Comments on Reviewer 2 - Anonymous (Referee RC2)

Specific Comments

The estimation of the shear strength of the basal sliding zone is based on backanalyses with UDEC for a pre-defined rupture plane geometry and an orthogonal set of fully persistent fractures in the sliding mass with uniform geometric and geomechanical properties.

It is known from many previous studies (for example Vajont), that the strength and stability of slides with compound ruptures also depends on the internal strength of the sliding mass. However, the study does not evaluate the effect of sliding mass properties on the back-calculated basal shear zone strength.

Comment: We absolutely agree with the reviewer and therefore we will also focus on the comment in the revised manuscript. This will include a re-analyses of the existing numerical models, but if necessary new modelling studies based on UDEC to focus on the characteristics and influence of the internal rock mass deformation on stability behaviour. The new results will be included in the revised manuscript.

In addition, the rock-mechanical modeling assumptions are poorly constrained and not related to field and lab data. In fact it seems that some of the field observations (for example the stepped rupture plane) are violated.

Comment: The observed rupture surface of the Köfels Rock Slide is entirely located in competent granitic rock masses (Augengneiss). In our study we considered laboratory tests (UCS, Young's modulus, Poison ratio) from this type of rock, and performed a detailed field investigation campaign concerning the discontinuity network. Based on laboratory test and discontinuity date we applied rock mass classification systems (GSI) to estimate roughly the rock mass strength. We agree that this empirical approach has some limitations, and of course in-situ shear tests of the discontinuities forming the basal rupture surface would be nice to have, but in our opinion hardly fundable. Most large-scale in-situ shear tests considering real stress conditions were performed in the scope of large dam projects (Please see Fishman 2014, Shear resistance along rock mass discontinuities: results of large-scale field tests, 41:6,1029-1034.). Nevertheless, it is assumed that the required rock mass properties can be estimated reasonably. In this context we would like to mention that the primary objective of the numerical modelling study was the back-calculation of the fully persistent basal shear zone which was formed by progressive failure during initial failure process.

In order to improve the manuscript and consider reviewer's suggestion we will improve, rewrite and change section 3.3.3 Material properties i.e. the input for the numerical modelling study, also by considering section 4.2.

I suggest to perform a modeling study which is less trivial, which considers the few available field data and known depth trends of fracture properties as good as possible. It might be fruitful, to treat the basal rupture plane not as a pre-defined fully developed shear zone, but to investigate how this surface formed progressively from a previously not fully interconnected fracture network. This would lead to more substantial insights into progressive failure, which is only superficially discussed in the current manuscript.

Comment: This suggestion is scientifically interesting and understandable, and gets to the heart of the initial formation of any landslide. Understanding progressive failure in fractured rock masses is the key in landslide research, and for us it is highly obvious that progressive failure is the main mechanism of the failure process at the Köfels rock slide. Progressive failure is related to a complex interaction between existing natural discontinuities and brittle fracture propagation through intact rock bridges which finally leads to the formation of fully persistent basal shear zone. At this stage the slope is able to fail. Furthermore, progressive failure is characterised by complex in-situ stress conditions (stress concentration) and time dependent strength degradation mechanisms which must also occur within the rock mass driving the slope towards instability.

Several numerical approaches to study the initial formation process due to progressive failure of a rock slide are available. For example, Brueckl and Parotidis (2001, 2005) performed 2D FEM calculations (continuum) to study the development of the "creeping rock mass", which represents the initial phase of the Köfels rock slide. In this model a transition of the originally compact rock mass to ''soft'' rock, controlled by a Mohr–Coulomb and no tension yield criterion was assumed. These FEM models focus on the initial failure process by considering progressive failure mechanisms, at least in a simplified way. Pre-existing discontinuities and therefore the anisotropic nature of the rock mass or the failure geometry was not considered. Furthermore, in order to study the progressive failure mechanism as realistic as possible, discontinuities and (time-dependent) fracture mechanics need to be considered. This can be done, for example, by the software ELFEN, which is able to simulate crack growth and coalescence. Applying ELFEN (or similar software products able to model fracture mechanics) to the Köfels rock slide would be highly interesting, but can be seen as a comprehensive standalone study for future investigations.

The scope of our study was to back-calculate the shear strength properties of the fully persistent basal rupture surface which developed by progressive failure and fracture coalescence. As a hypothesis for our study, ongoing slope deformation is only possible if the shear strength properties of the basal shear zone are sufficiently low to allow slip and subsequently acceleration to high velocities (i.e. transition to the dynamic friction angle). By implementing the reconstructed - but as realistic as possible - slope geometry and basal rupture surface into a distinct (discrete) element model provide slope scenarios (also different groundwater conditions) with a strong control on the "real" failure geometry and the shear strength parameters.

In our revised manuscript we intend to describe the working hypotheses and research questions in more detail (also the advantage of distinct element models) and include an extensive discussion of the concept of progressive failure in relationship to the Kofels Rock slide. In our revised manuscript we plan to improve the distinct element modelling part. Since we see certain advantages in using the distinct element method and a good complement to existing studies, we have not planned to use other software products, for example based on a continuum approach.

Another comment refers to the discussion and analysis of the rock slide runout. It is known from previous studies (for example Aaron et al 2020, Frontiers in Earth Sciences 30), that the dynamic friction angle during rapid runout motion can differ substantially from the static friction angle required.

Comment: Dynamic motion is a very important aspect of large, rapid landslide processes such as the Köfels event. We agree with the referee that the friction angles relevant for dynamic motion are completely different than those for landslide release – an experience to be made when optimizing the parameters for running mass flow models such as RAMMS or r.avaflow. Köfels represents even more a specific case in this respect, as melting processes have occurred at the sliding surface, a rare phenomenon documented only for very few cases worldwide.

We would like to include an analysis of dynamic motion, but to our knowledge, there is some lack in software products available to date which is able to appropriately reproduce large, rapid sliding processes where the rock slide mass is internally deforming to some extent, but not displaying a flow-like behaviour. We have tried various times to back-calculate the Köfels event with the r.avaflow software, but as it was to be expected with a mass flow simulation tool, the derived deformation and lateral spreading was much too strong, compared to the observation, so that we have decided not to include the result in the paper. There is certainly a need for simulation models accounting for this type of motion – an aspect we will emphasize more strongly in the discussion of the revised manuscript.