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# The impact of overlapping processes on rockfall hazard analysis – the Bolonia Bay study (southern Spain)

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For rockfall simulations, competitive case studies and data sets are important to develop and evaluate the models or software. Especially for empirical or data driven stochastic modelling the quality of the reference data sets has a major impact on model skills and knowledge discovery. Therefore, rockfalls in the Bolonia Bay close to Tarifa (Spain) were mapped. Here, the siliciclastic Miocene rocks (megaturbidites) are intensively joined and disaggregated by a perpendicular joint system. Although bedding supports stability as the dip is not directed towards the rock face, the deposits indicate a continuous process of material loss from the 80 m high cliff of the San Bartolome mountain front by single large rock falls. For more than 300 blocks data on size, shape, type of rock, and location were collected. The work concentrated on rockfall blocks with a volume of more than 2 $m^3$ and up to 350 $m^3$. Occasionally very long "runout" distances of up to 2 km have been observed.

For all major source areas and deposits, runout analysis using empirical models and a numerical trajectorian model has been performed. The most empirical models are principally based on the relation between fall height and travel distance. Beside the "Fahrböschung" from Heim (1932) the "shadow angle" introduced by Evans and Hungr (1993) is most common today. However, studies from different sites show a wide variance of the angle relations (Dorren 2003, Corominas 1996). The reasons for that might be different environments and trigger mechanisms, or varying secondary effects such as post-depositional movement. Today, "semi" numerical approaches based on trajectorian models are quite common to evaluate the rockfall energy and the runout distance for protection measures and risk evaluations. The results of the models highly depend on the quality of the input parameters. One problem here might be that some of the parameters, especially the dynamic ones, are not easy to determine and the quality of the digital elevation model has an large impact on energy estimations and travel paths. In the course of this study the model of "shadow angel", "Fahrböschung" and a numerical simulation using "Rockfall 6.2" (Spang & Sonser 1995) have been applied to the mapped rockfall deposits.

The results revealed a good coherence of all three modeling attempts in some cases. Especially for deposition areas where many single rockfall events could be identified as young all models performed well and showed nearly identical results. In other areas with large deposits and long travel distances, the model predictions vary strongly and the shadow angles do not fit the usual ranges at all. Here, post-depositional transport by surface-near landslides in a piggy-back style is postulated. Medium- and large-scaled landslides and creep in soils are proven in the whole bay. Landslide bodies can be observed in the deposition areas and were proved with GPR. Additionally, the weathered marls and clays of the Flysch deposits below the rock face are highly active and likely to be subject to sliding after heavy rainfalls. Another reason for the extraordinary long runout distances might be seismic triggering. Paleoseismological and archeoseismological investigations already showed that the study area suffered destructive earthquakes even in historical times (Silva et al 2009). This trigger mechanism was simulated for various blocks, but did not lead to the expected results in all cases. Strong winds have also to be considered as an additionally trigger mechanism for rockfalls by leverage as wind forces > 5 Bft are present in the forested study area more than 300 days per year.

The results show that simple stochastic analysis using large data sets without taking triggering mechanism and geological environment in consideration may lead to mere general models. More data sets and comparative

studies are necessary to evaluate the threshold values for the empirical models like the shadow angle. Anyhow the results from the described investigation show that on a screening and planning level the results of the empirical methods are quite good. Especially for numerical simulation, where back analysis is common to parameterize the models, the identification of "ideal" rockfalls is essential for a good simulation performance and subsequently for an appropriate planning of protection measures.

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