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Interactive comment on "Influence of extreme long-term rainfall and unsaturated soil properties on triggering of a landslide – a case study" *by* Håkon Heyerdahl

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To both referees

I want to express my thanks to both anonymous referees #1 and #2 for their efforts to give thorough and relevant comments and suggestions to the submitted paper. In my answers to the referee comments, I try to give answers to all comments.

According to the procedure of the NHESS discussion process, a revised paper is not submitted at this time, which means that intended changes in the paper are only described principally in my answers.

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Some referee comments are general and not possible to answer/solve directly in the answers. At the start of my answer to each referee, I discuss these general comments, before answering the specific comments from each of the Referees. For specific comments, I intend to improve the paper in line with my answers, or I give a clarification where there may be misunderstandings.

Finally, I hope that my response to the referee comments will give me the opportunity to present a revised paper at a later stage.

Referee #2

I am happy that Referee #2 considers the topic appropriate for NHESS, and I thank the referee for many constructive suggestions and comments. I have given them all a lot of thought, and hope my revised explanations and answers makes the purpose and aims of the work more clear, and that my answers to referee comments generally are found satisfactory.

The main motivation and purpose of the study is to improve the general understanding of reasons for increased landslide activity as experienced in Norway in recent years, through a case study based on events in year 2000. Applying internationally recognized methods for unsaturated slope analysis is clearly a part of this motivation, including collection of unsaturated parameters for soils not investigated before. Such methods may be considered "routine" (although rarely found outside academia), but data is new and to some extent surprising, as the unsaturated shear strength of silt. As a novelty I will now also include a suggestion for estimation of unsaturated shear strength in soils previously exposed to high suction (left out in the first version). For the case study I also think that the fact that soil parameters come from tests on intact specimens makes them more valuable, particularly for granular soils, that are normally hard to sample and test in an intact state.

To further justify the study: Many landslide studies have been presented internationally with virtually no real soil data. This case study covers many elements often missing

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in such studies: Site specific shear strength for saturated and unsaturated conditions, permeability and water retention properties and ground investigations, in addition to coupling to a documented landslide event and rainfall records.

Regarding "fill in some gaps. . .": Elaboration on this will be included in section 1.1, mainly referring to the scarcity, i.e. almost total absence, of local data ("fill in some gaps" is actually an understatement).

I recognize that a much more complete description of the site is necessary. I should not expect the referees to be clairvoyant! More details will be included to improve and complete the description of the site. Some details of the testing will still be found in referenced literature (e.g. details of WRC-testing (Heyerdahl and Pabst, 2017) and shear testing of sand (Heyerdahl, 2016), but main results will be summarized.

Regarding the conclusions: Considering results from numerical analyses, infiltration through unsaturated soil layers is the most important process. Failure indeed occurs primarily in saturated soil layers; however, this is a result of the parameters found. Starting the work it was not obvious what the outcome would be. For understanding the development of critical situations, it would be hard to omit slope stability analyses completely, although infiltration is the governing factor.

A point of learning is the fact that even with considerable data collection and soil testing, a "perfect explanation" for landslide triggering of a landslide was not reached (although the conceptual explanation is very clear).

Data from the study could be applied to study infiltration and slope failure of other slopes in Norway in similar soils, for instance shallow landslides resulting from infiltration on in "infinite slopes"; this would however go beyond the scope of this particular paper. For such studies, this case study show that cohesion of intact specimens is an important factor and govern the resulting slope stability.

Answers to specific comments:

1) Lines 5-10 on page 14 To improve the conclusions, comments will be included regarding why results are as they are (at least what I assume may be the reasons).

2) Lines 12-15 on page 14 No doubt, processes of infiltration and groundwater rise are generally known. However, in my view, a documented case study based on considerable data should have some interest. Not the least, it should be interesting what amount of rainfall that is necessary to induce a critical situation. A case study of an actual landslide should be an appropriate format for such investigations. The numerical analysis does not prove everything – but combined with the observed failure geometry, things start to fall in place.

Regarding the question "What new behaviour did the unsaturated analysis show that wouldn't have been apparent in a saturated analysis": The analysis applies site specific soil data and actual rainfall records to see how the response of the initially unsaturated slope matches with observed failure. The saturated analysis would give a different result for an infiltration analysis. It is recognized that the slope failure occurs in a saturated slope. This was not possible to know at the starting point of the study.

As mentioned, unsaturated shear strength of Norwegian soils, performed on intact specimens, are unprecedented and should give some value. Also, the results showing

3) Lines 15-18 on page 14 The section will be improved.

The analyses show that even for a saturated slope, failure does not occur. Effective friction angles for silty sand and sandy silt are quite reliable, which puts the uncertainty mostly on the cohesion. The cohesion must therefore be smaller for the gross volume of the soil than measured in specimens tested.

4) I will move the phrase "During the last decade. . ..rainfall intensities and durations" to the introduction part, adding to the motivation for the study. In the conclusion, I will elaborate more on the importance of increased knowledge on unsaturated infiltration (and shear strength), as the unsaturated state must be the starting point for triggering

of a rainfall triggered landslide.

Heyerdahl, H., 2016, Rainfall-induced landslides in Quaternary soils in Norway, in Proceedings 3rd European Conference on Unsaturated Soils (E-UNSAT 2016), Paris, France, 12-14 September 2016.

Heyerdahl, H., and Pabst, T., 2017, Comparison of experimental and predictive approaches for determination of water retention curves of intact samples of Quaternary soils Journal of Geotechnical and Geological engineering, p. 1-21.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-410/nhess-2017-410-AC4-supplement.pdf

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