Closure to the Discussions of:

"CASE STUDY: OSO Landslide of 22 March 2014 — Material Properties and Failure Mechanism" by

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The writers appreciate the interest and discussions by Richard M. Iverson, Jeffery R. Keaton and his co-authors of Keaton et al. (2014), and Vishnu Diyaljee.

The discussion by Iverson mainly focuses on the difference between the two-phase failure mechanism proposed by the writers in Stark et al. (2017) and the single-phase mechanism proposed by Iverson et al. (2015). Iverson et al. (2015) postulate that the Oso Landslide occurred in a single-phase that was followed by a relatively small debris avalanche from the nearly vertical headscarp, such as those shown in **Figures 1 and 2**. The initial stage of their single-phase mechanism starts at a low elevation and retrogresses upslope even though the slide mass traveled over 1.5 km. The retrogressive second-stage of the single-phase mechanism bumped into the first-stage and

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somehow accelerated it and the pre-existing colluvium along the slope toe enough to push it 1.5 km across the floodplain even though this occurred in a single, deep-seated, and coherent event.

Figure 1: Photograph on 22 May 2014 from headscarp looking down on small debris avalanche cited by the Iverson Discussion (see dashed red line) as cause of second 22 March 2014 recorded ground motion. (Photograph by T.D. Stark; DSC09275.jpg)

Conversely, the writers propose a mechanism with two distinct and significant phases of movement with the first-phase (Phase I) occurring at a high elevation and involving the top plateau or Whitman Bench. This first-phase moved downslope and impacted the pre-existing colluvium along the slope toe with enough force and energy to cause it to undergo a undrained large strength loss and displace over 1.5 km across the valley. The second-phase is a retrogressive landslide

(Phase II) that dropped-in behind and over-rode a portion of the Phase I slide mass but remained on the slope and maintained a frictional shear strength.

Figure 2: Close-up photograph on 22 May 2014 from headscarp of small debris avalanche cited by the Iverson Discussion (see dashed red line) as cause of second 22 March 2014 recorded ground motion. (Photograph by T.D. Stark; DSC09275.jpg)

Other field evidence that reinforces the writers two-phase slide mass is the morphology of the debris in the override zone or area of contact between Phases I and II (see Figures 10 and 11 in Stark et al., 2017, as well as Figure 7 in Aaron et al., 2017). The soils in the override zone show no evidence of high compressional stresses transferred between two slide masses, such as faults, thickening, or pressure ridges, which should have occurred if a single-phase event with compressional loading occurred as suggested by Iverson. Instead the runout of the Phase II slide mass was limited, because it was unsaturated and the soil shear strength remained mainly frictional, which is evident by the large and intact slide blocks in Phase II. **Figures 1 and 2** reinforce the unsaturated, variable, and strong nature of the outwash sands above and below the glacial till in the upper portion of the slope, which corroborates that these materials did not liquefy during the Oso Landslide on 22 March 2014.

Oso Landslide Volume

Iverson also raised some concerns about the writers' slide mass volume, mobility, and chronology, which are addressed in the following three sections. Stark et al. (2017) focus on the initiation and failure mechanics of the 2014 Oso landslide and does not include the accompanying volumetric and dynamic analyses of the landslide due to space constraints. A companion paper by the writers, i.e., Aaron et al. (2017), presents simulation of the landslide dynamics using the software DAN3D (Hungr and McDougall, 2009), which can analyze landslide motion over three-dimensional (3D) terrain. The DAN3D simulation results were verified using field evidence of the impacted area, evacuation and accumulation zones, slide mass thicknesses, and vulnerability indices. The 3D simulations resulted in a comparatively similar slide mass volume (~7.9 to 8.3 million cubic meters) as that calculated by Iverson et al. (2015). In particular, the DAN3D simulations in Aaron et al. (2017) yielded slide mass volumes for Phases I and II of the landslide of about 2.8 and 5.3 million cubic meters, respectively, for a total slide mass volume of about 8.1 million cubic meters.

