AVALANCHE RELEASE AND MOTION – By Art Mears

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Reno, Nevada

1 OBJECTIVES AND LIMITATIONS

1.1 Objectives

This notebook material accompanies the *Avalanche Release and Motion* lecture presented in the 2003 National Avalanche School in Reno, Nevada. The topics covered in the lecture and this notebook material include:

a. When does a slab exist?
b. Slab boundaries and fracture surfaces.
c. Material properties of snow.
d. Strain softening, failure, fracture, and stability sequences.
e. Spatial variability in a starting zone.
f. Criteria associated with human-triggered slabs.
g. Loose-snow avalanches.
h. Avalanche motion.

The objectives are to provide notebook material that is reasonably consistent with the main lecture on *Avalanche Release and Motion* and to direct the reader to selected references where some of the topics are covered in greater detail. The two textbooks listed in the references: *The Avalanche Handbook*, (McClung and Schaerer, 1993) and *Staying Alive in Avalanche Terrain*, (Tremper, 2001) are both excellent and highly recommended. The "Handbook" covers topics in greater technical detail, while "Staying Alive" is less technical and is intended for a broader audience. Several recently-published technical or scientific papers relating to slabs, weak layers, fracture, avalanche release and land-use planning for extreme avalanches are also listed

1.2 Limitations

The material summarized here is based on current research and the field observations of numerous practitioners. However, systematic study of snow and avalanches ("snow and avalanche science") is a relatively young discipline. The study of snow and avalanches began seriously in the first half of the 20th century and has progressed fairly slowly because relatively few researchers (compared to those involved in other studies) have been involved.

Because the science of snow and avalanches is a young one and is practiced by a small number of people, substantial modifications to some of the concepts presented here will no doubt take place in future years.

2 WHEN DOES A SLAB EXIST?

A slab exists when a stronger, more cohesive layer of snow overlies a weaker layer, as illustrated in Figure 1. If this strength relationship between the slab and the weak layer does not exist, only loose-snow avalanches will be possible. A wide range of slab density, strength, cohesiveness and wetness is possible as long as the strength relationship between the slab (stronger and more cohesive snow) and weak layer (weaker, less cohesive snow) exists. Slabs may range from as low as 50 kg/m^3 (5% water) to as much as 700 kg/m^3 (70% water) in density, may consist of dry snow be saturated with water.

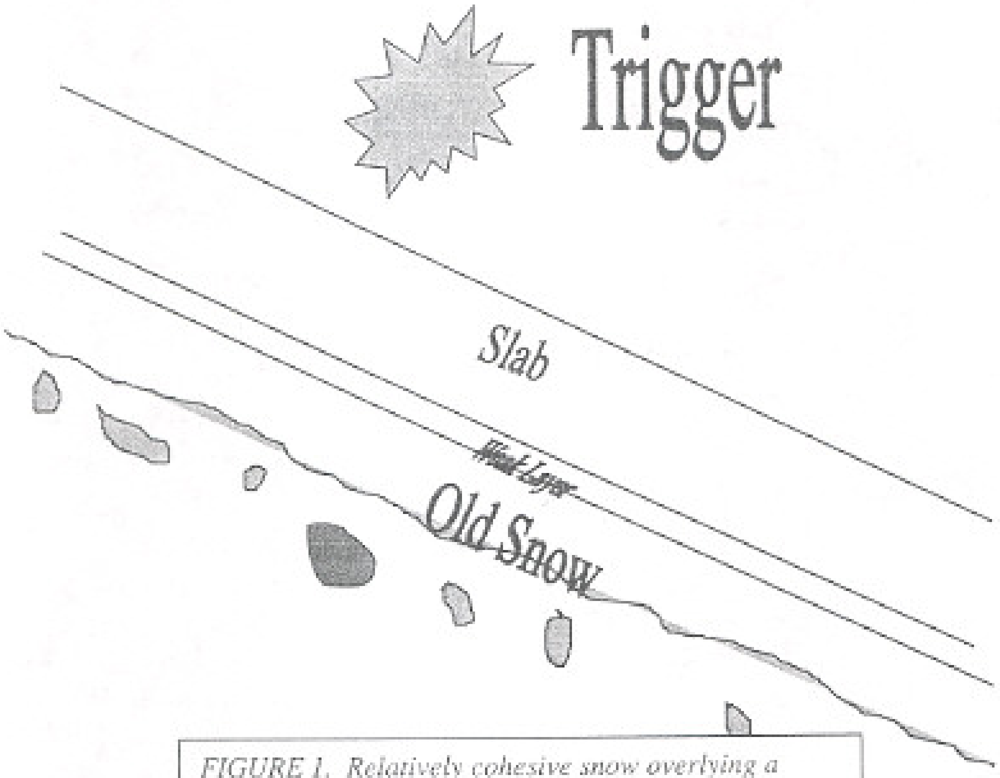


FIGURE 1. Relatively cohesive snow overlying a weaker, less cohesive layer constitutes a slab.

To produce an avalanche *some type of trigger* is also needed. This can be a shock load (explosives, cornice fall, snowmobile, human, etc.), a gradual load (new snow, drifted snow, rain, deformation of the slab on the weak layer), or further weakening of an already weak layer (by thaw, infiltrated rain, metamorphic changes).

In the absence of some type of trigger the slab may remain unstable and easily triggered for a long period of time if a weak layer persists. It then requires only some trigger to produce fracture in the weak layer and avalanche release.

3 SLAB BOUNDARIES AND RELATIVE SURFACE AREAS

A released slab is a block of snow bounded by fracture surfaces: the bed, the crown, the flanks, and the stauchwall (Figure 2).

