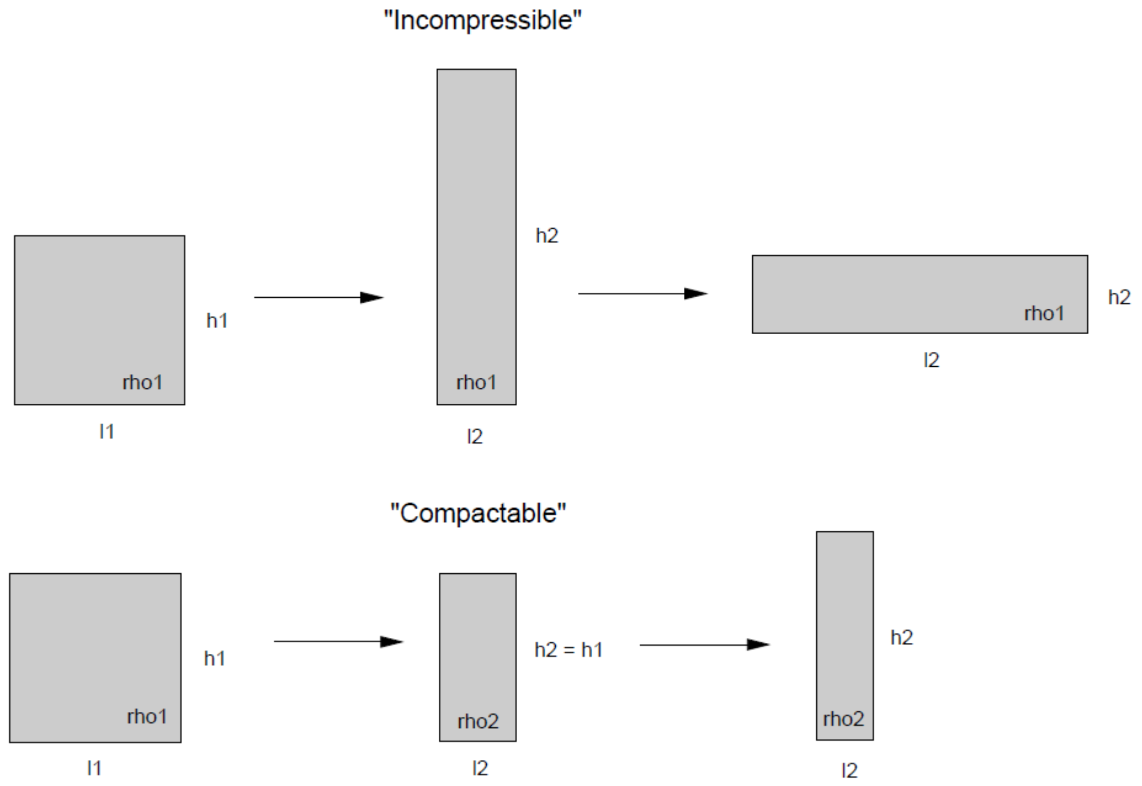
Dear Thierry,

We simply object to you calling our mass balance “wrong” or “flawed”. Furthermore, we have serious problems with your treatment of the snow pile-up process as a “shock” wave.

Mass conservation for a “compactible” material has many solutions. Consider a square of length l1 and height h1 and density rho1, A = (l1 h1). The first square represents the incoming avalanche mass (velocity u1) and the second and third squares represent the pile-up mass in front of the obstacle (velocity u2 = 0). For an “incompressible” material (rho1 constant) mass balance is simply given by the choice of h2 and l2. There are an infinite set of combinations of h2 and l2 which satisfy the problem.



For a compressible material there are even more possibilities, because we have introduced a third parameter, the “compacted” density rho2. Depending on this value, we still have an infinite number of possible solutions for l2 and h2 that satisfy mass conservation. The solution to the pile-up problem in front of the obstacle therefore requires a constitutive postulate stating how the mass piles-up. We can place more mass in the length l2 or more mass in the height h2. Be aware, however, that the choice is important, because it determines the braking distance (in the flow direction), and therefore the force on the obstacle.

The choice of the mass distribution (l2 and h2) and the choice of compacted density (rho2) (which, by the way we CAN and SHOULD measure in experiments or avalanche case studies) determines the “wave” speed. What is this “wave”? Here we make an analogy to vehicle traffic on a highway. For us it is simply the speed the interface is moving that exists between the moving avalanche mass (moving cars) and the piled-up snow mass (non-moving cars). It is moving away from the obstacle in the upstream direction. There might be a jump in height, or there might not be. It depends on how the avalanche snow compacts. (In vehicle traffic there is seldom a change in pile-up height, and each car loses all its kinetic energy in the non-moving zone. The pile-up interface exists without a jump in height.). We denote the speed of the interface Sdot. This speed (in the direction l2) depends on the constitutive assumption for the geometry of compaction. Clearly, in our model, avalanche mass that is missing on one side of the interface is gained on the other side (proof by simple geometry).

More importantly, an analogy to wave mechanics or shock waves is severely misplaced. For compaction (which is NOT the same as compression of an elastic body) the density of the incoming mass (volume*density) is NOT the same as the one of the stopped (smaller volume*higher density) mass. The mass is the same. In a shock wave, energy is transported, which in our model is not possible. The total kinetic energy of the stopped mass is dissipated during the reduction of the speed (over the braking distance d). S is not the position of a determined volume of mass. It is the location of the boundary, where we have the “compacted” density.

There is no way, we could agree with the wave concept, for energetic reasons. Snow is in our case simply an ideal inelastic material. If you have a travelling wave -- be it a shock wave or an “ordinary” wave -- you transport energy, which you certainly do NOT DO, when just stopping the material, “destroying” all its kinetic energy (transforming into heat/deformation). This is why the analogy to shock mechanics breaks down.
In a shock model, mass balance is formulated to accommodate the transfer of energy. In the pile-up process -- the avalanche impact problem – this is not necessary if you consider the stopping process to be completely inelastic.

The shock analogy therefore leads to results that are simply not in agreement with observations: we have observed avalanche pile-up zones with h1 = h2. We certainly do not want to exclude this case from the many possible set of pile-up configurations.

Finally we note the power of treating avalanche snow as an ideal inelastic material. The work theorem states that the change in kinetic energy ΔK is equal to the product of the force F (on the wall *from pile-up*) and the braking distance d of the avalanche mass stopped by the wall,

$$\Delta K = F\, d$$

Using the standard definition for impact pressure $p = {}^{F}/_{A}$

$$p = \frac{1}{2}\, C_d \rho\, U^2$$

(where C_d = stress intensity factor; ρ = density; U = approach velocity, A = cross-sectional area) we arrive at an interesting re-definition of the stress intensity factor:

$$C_d = \frac{V/_A}{d} = \frac{l}{d}$$

where V is the volume stopped by the wall. With $l = V/_A$. the stress intensity factor (for pile-up) is simply defined as the length of incoming mass scaled to the braking distance. In our model, if the obstacle stops the mass immediately (d=0), then Cd is infinite (as well as the wave propagation speed), meaning there is an infinitely large force acting on the obstacle. This is the correct result, supported by experiments where large (but finite) Cd values have been measured.

The approach of invoking the work-energy theorem thus opens many doors to consider different impact situations, including the interpretation of experimental results. Frankly, it is impossible to interpret experimental measurements without knowing $l(t)$ or $d(t)$. We think that it is very important for practicing avalanche engineers to be presented with basic, compelling and consistent explanations.