Oso Landslide Mobility

Iverson raises an interesting point about the challenge of putting the mobility of the Oso landslide in context. Iverson states that the Slope Height/Runout Length (H/L) ratio of the Oso landslide is unusually small for subaerial landslides of similar volume, which is described in detail in Stone and Service (2014). However, Iverson initially acknowledges that the H/L value of the Oso landslide does not appear to be anomalous compared to the H/L database compiled by Hunter and Fell (2001, 2003) for strongly retrogressive flowslides. Iverson then dismisses all of the strongly retrogressive flowslides in the Hunter and Fell (2001, 2003) database as good analogues for the Oso landslide due to differences in material type.

When these many strongly retrogressive flowslides are excluded from the Hunter and Fell (2001, 2003) database, the remaining landslide types consist primarily of failure types that Hunter and Fell (2001, 2003) classify as 'dilative' and flowslides in loose fills, coal waste spoil piles, coking coal, and chalk cliffs. It is unclear to the writers why these cases are better analogues to the Oso landslide, and can therefore serve as background data to justify the Iverson's conclusion that the Oso slide was anomalously mobile.

Instead the writers believe that because the highly mobile colluvium in the first phase of the Oso landslide underwent a large undrained strength loss, i.e., likely liquefied, this event should be classified as a flowslide (using the terminology of Hungr et al. (2014)). We therefore think it is meaningful to compare the mobility of the Oso landslide to that of the other flowslides in the Hunter and Fell (2001, 2003) database, including strongly retrogressive flowslides. By doing so, the mobility of the Oso landslide can be understood in the context of other landslides that occur in contractive not dilative materials. If other flowslides are included in the comparison, the Oso landslide is not anomalously mobile as Iverson concludes and describes in Stone and Service (2014). In fact, Aaron et al. (2017) use the empirical liquefied strength ratio correlation (Stark and Mesri, 1991 and Olson and Stark, 2002) developed from earthquake-induced liquefaction flow slides involving contractive materials to nicely explain the observed runout.

The writers do acknowledge that there are not many documented examples of flowslides in overconsolidated fine grained colluvium, and that this is a limitation of comparing the mobility of the Oso landslide to most H/L datasets, e.g., Hunter and Fell (2001, 2003). To the writers' knowledge, the only well documented flowslide that involved similar overconsolidated fine-grained materials and pre-existing colluvium is the Attachie flowslide, which had an H/L of 0.135 (Fletcher et al. 2002) compared to 0.105 for the Oso landslide. Additionally, there are at least two other long runout landslides located in close proximity to the Oso landslide. One is the Rowan landslide, which has an H/L of approximately 0.100 (Iverson et al. 2015). The other is an unnamed landslide located across the valley from the Oso landslide (Haugerud, 2014), which has an H/L of approximately 0.140. Relative to this small subset of flowslides, the mobility of the Oso landslide is also not anomalous for similar materials, slopes, prior slope movements, and environmental conditions.

Oso Landslide Chronology and Mechanism

The single-phase mechanism suggested by Iverson et al. (2015) is partly based on a dynamic analysis using their runout model D-claw. The D-claw analysis is based on problematic assumptions for the Oso landslide including the failure surface being a deep-seated log spiral and the slide mass materials being represented by homogeneous, loose, saturated, and liquefiable granular soil. In particular, Iverson et al. (2015) hypothesize that the failure surface is a deep-seated log spiral even though a log-spiral failure surface is only relevant for homogeneous and isotropic materials. This assumption does not comport with the differing, anisotropic, and unsaturated soil types involved in the Oso Landslide, e.g., unsaturated outwash sand layers and glacial till in the upper portion of the slope (see **Figure 2**) and unsaturated varved silts and clays of the advanced glaciolacustrine deposit in the lower portion of the slope. More importantly, the undisturbed native soils involved in the slide are glacially overconsolidated, unsaturated, and not statically liquefiable as required by the D-claw analysis. Only the pre-existing, disturbed, and water filled colluvium along the slope toe was susceptible to a significant undrained strength loss and exhibited liquefiable or flow behavior during the 2014 landslide. The unsaturated materials remained frictional in strength (see **Figures 1 and 2**).