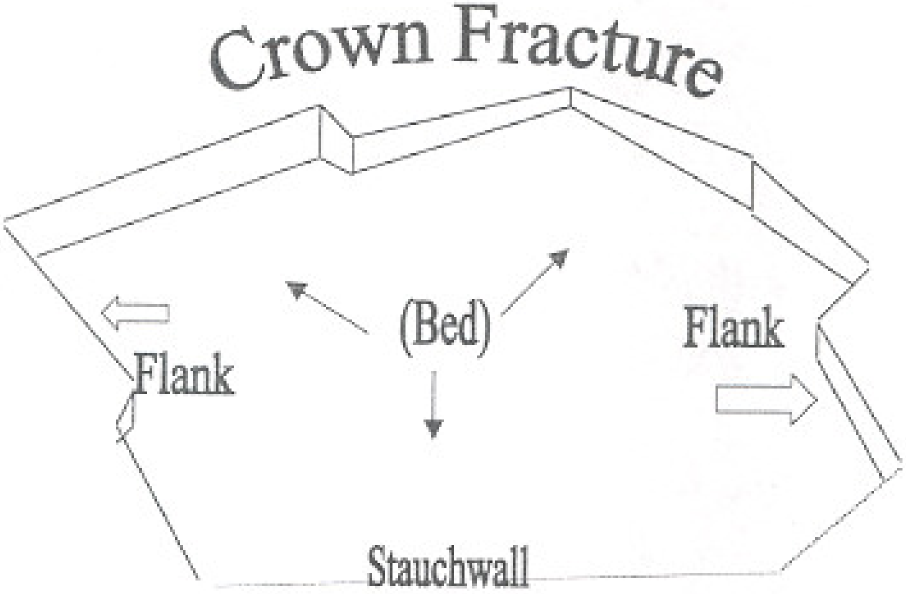


FIGURE 2. Fracture surfaces in a slab avalanche

In typical slab avalanches, the *bed*, which is subject to *shear fracture* (one surface slides over the adjacent surface parallel to the stress), is by far the largest, exceeding, in typical cases, the combined areas of the crown, flanks and stauchwall by a factor of 30 to300 or more. The *crown*, is subject to tensile fracture (at right angles to the direction of stress), the *flanks* to both shear and tensile fracture, and the *stauchwall* to shear fracture, although it is loaded in compression prior to slab release. Direction of these fractures are shown in Figure 3.

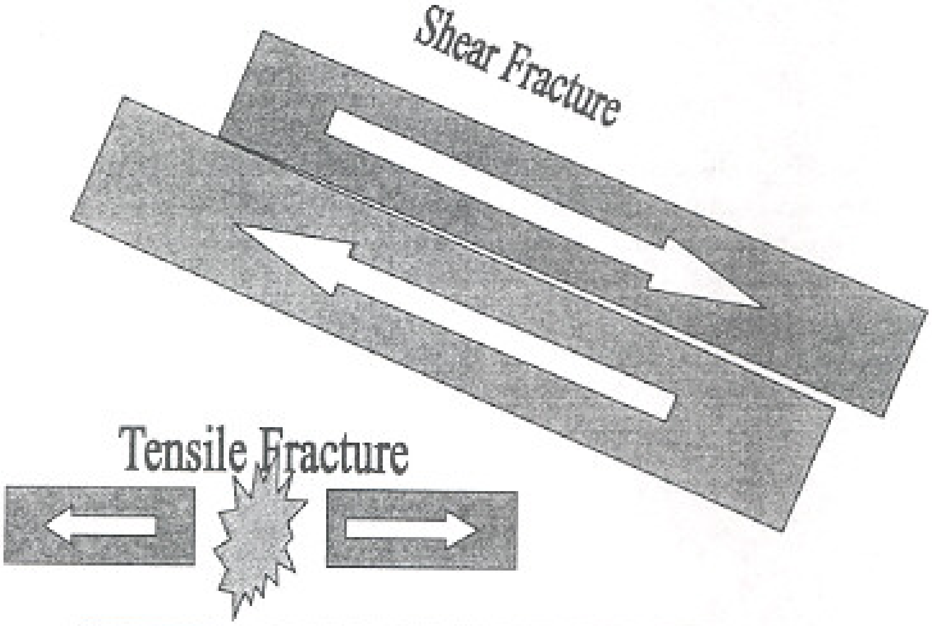
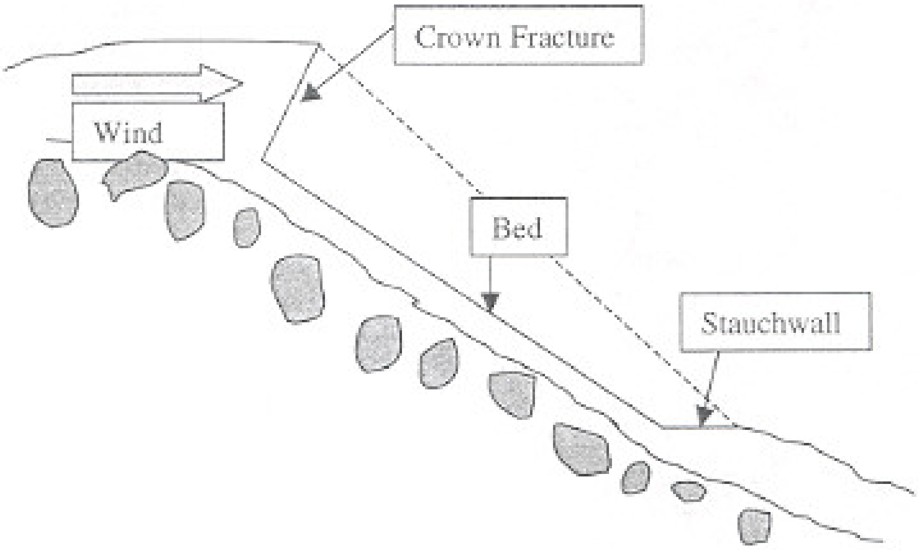


FIGURE 3. Shear fracture is parallel to the direction of stress (arrows); tensile fracture is perpendicular to the stress.

There appears to be no limit to the size of slab fractures although the smaller slabs usually consist of low density snow and the larger fractures are usually of somewhat higher density. The larger slabs exhibit a greater "fracture toughness" which enables larger slab depths and fracture sizes. When slab and weak layer are both present, when terrain is continuous over long distances, and a trigger of some type is applied, fractures have been observed to extend for 1000's of meters, but they can be a short as 1m-5m. Slab thickness is the perpendicular distance from the top of the snow to the weak layer and often varies considerably over the slab area. Slabs are usually thickest in the crown because of wind redistribution of snow and becomes thinner lower on the bed (Figure 4). In typical avalanches the average thickness of the crown may range from about 0.3m to 1.0m; in very large avalanches 1.0m to 3.0m and in small avalanches 0.1 to 0.3m. Larger thickness (up to roughly 10m) have been observed in crown fracture areas of deep wind-blown snow. Unless constrained by topographic features, the width of a slab fracture (flank to flank distance) usually exceeds the distance between the crown and stauchwall fractures by a factor of 2 or more. As discussed more fully in Section 5, the initial fracture is in shear within a weak layer or a thin interface below the slab. This fracture propagates rapidly to the crown and flanks (which fracture in tension and shear). The stauchwall then fractures in shear as it is overrun by the sliding slab.

