothing (LOWESS). It also shows two derivatives of displacement—velocity and acceleration—along with their corresponding LOWESS smoothed curves. These types of plots with derivatives were created periodically (not in near real-time) and made available to the Landslide Monitoring Team during the response. Also available were cumulative precipitation data from a rain gauge located upslope of the main headscarp. Several trends are notable in Fig. 11. Overall the average speed of the main slide mass was about 0.01 m/day (dashed line in Fig. 11 and categorized as “slow” on the Cruden and Varnes (1996) velocity scale). Over time, velocities decreased slightly, except after April 16 when small velocity or acceleration increases occurred during or shortly following modest pulses of rain (Fig. 11). Vertical GPS-derived displacements were similar to those obtained from differencing repeat TLS scans. Positional data from the other two GPS-enabled spiders (OSO1 and OSO2) placed upslope of the headscarp and on the western slope were sparse, as the units were located in thick forest that resulted in poor GPS satellite visibility. Despite the relative paucity of GPS-derived positions from both of these spider





**Fig. 8** Elevation differences over a 2-week period on the headscarp and remaining main mass of the Oso landslide obtained from repeat terrestrial laser scans (TLS). Small white numbers are local elevation differences in meters. Black areas indicate regions of no TLS data. Image available to the LMT during the landslide response, with notations added here

units, the data that were available indicated no appreciable motion.

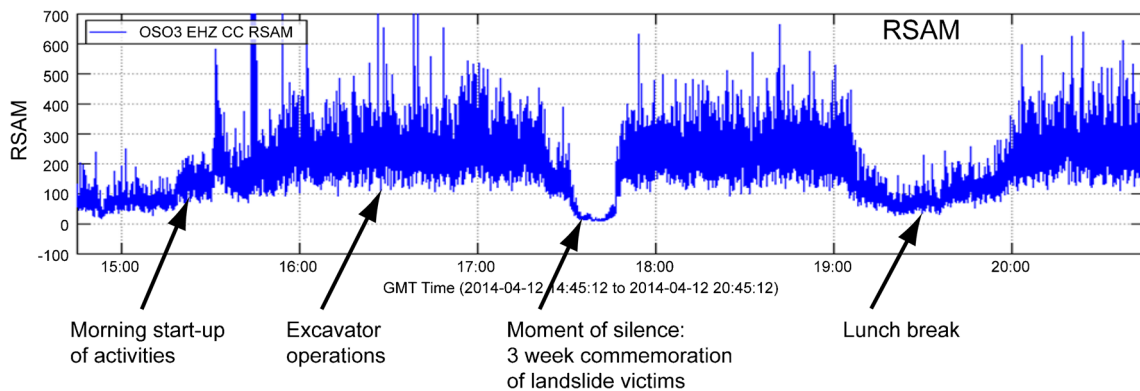
#### Discussion of lessons learned

Responses to landslide crises can vary widely, ranging from the assessment of recent activity relative to past landslide events, to on-going monitoring of current movement, to collecting perishable data to aid future event forecasting (Collins et al. 2021). The 2014 Oso landslide response involved a combination of all these aspects. Lessons learned from our monitoring efforts that may aid future rapid responses and support crisis management include the following: (1) the necessity of ready-to-go technical capabilities; (2) the value of redundant sensors, on-site observers, and multiple techniques in a complete monitoring system; (3) the benefits of clear avenues of communication; and (4) the importance of