Recorded Ground Motions

The Iverson et al. (2015) single-phase mechanism requires the low elevation and high elevation stages of their single-phase landslide to occur within the first recorded ground motion, i.e., about two minutes duration, even though both recorded ground motions on 22 March 2014 are of similar magnitude and duration (see **Figure 3**). The two recorded ground motions on 22 March 2014 are separated by about two minutes, which would mean no small debris avalanches occurred until two minutes after the single-phase event postulated by Iverson. This also means there would only be one small debris avalanche from the nearly vertical headscarp after the single-phase event because no other similar ground motions have been recorded since the Oso landslide. The writers find this to be unlikely because there were small avalanches still occurring during the first writers' site visit about two months after the slide on 22 May 2014 (see **Figures 1 and 2**). One such small avalanche was video recorded on 25 April 2014, about one month after the 22 March 2014 landslide, by Jeffrey Jones of Snohomish County as discussed below.

Iverson mentions a small debris avalanche involving the toppling of the unsaturated outwash sands and glacial till in the upper portion of the headscarp occurred on 24 April 2014 and concludes the recorded ground motion is similar in frequency and duration as that recorded in the second seismic signal of the 22 March 2014 event (see **Figure 3**). The writers think the discusser is referring to the debris avalanche recorded by Jeffrey Jones on 25 April 2014, and referred to in Iverson et al. (2015). Jeffrey Jones of Snohomish County video recorded this avalanche on 25 April 2014 at 14:42:10 Pacific Time or 21:42 Universal Time (UT or local time + 7 hours), which can be viewed at: http://blogs.agu.org/landslideblog/2014/07/07/oso-landslide-continued-small-scale-activity/.

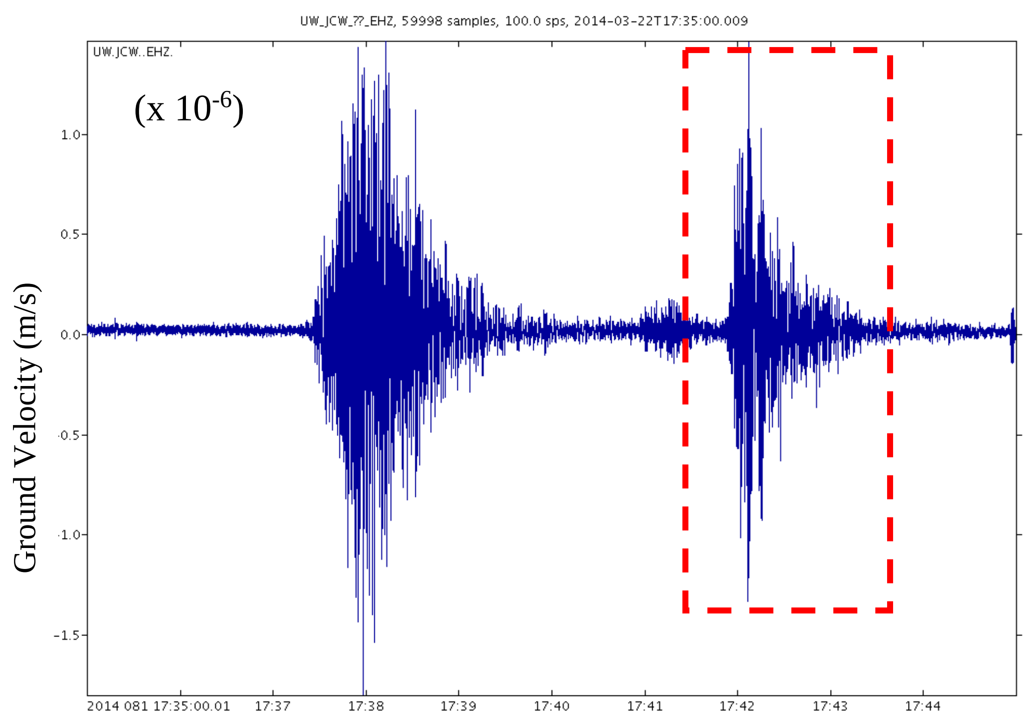

Figure 3: Close-up of recorded ground velocity at JCW during Oso Landslide on 22 March 2014.