FIGURE 4. Cross section of a slab, showing typical variation in slab thickness from the crown to the stauchwall.



4 MATERIAL PROPERTIES OF SNOW

The following properties contribute to the some of the observed behavior of snow slabs:

- Snow usually exists very close to its "*triple point*;"
- New snow is highly compressible;
- Weak layers below the slab undergo "*strain softening*;"
- Snow has both "*viscous*" and "*elastic*" properties.

4.1 Triple Point

The "triple point" is the *temperature* at which a material (snow, in this case), can exist in solid, liquid, and vapor forms simultaneously. Snow can exist from the minimum temperature of -273°C (absolute zero, the coldest possible temperature), up to 0° C (snow's melting or triple point). However, within temperate climates snow usually is within the warmest 5°C to 20° C of it's possible temperature range (its upper 2%-8%). It becomes highly volatile and is easily deformed within the final 5° C where relatively large amounts of water vapor saturate the ample pore space (50-90% of the volume) and liquid water may also be present. Because snow is so near the triple point it can change rapidly through metamorphism, deformation, and water saturation.

4.2 Compressibility

Snow is highly compressible when compared with most solid materials. Dry snow often accumulates on the ground at less than 100 kg/m^3 density (10% water) but can compress to 200 – 300 kg/m^3 under its own weight in a few days or weeks, even in the absence of wind, other mechanical disturbances, sun or rain. An old dry snow layer may reach 400-550 kg/m^3 . In the first few days after a major snowfall, compression of new snow substantially changes its strength and porosity. The density and tensile strength increase, and its resistance to deformation by settlement and downslope creep also increase. As a result of strength and viscosity increase, snow also shears on any underlying weak layer much more slowly as it compresses and becomes stronger. This compression of the new snow is one of the several metamorphic processes and is sometimes known as *pressure metamorphism* which is probably the fastest-acting metamorphic change in a dry, new snow layer during the first days after a snowfall. Pressure metamorphism can increase the tensile strength (and probably viscosity) of snow by a factor of 10 or more in a few days, particularly when snow temperatures are within 5° - 10°C of the triple point.

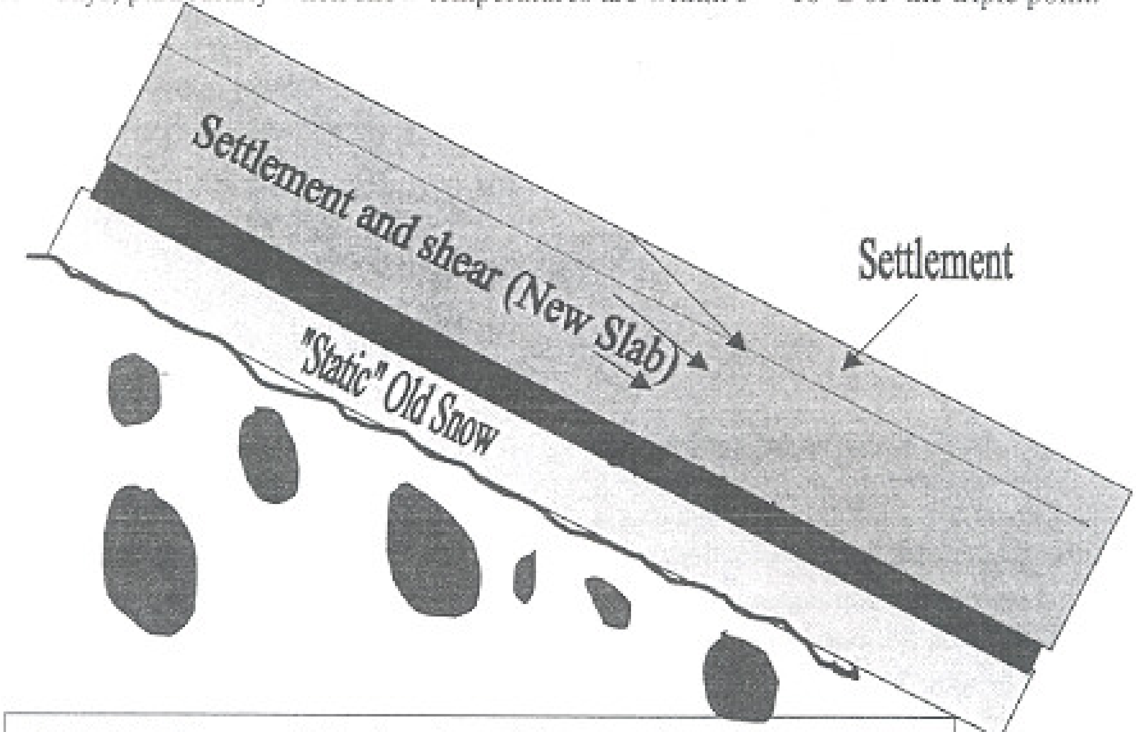


FIGURE 5. The new slab both settles and shears on the weak layer. This shear may produce strain-softening, a decrease in strength within the layer and failure. This can lead to shear fracture and slab release.

Weak layers below the slab become progressively weaker as the shearing proceeds (Figure 5). The deficit zones probably vary in length from about 0.1m to 10m and may be widespread across a slab. As rapid shearing and strain-softening continues, the super-weak deficit zones "fail." They become progressively weaker when bonds between snow grains are being broken faster than they can form. These deficit zones can spread and combine with each other until the overall shear strength of the weak layer is overwhelmed by the shear stress produced by the weight of the slab. This sets the stage for shear fracture (Section 5).

4.3 A *Strain-Softening* material

As discussed above, a new snow slab also deforms downslope on the underlying weak layer. If this shear proceeds rapidly enough it can lead to *strain softening* within this weak layer, a process in which super- weak (deficit) zones develop in the already weak layer. This can undermine the weak layer strength and lead to fracture.