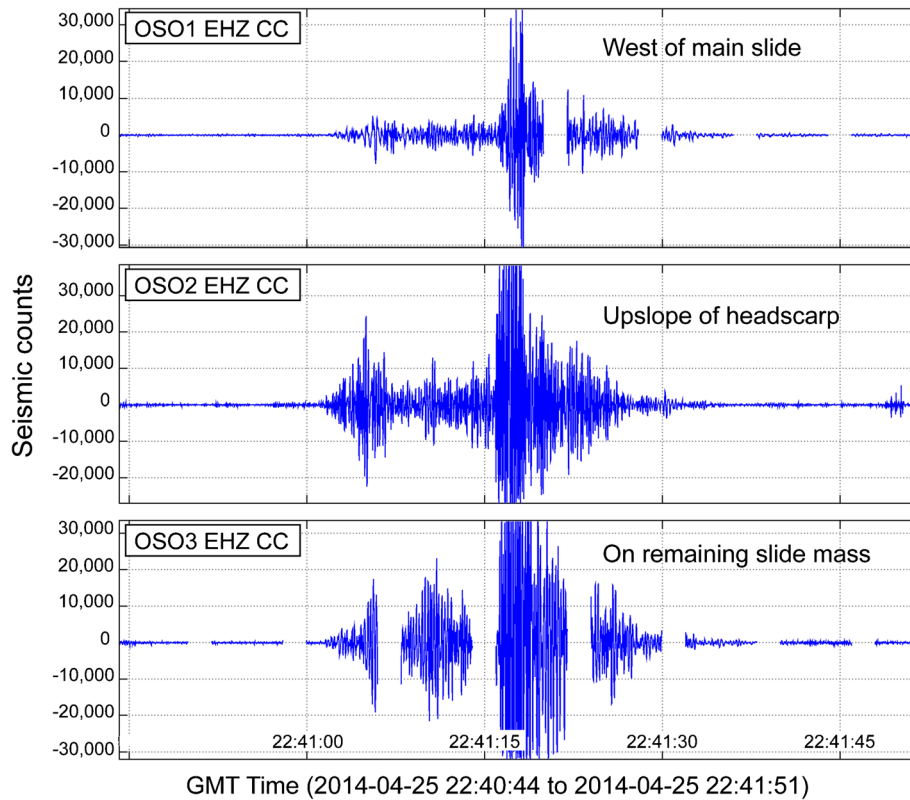
continued research efforts to utilize near real-time data to provide adequate warning. We draw from the activities described above to illustrate these points.

#### Need for technical capabilities

To quickly evaluate and monitor an active landslide, landslide expertise and ready-to-deploy technical capabilities are needed. During the Oso event, many landslide experts from multiple agencies contributed to the monitoring efforts; these experts had a wide range of experience evaluating different styles of landsliding and their understanding of landslide processes directly aided search operations. Moreover, several of the agencies (USGS and WSDOT) had extensive capabilities in both installing and maintaining near real-time monitoring systems and detecting ground changes



**Fig. 9** Integrated seismic energy (over 10-s intervals) portrayed as RSAM (Real-time Seismic Amplitude Measurement) for a 6-h period (on 12 April 2014) recorded by a spider unit (OSO3) located on the remaining landslide mass



**Fig. 10** Seismic waveforms generated by small headscarp failures on 25 April 2014 and recorded by geophones from three spider units (see Fig. 6 for locations). Energy units are shown as seismic counts. Short gaps in data are presumably from transmission losses

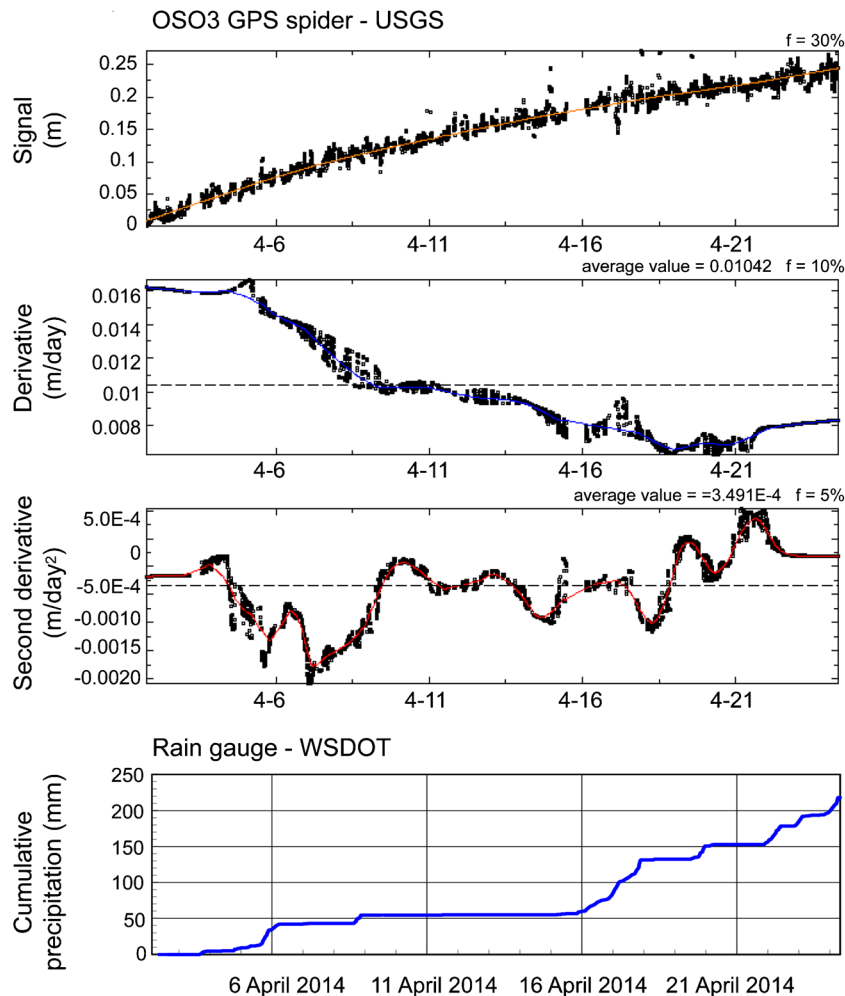
through repeat surveys. This wide-ranging experience, combined with having caches of ready-to-deploy equipment, enabled a rapid response. For example, USGS spider units had been previously deployed on other landslides (Harp et al. 2008) and units scheduled for installation on the Cleveland Corral landslide perched above U.S. Highway 50 in California were able to be readily diverted to Oso. We also found that a variety of complementary techniques allowed a more comprehensive view of landslide activity. The upslope survey lines and extensometers were crucial to assessing the potential for large-scale slide retrogression. Continuous GPS and repeat TLS scans detected motion of the remaining slide mass, whereas seismic analysis revealed the occurrence of smaller headscarp failures.