The duration of the small debris avalanche on 25 April 2014 is shorter (~25 seconds) than the second seismic recording on 22 March 2014 (~90 seconds) shown in **Figure 3**. The writers examined the ground velocity signal recorded at JCW on 25 April 2014 at 14:42:10 Pacific Time and the duration of the recorded small debris avalanche is difficult to assess because there is no discrete event, as is the case with the second seismic signal on 22 March 2014 (see **Figure 3**). As a result, the duration of the small debris avalanche on 25 April 2014 (~25 seconds) was obtained from the video recording made by Jeffrey Jones described above and not the ground motion time history. This indicates that similar small avalanches would not create a seismic signal that is similar to the second seismic signal on 22 March 2014.

In summary, the seismic recording at Station JCW during the small debris avalanche on 25 April 2014 is not "remarkably similar" in duration to that recorded at JCW during the second seismic event of March 22, 2014 as claimed by Iverson. In addition, many of Iverson's points about the seismic signals have been previously addressed in Allstadt (2015) and Hibert et al. (2015a and b). In particular, the Hibert et al. (2015b) discussion raises concerns about the methodology used by Iverson et al. (2015) to perform their seismic inversion of the Oso landslide seismic signals, and questioned their conclusions regarding the interpretation of both the first and second seismic signals. To the writers' knowledge, this controversy surrounding the interpretation of the seismic signals has yet to be resolved. Finally, the seismic recording of the 25 April 2014 debris avalanche by a USGS seismometer temporarily deployed near the site is no longer available and should not be mentioned by Iverson because it cannot be assessed by the writers or others.

Keaton and his co-authors

The discussion by Jeffery R. Keaton and his co-authors and subsequent correspondence claims that the hypothesized failure mechanism presented by Stark et al. (2017) "is similar in many respects to that described in Keaton et al. (2014)". **Figures 4** shows the schematic rupture surface presented in Keaton et al. (2014) to illustrate their remobilization to the prehistories slide surface (Phase I) and thinking regarding the source zones of Phase 1 and 2. Some similarities between the Keaton et al. (2014) and Stark et al. (2017) schematic or conceptualized rupture surfaces include:

- Both mechanisms are two-phase mechanisms
- In both mechanisms, the Phase I rupture surface does not reach the upper plateau or Whitman Bench.
- The Phase II source material is primarily comprised of material from the Whitman Bench.

However, based on a comparison of **Figure 4** and Figure 9 of Stark et al. (2017) there are some important and significant differences between these schematic or proposed rupture surfaces, which include:

- In the Keaton et al. (2014) mechanism, their Phase I or Stage 1 failure surface is deep-seated and daylights into the bottom of the Stillaguamish River, which means a significant portion of the failure surface passes through what we interpret to be dense/strong sands and gravels underlying the weaker glacio-lacustrine clays. We note that Keaton et al. (2014) may have interpreted the site stratigraphy (and therefore the elevation of the basal sands and gravels) differently.

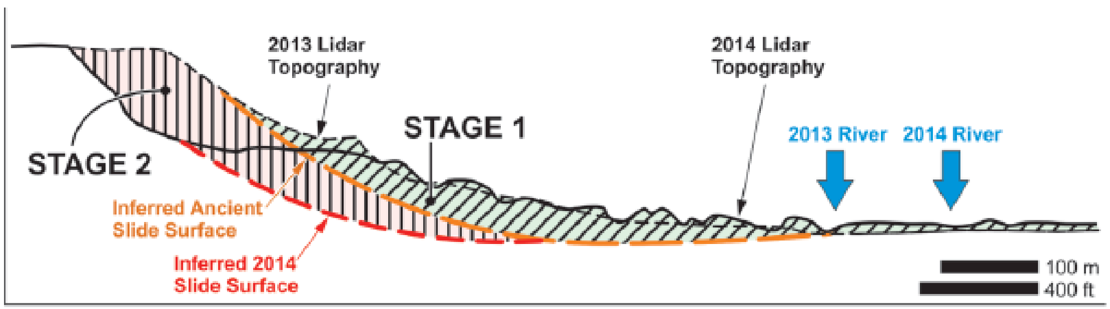

Figure 4: **Schematic or hypothesized failure mechanisms from Figure 6.1.2 of Keaton et al. (2014) (image courtesy of GEER).**