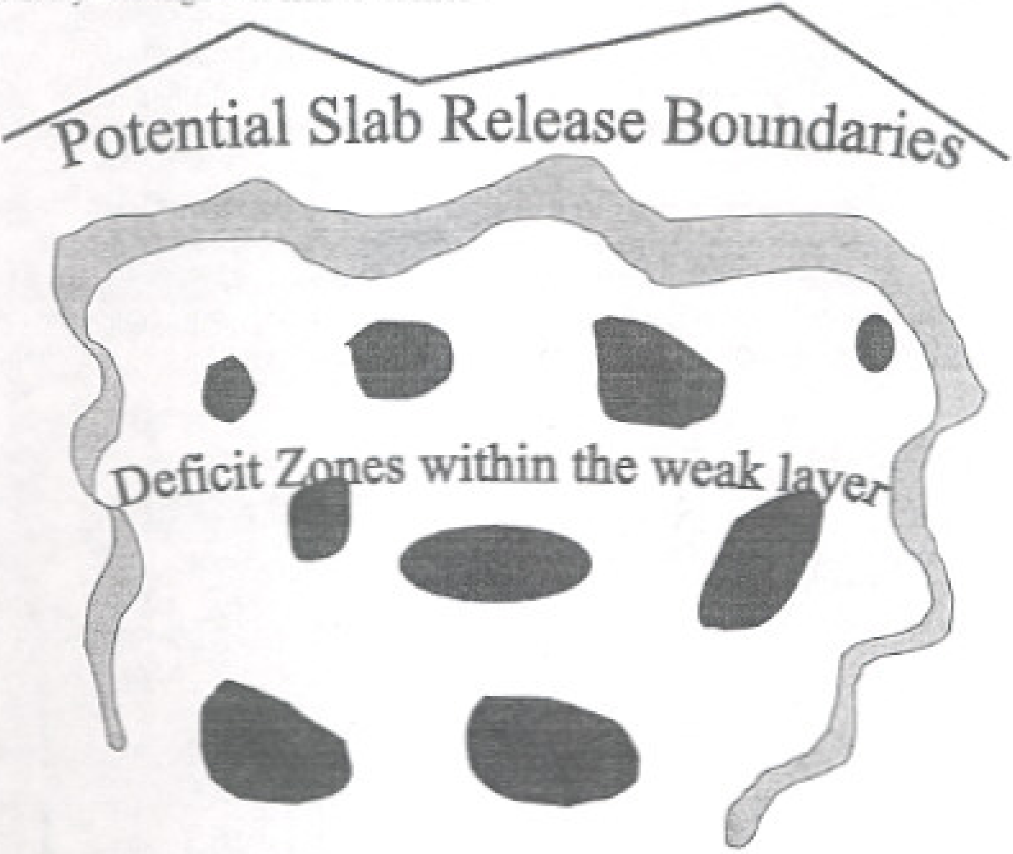


FIGURE 6. A bed surface with developing deficit zones. With progressive shearing, these areas will increase in size and combine with one another possibly leading to shear fracture and slab release.

4.4 *Visco-elastic* snow

A visco-elastic material (including snow) has both *viscous* properties (it can flow, like warm honey) and *elastic* properties (it can bounce back, like a rubber ball). Because of its purely viscous properties, honey, by itself will not bounce; in contrast a rubber ball, being an elastic material will not flow. In a snowpack this "model" (the linking of the viscous and elastic properties) applies to the slab, the weak layer, and the older snow. They are all behaving in a visco-elastic manner but at different rates.

The speed at which a viscous material can deform through slow "flowing" is highly dependent on its temperature. Warmer snow is capable of deforming faster before it fractures while colder snow is more brittle, less tolerant of fast deformation and therefore fractures more easily. This is why warm or wet slabs are more difficult to fracture with explosives.

However, when snow is subject to a rapid load by a person, machine, explosive or other rapid external force it will deform at first and then may "bounce back," assuming the snow did not fracture as a result of the load. This bounce is the "elastic" property of snow. If snow were not elastic as well as viscous it would not fracture at all and slab avalanches would not be possible.

The visco-elastic property can be conceptualized as a block of snow on a flat table (Figure 7). First this sample is subject to a force that causes it to deform (the viscous part). When the force is quickly removed the snow bounces back a small amount (the elastic part). The viscous part enables the snow to adjust to new stress while the elastic part can transfer stresses through the snowpack and is manifested as fracture.

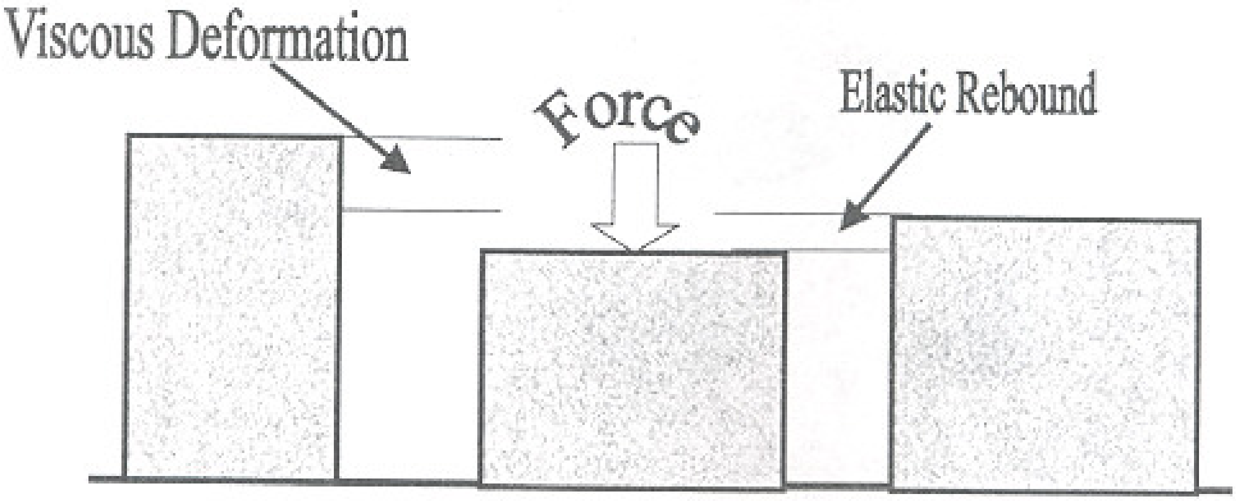


FIGURE 7. The behavior of visco-elastic snow can be conceptualized as a block of snow on a table. It deforms viscously when a force is applied slowly but bounces back a small amount (elastic rebound) when the force is removed. The viscous component enables slow deformation while the elastic property enables fracture.