In addition, other types of landslide expertise were highly valuable during the Oso response. Crucial analyses, conducted off site, included the development of deposit thickness maps from lidar DEM differences, the assessment of past regional landslide activity (Haugerud 2014; Badger 2015), and the numerical simulation of landslide dynamics to guide search and recovery operations (Iverson et al. 2015; Iverson and George 2016). Due to the duration of continuous monitoring efforts, many different teams of USGS geologists rotated into positions with responsibility for constantly interpreting the incoming near real-time data. Not all these teams, however, had prior experience evaluating the monitoring observations and near real-time data streams. This lack led,

in some cases, to minor misinterpretations of noise in the seismic and extensometer data which were subsequently corrected through training. This issue highlights the need for even experienced landslide responders to have direct familiarity with the types of data and anticipated behaviors detectable from the deployed monitoring systems.

Most landslide scientists do not have training in crisis response. Those providing technical advice to emergency managers during landslide crises would likely benefit from prior training in the Incident Command System (Phillips et al. 2011), which is used internationally. Given that postevent trauma following fatal events is relatively common, an awareness of incident stress and the techniques and resources used to manage such situations would be a valuable asset to landslide crisis responders (Everly Jr. et al. 2000).

Acknowledging this lesson, the USGS has added landslide technical expertise and monitoring capabilities in the years since the Oso event. These additions include having prescribed mission assignments for providing technical assistance to incident managers, as well as hiring a landslide seismologist and a landslide disaster response coordinator. The USGS has developed and performed training for a GPS-seismic spider system designed for rapid deployment, named LORAS (Landslide Optimized Real-time data Acquisition System). It has also acquired new instrumentation for remotely monitoring hazardous landslide sites, including long-range TLS capabilities.



**Fig. 11** 3D downslope displacement (measured signal), velocity (derivative), and acceleration (second derivative) of the GPS-enabled spider (OSO3) on the remaining main Oso slide mass during April 2014. Fifteen-second epoch GPS data from the spider units were processed every 10 min. GPS data available in Reid et al. (2021). As derivatives are sensitive to noisy data, curve fits using LOWESS smoothing with  $f$  percentages are shown. Precipitation data from rain gauge located above headscarp also shown. Data portrayed in local time

### Value of redundant techniques in a complete system

Given the uncertainties in the general forecasting of large landslide behavior, as well as reliably predicting postevent Oso landslide behavior combined with the potential risks to hundreds of recovery workers from subsequent collapse, installing a robust and comprehensive monitoring system was paramount. We utilized multiple and somewhat redundant techniques with clearly defined monitoring objectives, namely, detecting precursory ground deformation that might precede additional large-scale, rapid slope failure. Moreover, we designed and deployed an end-to-end system that included field sensors, telemetry, a web-based Information Technology structure to capture and display data via the internet, and defined protocols with specific action items that depended on the level of slide activity. Use of different sensors with different telemetry systems combined with periodic ground and aerial lidar surveys enabled accurate assessment of current conditions. Because the various agencies involved already had experience with these techniques, they could be quickly deployed, and their data readily interpreted. System redundancy ensured the

acquisition and availability of at least some current data, even if specific sensors malfunctioned or provided ambiguous results. Geologists stationed in the field were also a crucial element of the system. For example, if the origins of seismic signals were ambiguous in the incident command center, a quick call to the field observer often clarified the situation and calmed nerves regarding possible failures. Redundancy in monitoring data also reduced the uncertainty in assessing the landslide's current status and displacement trends.