- The Keaton et al. (2014) Stage 1 failure surface rises up into the Stillaguamish River, which would stabilize the slide mass and not impart sufficient potential energy to cause the slide mass to flow 1.5 km across the valley. The writers believe the Stage 1 (Phase I) slide mass had to flow over the river not under the river to travel 1.5 km. Eye witness accounts reinforce this conclusion and state that the slide mass crossed over the river and displaced some of the river water instead of entering the river from below, such as:

Eyewitness #4:
"When (the landslide) hit the water, it shot way up, way taller than the tallest trees. Then I saw this big black wall — it must have been more than 100 feet high — rise high above the (Steelhead Drive) neighborhood. The houses, in comparison, looked minuscule. It was unbelievable." ***Seattle Times May 27th 2014***

and

Eyewitness #3:
"Eyewitness looked out a window and saw half of a ... foothill break away and surge across the North Fork of the Stillaguamish River toward her house on the opposite bank...A wall of mud estimated to be 25 feet high crashed through the home, taking both occupants with it. "Then it hit and we were rolling, the house was in sticks. We were buried under things and we dug ourselves out." ***Seattle Times May 27th 2014***

- The writers also interpret the colluvium along the slope toe from prior low elevation landslides to be much shallower than that interpreted by Keaton et al. (2014). As a result, the Keaton et al. (2014) failure surface for their Stage 1 is below the water filled colluvium so it does not directly impact the colluvium and cause it to undergo a large undrained strength loss and flow 1.5 km, which is the key to the Stark et al. (2014) proposed failure mechanism.
- The override zone or area of contact between Phases I and II (see Figures 10 and 11 in Stark et al. 2017, as well as Figure 7 in Aaron et al., 2017, and Keaton et al. (2014)) is an important post-failure observation that was recognized by Keaton et al. (2014). However, the Keaton et al. (2014) failure mechanism can only explain the override zone if their Stage 1 completely evacuated the source zone, and was later overridden by their Stage 2 slide mass. If Stage 1 completely evacuated the source zone, it is unlikely that Stage 2 would exhibit a deep-seated failure surface as shown in **Figure 4** because the entire source area is unbuttressed and there are weak layers near the top of the Advanced Glacio-Lacustrine Deposit that would

have accommodated development of a failure surface and resulted in a shallower slide mass as discussed by Stark et al. (2017)).

- The curved cross-section in **Figure 4** by Keaton et al. (2014) starts at the middle of the final scarp, which conflicts with the slide starting on the east side of the slope because the ancient landslide bench was considerably narrower on the east side than in the middle of the ancient bench. This is a key pre-failure observation that Keaton et al. (2014) does not mention and/or did not recognize.

Keaton et al. (2014) revised their deep-seated circular failure mechanism in **Figure 4** to a more similar failure mechanism as Stark et al. (2017) in Wartman et al. (2016) (see **Figure 5**). Comparing the revised hypothetical failure surfaces in **Figure 5** with Figure 9 of Stark et al. (2017) shows there are still significant differences between the revised schematic failure mechanism in Wartman et al. (2016) and the Stark et al. (2017) schematic failure mechanism, some of which are briefly summarized below:

- Wartman et al. (2016) now use a three (3) stage failure mechanism instead of a two (2) stage mechanism as in Stark et al. (2017).
- The Wartman et al. (2016) failure surfaces are still much deeper, about 50 m deeper, than the Stark et al. (2017) Phase I failure surface, which does not comport with the Phase I slide mass impacting the water-filled colluvium and causing a large undrained strength loss.
- Stage 1a in Wartman et al. (2016) is shallower than in Keaton et al. (2014) and may be able to disturb some of the water filled colluvium along the slope toe and cause

an undrained strength loss as proposed by Stark et al. (2017), which is a key difference between the Keaton et al. (2014) and Wartman et al. (2016) failure mechanisms. However, the Stage 1a slide mass still appears to be deep-seated and located in the dense sands and gravels of the Olympia Formation, which is unlikely as described above.