5 STRAIN SOFTENING, FAILURE, FRACTURE AND STABILITY SEQUENCES

As illustrated schematically in Figure 8, the evolution of a snowpack from stable to unstable to fracture (or re-stabilization) follows certain steps:

a. The new slab accumulates on a weak layer through storms, wind loading, or both;
b. The new slab deforms internally and produces shear stresses within the weak layer or on a thin interface;
c. Super-weak deficit zones begin to form in the weak layer; they may combine to form larger deficit zones; small bonds break faster than they grow.
d. As steps "a" through "c" continue simultaneously, the slab settles and becomes denser and stronger; this can *reduce* the deformation rate on the weak layer because the slab deforms more slowly on this layer. This may lead to bonding between the slab and the weak layer as bonds grow faster than they break.
e. If additional weight of the slab on the weak layer stops or slows, the deformation rate on the weak layer slows down, bonding increases and the *trend is toward stability*.
f. If the formation of deficit zones continues and these zones combine, failure in the weak layer will take place; the snowpack may then reach "the point of no return;" shear fracture may follow failure.
g. Fracture in the weak layer propagates to the crown, flanks and eventually the stauchwall.
h. If all surfaces fracture in one event, *slab avalanche release* occurs.

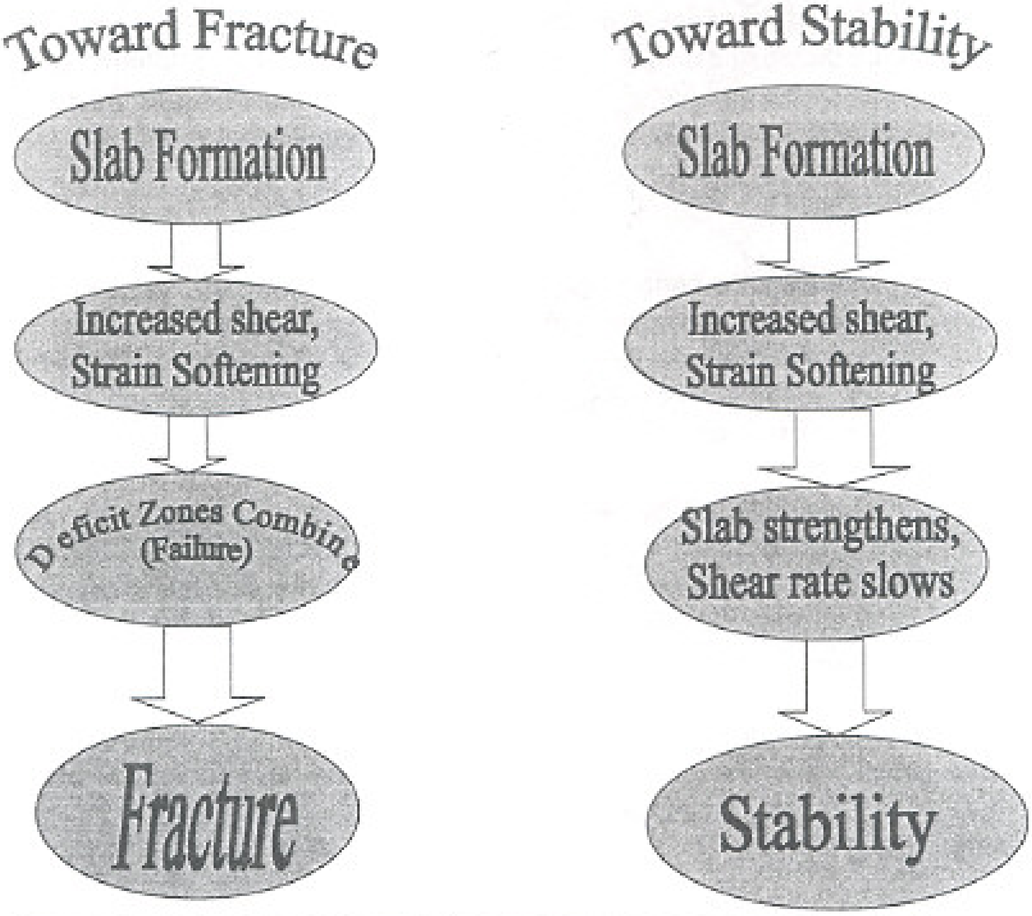


FIGURE 8. Processes tending toward slab fracture or stability.

The temperature in the slab and weak layer also have an important effect on stability. Warm snow tends to either stabilize or fracture sooner than cold snow because all the processes (settlement, shear, weak-layer deformation, breaking and building of bonds) occur faster at warmer temperatures. Slabs stabilize faster (and may fracture sooner) at warmer temperatures. Persistent cold temperatures (in the slab and weak layer) can lead to persistent weak layers and prolonged instability in the snow.

On the other hand, warm slab temperatures enable disturbances at the snow surface such as the weight of a skier or snowmobiler to penetrate to and disturb the weak layer more easily than in cold slabs of similar thickness. If this weak layer below the slab is already undergoing high deformation rates and possible strain softening, avalanches may be triggered more easily when the slabs are relatively warm.

Slabs are commonly fractured and avalanche released by "shock loads." This can occur deliberately, unintentionally, and naturally. Types of shock loads include explosives cornice falls, smaller slab and loose-snow avalanches, leaping and impacting snowmobiles, people, earthquakes, etc. These loads occur so rapidly that the snowpack has no chance to adjust viscously to the new stress. Therefore, the most effective application of a shock load occurs when a weak layer or interface under the slab is already undergoing strain-softening and failure. At these times the snowpack is sometimes described as "unstable" and can be more easily be fractured.

Deliberate applications of shock loads for avalanche-hazard management are often most effective during a relatively "short window of snowpack instability." This window of instability tends to be relatively short in warm snowpacks and longer in colder snowpacks. This is consistent with the general observation that an "unstable condition" lasts longer in colder snow.

6 SPATIAL VARIABILITY

Snow slabs are commonly assumed to be relatively uniform over starting zones and are often field tested for stability by shear tests, rutschblocks and other methods. Results of tests in a single pit are all too often confidently extrapolated to a much larger starting zone. Results of these pit tests are sometimes used to make important safety decisions in and near starting zones, decisions that may not be justified on the basis of isolated tests.