Commonly used monitoring techniques that we considered deploying but did not include: ground-based (GB) radar techniques such as GB-InSAR (Casagli et al. 2010; Meier et al. 2016), DEM differencing using structure-from-motion (SfM) analysis of imagery from repeat drone or unmanned aerial vehicle (UAV) flights (Cook 2017; Warrick et al. 2019), and continuous near real-time video streaming of the landslide scarp and deposit. These techniques were not employed at Oso for various reasons. At the time, our ability to rapidly interpret ground-based radar data in near real-time was limited and, importantly, the estimated



mobilization time for this type of monitoring was longer than the initial 2-week response window. Airspace over the slide area was highly restricted and most federal agencies at the time were legally unqualified to operate UAVs, thereby restraining drone usage. In addition, internet bandwidth needed for continuous video streaming at the relatively remote site was limited and in demand by various concurrent emergency uses. If these methods had been readily available, they could have aided our monitoring efforts. Instead, we focused on the value of implementing multiple techniques that we could rapidly deploy and readily interpret.

#### Benefits of clearly defined communication channels

In the chaos of a massive and deadly landslide disaster, clear lines of communication between the landslide experts and a variety of different audiences are crucial. On-site landslide experts typically need communication channels between other landslide experts, between the emergency response or local government managers, between their own agency or company managers, and between the public and news media. Moreover, conveying large uncertainties about future behavior requires different approaches for different audiences (e.g., DeGraff et al. 2015). During the Oso event, the Landslide Monitoring Team, composed of geologists and geotechnical engineers from the responding agencies, conducted daily meetings and conference calls to keep all team members informed about current activity levels. Members of the team that performed the previous day's continuous monitoring would prepare a summary of daily activities for the following day's meeting. Team members also had access to available monitoring data, including the near real-time data streams at all times, and could readily contact other team members with questions or concerns. This format worked well overall, incorporating diverse expertise and building crucial trust between geologists on the team. In hindsight, the approach might have benefitted by designating time to reassess the overall landslide status, such as potentially modifying the “no-go” line location in light of updated information. However, the large uncertainty about an ending date reduced the impetus to reevaluate earlier decisions.

During the monitoring phase of the Oso response, routine daily communications between the Landslide Monitoring Team and the emergency managers of the Incident Management Team directing the rescue and recovery operations were handled through one conduit—the geology liaison—this is typical of Incident Command System structures. Distilling scientific observations and expert opinions from the LMT into a cohesive and coherent message was an ongoing challenge and priority during the evolving crisis. This format worked quite well and also built trust between the LMT and IMT. In addition to routine communications, members of the LMT did have the ability to connect directly to field operation managers if landslide activity warranted an immediate evacuation.

During the response, communications with the public and news media about the landslide were typically handled through an on-site point-of-contact public affairs officer working with the IMT. Although this was an effective conduit for public briefings on recovery activities, the amount of scientific information conveyed about the landslide was limited. This led to a dearth of technical information released about the landslide event itself, and it contributed to unsubstantiated and widely disseminated speculation from other geologists not involved in the response. Although the

ICS structure has proven effective in many disaster responses, its strict control can create challenges for communication, data sharing, and access to a disaster location, particularly for academics and other interested parties. Later in the response, after the initial evaluation and monitoring deployment phase, the USGS did post current information and simulations on its web site. However, future responses could benefit from having a scientific public information plan in place at the onset, to keep the public and news media outlets better informed about the nature of the event. Since the Oso event, discussions between the USGS and academic researchers have focused on developing an organizational structure to better integrate hazard activities during future crisis response efforts, given liability and chain-of-command issues.

#### Importance of research efforts for warning

Despite the widespread use of landslide monitoring, forecasting rapid failure using monitoring data remains an active research area. Such forecasting is fraught with uncertainty, even with multiple near real-time data streams. To better understand landslide movement behavior, large investigative monitoring networks using sophisticated surface and subsurface monitoring techniques have been deployed at sites such as Randa, Switzerland (Loew et al. 2012), Turtle Mountain, Canada (Froese et al. 2012), and Åknes, Norway (Blikra 2012). However, time and resources are required to construct these extensive networks and a past record of landslide activity is needed to enable confident behavior forecasting. During a landslide crisis, both of these are absent. Responders in an emergency effort do not have the luxury of collecting observations, analyzing data, and then developing models and failure criteria.