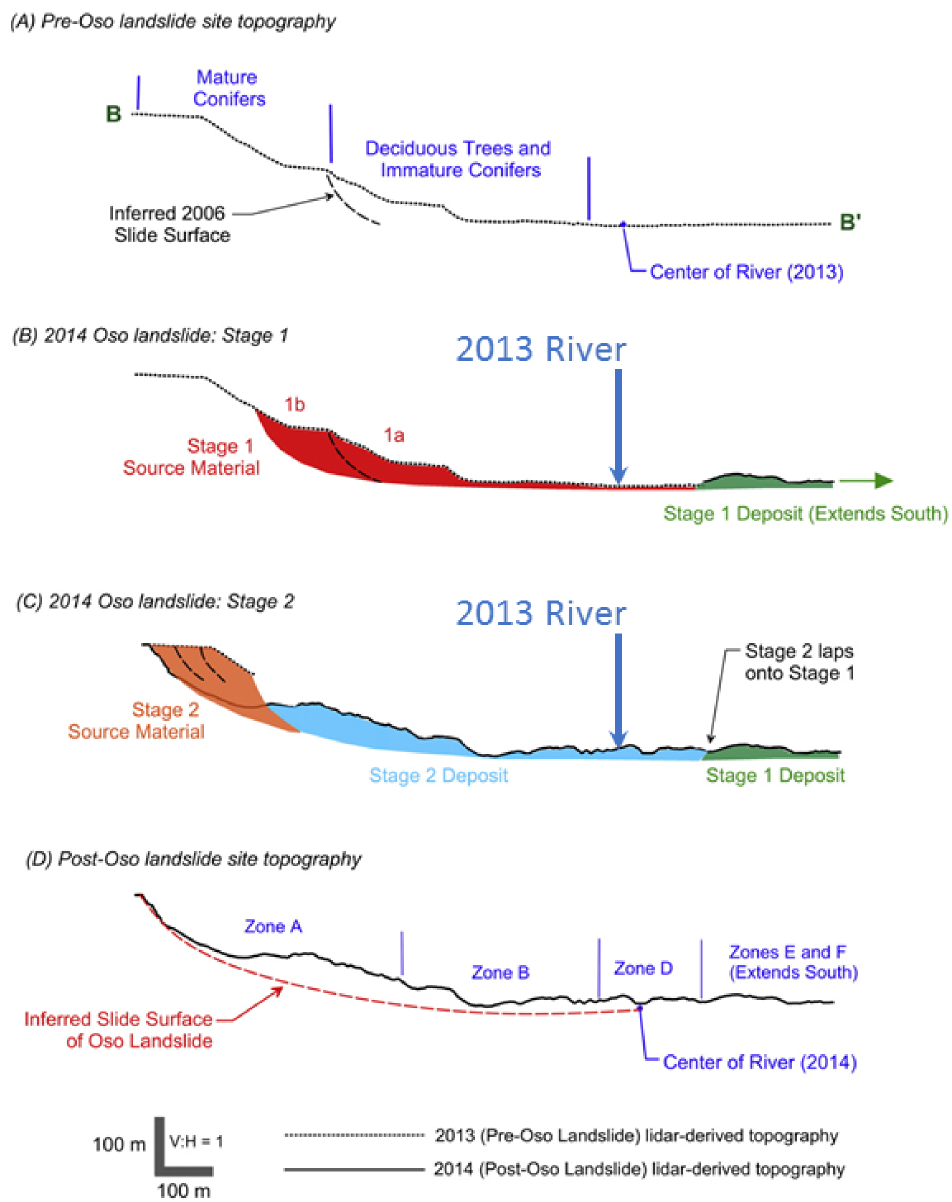

Figure 5: **Hypothesized failure mechanism from Wartman et al. (2016) (image courtesy of Journal of Geomorphology).**

- For the Wartman et al. (2016) mechanism to be similar to the writers' mechanism, the bottom of the Stage 1b failure surface would have to be higher so it can daylight near the top of the Stage 1a slide mass and thus generate less shear resistance and also override a portion of the Stage 1a slide mass. **Figure 5** shows the Stage 1b failure surface also passes through the dense sands and gravels of the Olympia Formation, which makes it difficult for a portion of Stage 1b to override Stage 1a because it is well below the ground surface.