It has long been known that stability is highly variable across a *mountain range*, with *elevation and exposure*, and within a *complex starting zone*. Recent research, which has been based on detailed strength and stability tests, has also found slab stability to vary significantly over a single small, uniform area (Landry, et. al, 2002; Birkeland and Landry, 2002). Some important findings of Landry's recent research can be summarized:

a. Stability tests in individual pits represented the stability in a 30m x 30m plot area (the size of a small starting zone) that included the pit site only about half of the time. In the other half of the cases, the pits either overestimated or underestimated the overall strength of the plot.

b. The spatial variability within a plot (or starting zone) seems to *increase* as overall stability increases. Therefore the strength differences between the relatively strong and relatively weak areas below the slab increase through time.

c. The spatial variability within a plot seems to *decrease* as overall stability decreases. Therefore, as a loading event (such as a snow storm) is taking place and is "forcing" high shear rates in the weak layer, the strength differences between the strong and weak layers decrease.

These findings have important implications for backcountry stability evaluation. Most avalanche accidents (1) are triggered by the victims, and (2) occur days (possibly weeks) after the storm event that produced widespread natural avalanches. Experienced persons will probably avoid starting zones when conditions are obviously unstable (when condition "c" prevails). They will wait until overall stability has improved and may go into avalanche starting zones while condition "b" prevails. At these times strength has greater variability within the starting zone and individual tests may be less reliable. When performing stability tests these limitations should be considered.

Backcountry users of avalanche terrain may therefore be faced with a dilemma: If they wait for overall stability to improve they will be confronting a snowpack that is becoming increasingly variable in stability from point to point. A stability test or pit at on site may therefore become less reliable an indicator of local starting zone stability. This is indicated schematically in Figure 9. The choice of a site in which a stability test is made can be somewhat subjective. A sufficiently steep slope angle must be chosen for any stability test. Generally a slope within the 25° - 30° range which is safe from avalanches must be used. However, if there exists a 50% or less chance that a pit stability test will represent the strength of a potential starting zone, there is a strong probability the test may not represent the stability of the starting zone. As a result of this uncertainty, other indicators of slab stability (multiple tests, recent avalanche activity, changes in weather conditions, etc.) must be used as well as stability tests.

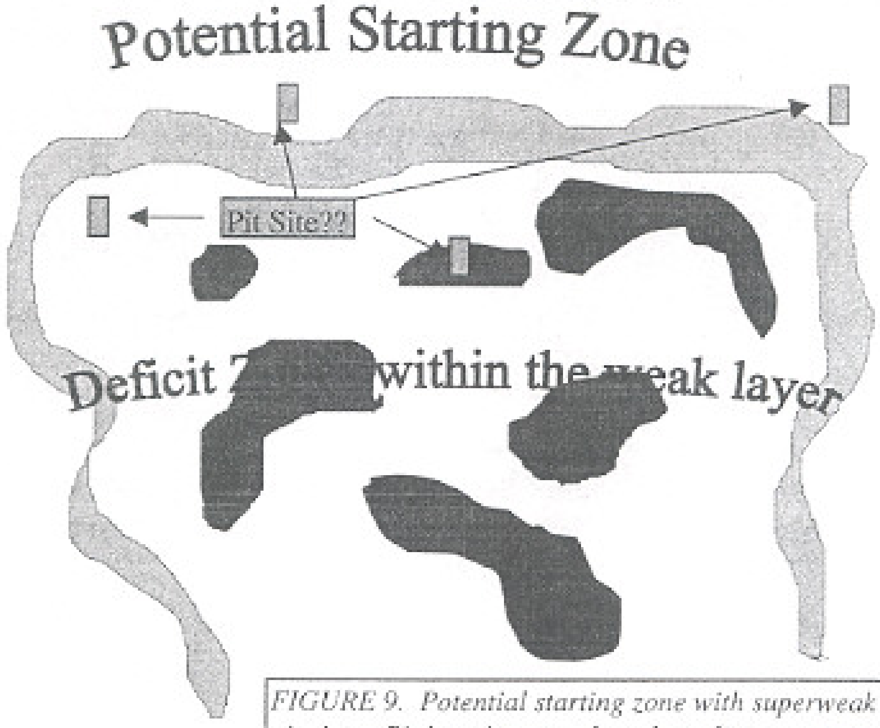


FIGURE 9. Potential starting zone with superweak "deficit" areas and test pit sites. Pit location must be selected to represent slab, if possible however this may be difficult or impossible.

7 SOME CHARACTERISTICS OF HUMAN-TRIGGERED SLABS

The majority of avalanche accidents are caused by slabs which are triggered by people or people using over-snow machines. Recent studies of many of these human-triggered avalanches in Canada and Switzerland provides some insight into characteristics of human-triggered avalanches in the snow climates in Canada and the Swiss Alps. These are discussed in McCammon and Schweizer (2002) and Schweizer and Jameison (2002).

The following factors were found to be important in a majority of the 145 triggered avalanches studied by McCammon and Schweizer.

a. Depth of fracture (< 1.0m) – 96% of cases had a fracture (measured near the crown where snow tends to be thicker) of less than a meter.
b. Hardness difference (> 1 step) – 90% of cases had a hardness transition across the weak layer of 1 step, as measured by a standard hand-hardness test.
c. Grain type (persistent) – 86% of cases involved persistent grain types (facets, surface hoar, depth hoar, ice lenses and crusts) within the weak layer or interface.
d. Weak-layer thickness (< or = 10cm) – 78% of the cases had weak layer thicknesses of less than 10cm.
e. Grain-size difference (> 1mm) – 65% of the cases had a grain-size difference across the weak layer of 1mm or more.

Human-triggered avalanches appeared to be more likely when 3-to-4 of the above factors were present within the 145 avalanches in Canada and Switzerland studied.