In most cases, the inability to accurately forecast landslide behavior during a rapid response is due to gaps in scientific knowledge about the meaning of broad landslide movement patterns and to a lack of knowledge about site-specific conditions. A variety of factors influence the propensity for rapid, catastrophic failure, including material properties and slide geometry (e.g., Fell et al. 2007). In general, a moving landslide is of more concern than a static hillslope and an accelerating landslide is of more concern than one with steady or decelerating motion. Beyond these simplistic rules-of-thumb, landslide behaviors can vary greatly. This uncertainty emphasizes the need to adapt any responses to changing conditions in the extent and amount of landslide activity.

To address near real-time forecasting needs, a wide spectrum of researchers have advocated that specific patterns in velocity, the reciprocal of velocity, or acceleration of a moving mass can reliably predict the timing of rapid, catastrophic failure (e.g., Saito 1965; Varnes 1983; Fukuzono 1985; Salt 1988; Voight 1989; Crosta and Agliardi 2003; Rose and Hungr 2007; Federico et al. 2012; Dick et al. 2015; Segalini et al. 2018; Intrieri et al. 2019; Chen and Jiang 2020). Because near real-time data can be noisy, other investigators have developed supplemental techniques to enable more accurate time-of-failure predictions (e.g., Intrieri and Gigli 2016; Manconi and Giordan 2016; Carlà et al. 2017; Zhang et al. 2020; Zhou et al. 2020). Despite notable successes, approaches based on velocity or acceleration patterns have not always led to reliable timing forecasts for all slides (e.g., Petley et al. 2002; Rose and Hungr 2007; Dick et al. 2015; Intrieri and Gigli 2016). The amount of accumulated strain prior to catastrophic failure is also of concern and laden with uncertainty, particularly in materials susceptible to rapid strength loss under large strains.

A landslide crisis is a difficult environment in which to divine patterns and forecast behavior. Instead, research efforts to construct a framework for assessing potential behaviors are needed beforehand. Advanced monitoring techniques, such as TLS, GPS, ground-based radar, SfM, and seismic analysis, can provide a plethora of information about landslide activities, including the detection of precursory deformation and seismic activity. Nevertheless, the overarching challenge is to forecast landslide behavior using data obtained in near real-time.

### Conclusions

The rapid failure of the Oso landslide in March 2014 resulted in a deadly, highly mobile debris avalanche-flow. For weeks following the event, hundreds of workers toiled beneath the landslide scar, unable to avoid potential exposure from any additional slope failures. Using the monitoring experiences of multiple governmental agencies, we quickly installed several near real-time systems and performed numerous episodic surveys to detect any precursory ground movement that might provide advance warning of another catastrophic slope failure. We found that total station surveying methods, repeat TLS scans, extensometers, continuous GPS, seismic monitoring, and on-site observers each provided crucial information. Absent the technical guidance and monitoring information provided to emergency managers at Oso, search and recovery operations would have been operating with greater uncertainty, potentially affecting their efficiency and safety. Lessons learned from this case-study include the following: (1) the need for preexisting technical expertise and ready-to-deploy capabilities; (2) the value of redundant monitoring techniques in a complete system; (3) the benefits of clearly defined lines of communication; and (4) the importance of research efforts to improve forecasting of landslide behavior and issuance of appropriate warnings, particularly using near real-time data streams. These lessons should prove beneficial in future landslide crises.

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with similar URL naming conventions for the other spiders). IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the U.S. National Science Foundation under Cooperative Agreement EAR-1261681. Kate Allstadt (USGS), Jason Kean (USGS), and an anonymous reviewer helped improve this manuscript. Finally, we would like to thank all those who contributed to the Oso emergency response, including first responders, local volunteers, and recovery teams. Author affiliations reflect their employing institutions at the time of the Oso response. Supplemental funding for monitoring equipment and response efforts was provided by a Mission Assignment from the U.S. Federal Emergency Management Agency (FEMA). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

### Declarations

No conflicts of interest are noted. GPS monitoring data from the USGS spider units are available in the Reid et al. (2021) data release cited in the manuscript. Seismic monitoring data from the USGS spider units are available through IRIS. All authors contributed to the Oso landslide response and commented on previous versions of the manuscript.

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