Effect of River Erosion

The writers agree with the Discussion comments of Dr. Diyaljee that the previous river locations could have created a zone of preferential seepage. However, the river channel had been pushed significantly south of the slope toe by the 2006 landslide (see Figure 6 in Stark et al. 2017) so the impact of the river seepage on the 2014 landslide was limited. However, this is an interesting aspect for future studies.

Clarifications

For clarification purposes, the writers do not identify a “precise location” of the head of their first-phase as Iverson claims but state that the first-phase involves the Upper Plateau or Whitman Bench. An inverse stability analysis was performed to identify a compound failure surface on the east side of the slope that could mobilize the Upper Plateau and release a slide mass with sufficient potential energy to liquefy the water-filled colluvium along the slope toe and displace it about 1.5 km across the valley. This possible failure surface is shown in Figure 9 of Stark et al. (2017) for illustration purposes and is not meant to delineate the “precise” location of the Phase I scarp because there is no photographic or other evidence of the first-phase.

Another clarification is Iverson claims that the Phase I slide mass of the writers’ mechanism “traveled at high speed across the entire North Fork Stillaguamish River floodplain”. Figures 10 and 12 and the accompanying text in Stark et al. (2017) clearly states that most of the Phase I slide mass stopped well before SR530 and only the disturbed and water-filled colluvium traveled about 1.5 km across the floodplain and not “across the entire” floodplain as stated by Iverson in his Discussion. Figure 9 of Stark et al. (2017) also shows that the Phase II failure surface daylights well above the river in the Advanced Glacio-Lacustrine deposit and thus is not deep-seated like the failure surfaces hypothesized by Iverson et al. (2015) and Keaton et al. (2014).

Acknowledgment

The writers are greatly saddened to acknowledge the unexpected passing of Professor Oldrich Hungr before he could review the final version of this Closure. Thus, this Closure does not necessarily reflect the views and insights of our distinguished and highly knowledgeable co-author. Professor Hungr will be greatly missed by those who had the pleasure and honor to know and work with him.

References

Aaron, J., Hungr, O., Stark, T.D., and Baghdady, A.K., (2017). "Oso, Washington, Landslide of March 22, 2014: Dynamic Analysis*." J. Geotech.Geoenv. Eng.,* 143 (9) September, 2017, pp. 05017005-1 – 05017005,-DOI: 10*10.1061/(ASCE)GT.1943-5606.0001748.*

Allstadt, K. (2015). "Interactive comment on 'Seismology of the Oso-Steelhead landslide' by C. Hibert et al." *Nat. Hazards Earth Syst. Sci. Discussions,* 2, C3274-C3282, http://www.nat-hazards-earth-syst-sci-discuss.net/2/C3274/2015/nhessd-2-C3274-173 2015.pdf. Fletcher, L., Hungr, O., and Evans, S. G. (2002). "Contrasting failure behaviour of two large landslides in clay and silt." Can. Geotech. J., 39(1), 46–62.

Fletcher, L., Hungr, O., and Evans, S. G. (2002). "Contrasting failure behaviour of two large landslides in clay and silt." Can. Geotech. J., 39(1), 46–62

George, D. L., and Iverson, R. M. (2014). “A depth-averaged debris-flow model that includes the effects of evolving dilatancy. II: Numerical predictions and experimental tests.” Proc. R. Soc. London: Math. Phys. Eng. Sci., 470(2170), 20130820.

Haugerud, R. A. (2014). “Preliminary interpretation of pre-2014 landslide deposits in the vicinity of Oso, Washington: U.S.,” USGS Report. No. 2014–1065, Geological Survey, Reston, VA.

Hilbert, C., Stark, C.P., and Ekström, G. (2015a). “Dynamics of the Oso-Steelhead landslide from broadband seismic analysis,” *Nat. Hazards Earth Syst. Sci.*, 15, 1265–1273. http://dx. doi.org/10.5194/nhess-15-1265-2015.

