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Shapes of standing jumps formed in granular flows down inclines: implications for the design of snow avalanche protection dams

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The European guidelines for the design of avalanche protection dams mainly rely on a couple of criteria based on the formation of granular jumps upstream of obstacles. The equations proposed to describe granular jumps are strictly valid for incompressible and frictionless fluids but generally hold for rapid granular flows mimicking snow avalanches. We have conducted a series of tests on a newly established granular chute to investigate in detail the shape of the steady jumps by varying both the slope angle and the mass discharge. Our laboratory tests confirm that the traditional shallow-water shock equation works well for the steep jumps formed in rapid and dense flows (characterized by a Froude number in the range 4-7 at high inclination and high mass discharge) but the equation fails for either low slope angles or low mass discharges. At low slope angles and high mass discharges, the jumps are very diffuse and elongated. The traditional shock equation underestimates the jump height. At low mass discharges, the incoming flows become dilute and produce compressible jumps for which the density variation across the jump cannot be neglected. A full jump equation accounting for the source terms (weight of the jump itself minus its effective friction) and the density variation as well is proposed. Approximate solutions are discussed to describe the transition between steep and diffuse jumps on the one side and the transition from incompressible to compressible jumps on the other side. Our study clearly reveals the limits of the current European guidelines for the design of avalanche protection dams when the incoming flows are relatively slow (Froude number about 1-3 in our tests). The latter avalanche flow-regime is relevant for many situations in avalanche run-out zones where protection dams are generally settled.