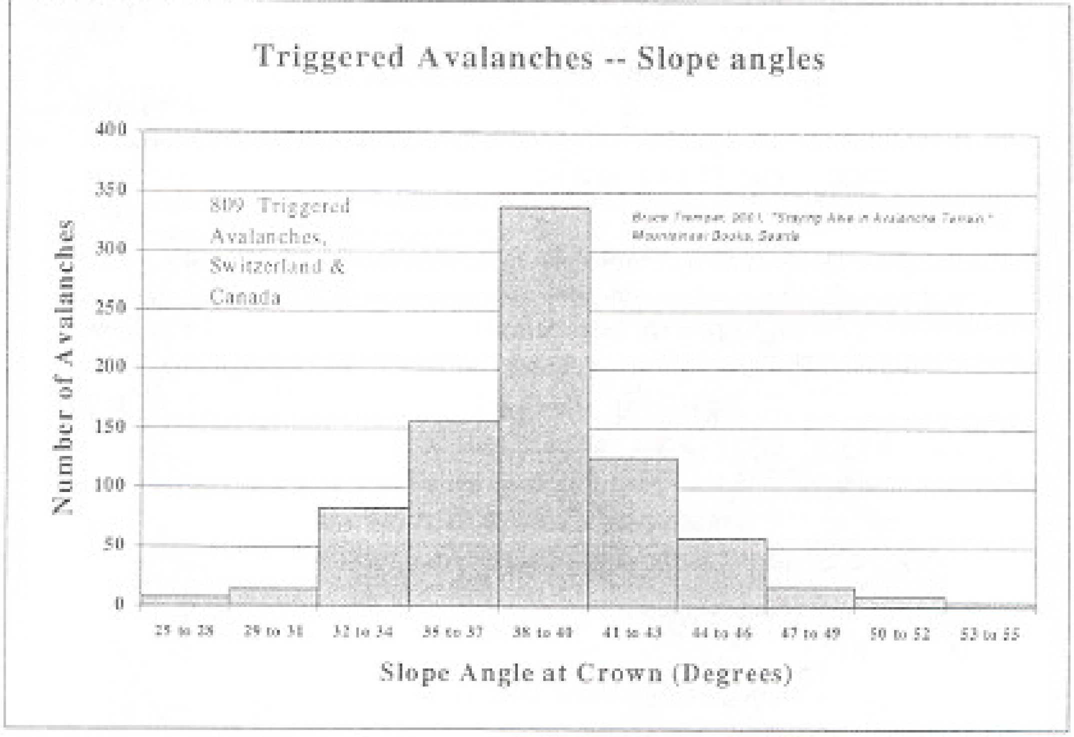
In a similar study by Schweizer and Jamieson (2002) stable and unstable snowpack profiles were compared. They found the following characteristics to be significant in contrasting these profiles. Table 1 provides the median values for the stable and unstable cases of the significant characteristics. The differences in the median values was highly significant, as determined by standard statistical tests.

Table 1. Data from Schweizer and Jamieson (2002)

Variable	# of cases	Stable	Unstable
Fracture layer grain size (mm)	421	1.1	2.0
Fracture layer hardness (hand test)	401	#2 (4 fingers)	#1 (fist)
Size difference across interface (mm)	356	0.5	1.1
Hardness difference (hand)	401	1.0	1.7
Rutschblock score	369	5	3

Slope angle of slabs are usually measured at the crown fracture. As shown in a study of 809 human-triggered slab avalanches in Canada and Switzerland, 76% of slab avalanches were triggered in the 35° to 43° range, although 24% have been triggered in the 25° - 34° and 44°- 55° range. During extremely rare conditions slabs have been triggered outside of this range.

FIGURE 10. Slope angles, measured near the crown, of 809 human-triggered avalanches (from Tremper, 2001)



Bruce Tremper, 2001, "Staying Alive in Avalanche Terrain." Mountaineer Books, Seattle

8 LOOSE-SNOW AVALANCHES

A loose-snow (point-release, or sluff) avalanche consists of loose, unconsolidated snow sliding downslope. Small loose-snow avalanches are sometimes called "sluffs." In contrast to slab avalanches which fracture at a distinct line, loose-snow avalanches start at a point as a small volume as unconsolidated and cohesionless snow exceeds its local angle of repose and slides downslope. They typically become wider and deeper and descend until the frictional and ploughing resistance of the moving snow exceeds the gravitational driving force. They are common on steep slopes and are often begin below disturbed areas (like ski tracks), rather than above them, thus may differ from slab avalanches in this important respect.

Loose-snow avalanches can be a sign of a stabilizing snowpack as small point-release avalanches gradually distribute snow from steep to less steep slopes where it may be less prone to slab fracture. They are common during thaw events (including rain) and adjacent to rocks, trees, or soil that absorb heat.

Although loose-snow avalanches are often "small and harmless," this is not always the case. A small point-release, loose snow avalanche can be a significant danger to a person exposed on a steep slope. For example, ice-climbing routes often will be located in small, steep drainages that can channelize small loose-snow avalanches. Occasionally they trigger the larger and more dangerous slab avalanches and, during certain optimum conditions (e.g., saturated snowpack on a long, steep slope) they can be sufficiently large and energetic to travel long distances and destroy a building.

9 AVALANCHE MOTION

After a slab avalanche fractures and avalanches begin, the initial rigid slab can quickly break into chunks that slide, roll, bounce, disintegrate and break apart into progressively smaller pieces. If the avalanche travels far enough or falls over steep, rough terrain, it can develop into a fully-developed "flow," consisting of a mixture of chunks of the slab, finely-pulverized snow and entrained air. Because avalanche motion resembles, superficially, the flow of a fluid, avalanche motion has sometimes been represented or modeled as fluid flow.

Avalanches can increase in mass, speed, and energy as they accelerate downslope and entrain snow and air. The phases of avalanche motion are illustrated in Figure11 and consist of (1) acceleration and entrainment of new snow, (2) maximum speed and mass is attained, and (3) deceleration and deposition. The distance an avalanche moves within a particular avalanche path depends on its mass and the type of snow involved in a particular event. While typical large avalanches may stop fairly high in the avalanche path (on slopes of 10° - 15°) the rare or unusual events of interest in engineering and land planning may travel unexpectedly long distances on gentle terrain. Some large avalanches have been known to travel more than 1,000m on slopes of less than 5°, destroying mature forest as the runout zone was extended.