Hibert, C., Stark, C. P., and Ekström, G. (2015b). “Interactive comment on ‘Seismology of the Oso-Steelhead landslide’ by C. Hibert et al.” *Nat. Hazards Earth Syst. Sci. Discussions*, 2, C3671-C3689, https://www.nat-hazards-earth-syst-sci-discuss.net/2/C3671/2015/nhessd-2-C3671-2015.pdf.

Hunter, G. J., and Fell, R. (2001) “Rapid” Failure of Soil Slopes.” UNICIV Report No. R-400 (ISBN:85841 367 1). The University of New South Wales, School of Civil and Environmental Engineering, Sydney, Australia.

Hunter, G. J., and Fell, R. (2003). “Travel distance angle for ‘rapid’ landslides in constructed and natural soil slopes.” *Can. Geotech. J.*, 40(6), 1123–1141.

Hungr, O., and McDougall, S. (2009). “Two numerical models for landslide dynamic analysis.” Comput. & Geosci., 35(5), 978–992.

Hungr, O., Leroueil, S., & Picarelli, L. (2014). “The Varnes classification of landslide types, an update.” Landslides, 11(2), 167–194. https://doi.org/10.1007/s10346-013-0436-y

Iverson, R. M., and George, D. L. (2014). “A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I: Physical basis.” Proc. R. Soc. London A: Math. Phys. Eng. Sci., 470(2170), 20130819.

Iverson, R.M., George, D.L., Allstadt, K., Reid, M.E., Collins, B.D., Vallance, J.W., Schilling, S.P., Godt, J.W., Cannon, C.M., Magirl, C.S., Baum, R.L., Coe, J.A., Schulz, W.H., and Bower, J.B. (2015). "Landslide mobility and hazards: implications of the 2014 Oso disaster." *Earth and Planet. Sci. Let.*, 412, 197-208. doi: 10.1016/j.epsl.2014.12.020.

Iverson, R.M., and George, D.L. (2016). "Modeling landslide liquefaction, mobility bifurcation and the dynamics of the 2014 Oso disaster." *Géotechnique*, 66, 175–187, doi: 10.1680/jgeot.15.LM.004.

Keaton, J. R., Wartman, J., Anderson, S., Benoit, J., deLaChapelle, J., Gilbert, R., Montgomery, D.R., (2014). "The 22 March 2014 Oso Landslide, Snohomish County, Washington." Geotechnical Extreme Event Reconnaissance Report GEER-036 (GEER), July 22, 2014, 186 p.

Olson, S. and Stark, T. D. (2002). "Liquefied strength ratio from liquefaction flow failure case histories." Can. Geotech. J., 39(3), 629–647.

Stark, T.D., Baghdady, A.K., Hungr, O., and Aaron, J. (2017). "Case Study: Oso, Washington, Landslide of March 22, 2014 — Material Properties and Failure Mechanism." *J. Geotech.Geoenv. Eng., 143(5), May*, 2017, pp. 05017001-1 - 05017001-13, http://ascelibrary.org/doi/pdf/10.1061/(ASCE)GT.1943-5606.0001615 .

Stark, T. D. and Mesri, G. (1992). "Undrained shear strength of liquefied sands for stability analysis." J. Geotech. Eng., 10.1061/(ASCE)0733-9410(1992)118:11(1727), 1727–1747.

Stone, R. and Service, R.F. (2014). "Even for slide-prone region, landslide was off the chart." *Science*, 344, 16-17.

Tart, R. G. (2016). "Why the Oso landslide caused so much death and destruction." Proc., 2016 Geotechnical and Structural Engineering Congress, ASCE, Reston, VA , 1545–1554.

Wartman, J., Montgomery, D.R., Anderson, S.A., Keaton, J.R., Benoît, J., de la Chapelle, J., and Gilbert, R. (2016). “The 22 March 2014 Oso landslide, Washington, USA.” *Geomorphology*, 253, 275–288. doi: 10.1016/j.geomorph.2015.10.022.