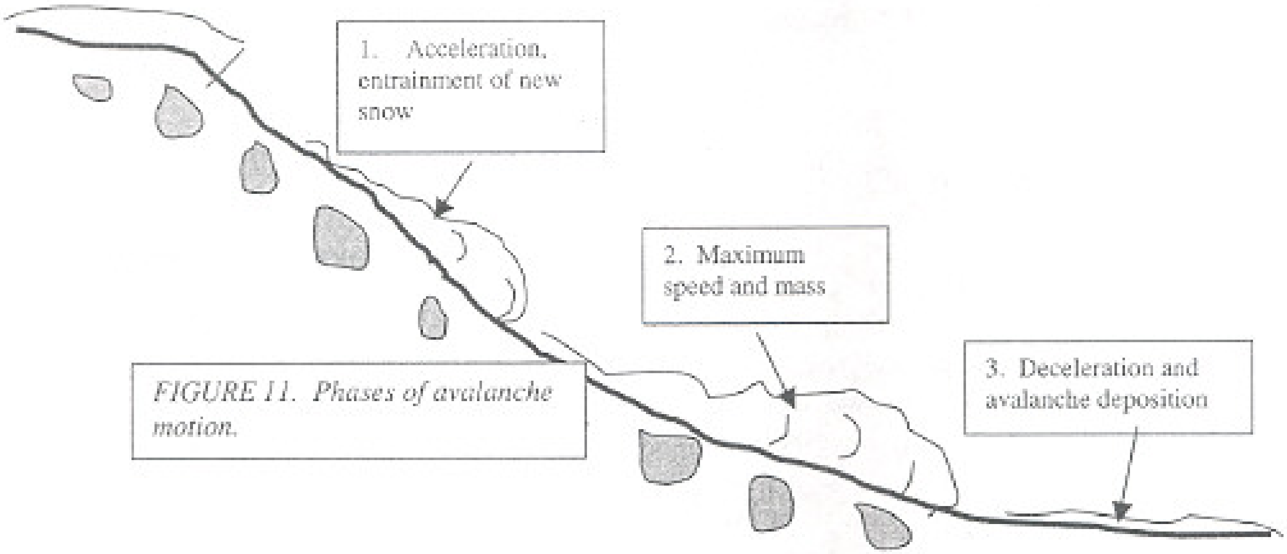


FIGURE 11. Phases of avalanche motion.

A fully-developed avalanche moves by *sliding* on its running surface (old snow or ground) and by deforming internally (*flowing*) as it also slides. Sliding dominates the motion of some wet-snow avalanches and small avalanches because the energy of flow is not sufficient to overcome the cohesion of the moving mass. Such avalanches remain close to the ground, and do not become well developed. However, when dry-snow avalanches exceed approximately 20m/sec (45mph) velocity, they become "fully developed" mixtures of snow, pulverized snow, and air. Typical and extreme avalanche speeds are summarized in Table 2.

Table 2 provides rough estimates of avalanche speeds related to the total vertical fall height of the avalanche event. Total avalanche mass usually increases with vertical fall.

Table 2. Avalanche Speeds related to vertical fall

Vertical Fall (m)	Speed Range (m/s for dry snow)	Speed Range (m/s for wet snow)
100-200	20-35	10-20
200-500	35-55	15-30
500-1000	55-70	20-35

Note: 1 m/s = 2.24 mph.

Speeds of several large dry-snow avalanches have been measured in Switzerland, Canada, Norway, and Colorado. Maximum speeds for the larger events are in excess of 60 m/s (130 mph) for these large events, usually after they have fallen at least 200m. Large dry-snow avalanches, which invariably result from fracture of large, dry slabs, reach the highest speeds although wet snow avalanches can also reach high speeds, particularly when they fall over very steep terrain and cliffs.

Knowledge of avalanche dynamics and runout prediction are important, sometimes essential, in land-use planning and engineering of structures in exposed terrain. A significant amount of research and practical work has been devoted to these subjects, particularly in Europe where development of mountains population centers has exposed large concentrations of people mostly during the past century as the population has increased. These subjects (dynamics and runout) has received less attention in the United States, because only a small part of the population has developed within avalanche terrain. This has begun to change in the past 20-30 years as mountain resorts have expanded in mountain regions and suburban areas have begun to develop near urban centers.

The maximum avalanche runout area of an avalanche, or the maximum runout that can be expected in a 100-300 year return period, is therefore a fundamental question in land planning and one that is difficult to address objectively. If these areas *can* be objectively determined, using current and accepted procedures, construction may be avoided in the "design-magnitude" or "long-return period" avalanche areas. This is clearly the most efficient, cost-effective, and environmentally sound method of avalanche-hazard mitigation. However it is not always desirable when property prices are high and private land is available on the real-estate market. When the history is long, complete, and detailed, such as in some European countries, these design-magnitude events may be avoided simply by referring to the historical record. However, this is rarely possible in the United States because of the relatively short historical record in virtually all mountain areas. When long-term historical records are not available avalanche runout maxima are then estimated by a variety of techniques such as: a) Interpretation of forest and vegetation effects, b) analysis of tree rings (dendrochronology), c) study of land-form changes due to avalanches (geomorphology), d) statistical runout models based on regional performance of avalanches in the local mountain area, and e) calculation of speeds and runout distances. Ideally, in the absence of reliable historical data over a long time period (a 100 to 300 year period is essential), some of the above indirect methods should be used. It is *not acceptable* to simply estimate the maximum extent and effects of avalanches without basing the estimate on some sort of acceptable, recognized method. One subjective estimate may differ from another and may, in some cases be biased by "vested interests" in the outcome, particularly when expensive land is for sale.

Once runout areas have been objectively determined, the next question usually relates to the destructive effects of the avalanche and how objects can best be protected. These engineering problems may require an estimate of the impact-pressure (or design pressure) on an exposed object. Avalanche impact pressure is usually estimated by the simple equations

$P_I = \rho V^2$ (dry or wet flowing avalanches), or

$P_S = ½ \rho V^2$ (powder avalanches).

In the above equations, P_I is the impact pressure (subscript "I") and P_S is the stagnation pressure (subscript "S"), ρ is the avalanche flow (or powder) density, and V is the speed. The speed must be computed, based on the design runout distance which should be determined for the avalanche return period relevant to the particular land use.

Quantification of avalanche dynamics has received a great deal of attention over the past few decades. Proper application of the engineering techniques has resulted is safer mountain development, appropriate mitigation techniques being applied, and generally safer development in some mountain jurisdictions. The Canadian Avalanche Association has recently published two manuals that relate to avalanches and land-use considerations (Canadian Avalanche Association publications in references).