Snow Pit Measurements And Avalanche Forecasting Models

by

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Snow Pit Measurements

And

Avalanche Forecasting Models

List of Symbols and Notations

α	Slope Angle	Deg.
μ	Coefficient of Sliding Friction	
ρ	Snow Density	k/m^2
ρ_a	Average density of two or more layers	kg/m^3
T_s	Shear Strength	kPa
T_t	Tensile Strength	kPa
ω	Weight of single layer	k/m^2
A	Area	m^2
g	Gravitational acceleration	m/sec^2
L	Length	m
S_s	Shear Stress	kPa
S_t	Tensile Stress	kPa
t	Layer thickness	m
$w_{f,b}$, b	Width	m
W	Total weight of two or more layers	kg/m^2

Snow pit measurements are made to satisfy several different requirements. For the experienced backcountry traveler, the snowpit is used to establish a base of knowledge from which future observations can be added. Having established the base, a cursory pit is used to update snowpack conditions.

The basic investigation should be a thorough analysis of the snowpack including the documentary data of site location, elevation and aspect, date time, etc. All significant layers and layer boundaries should be identified and analyzed from the surface to the ground level. This includes density, hand hardness, metamorphic states, temperature gradients, and the existence and location of weak layers in the snowpack.

The cursory snowpit measurements that follow assess the impact of weather events that have occurred subsequent to the initial rigorous snowpit.

For the more serious observer whose purpose is avalanche hazard forecasting on a daily basis, or whose purpose is some form of research or study in snow and avalanche mechanics, rigorous snowpit analyses are performed more frequently. Measurements of shear stress and shear strength are often included, as are measurements of tensile strength and stress.

The weight of the snowpack above the layer and the angle of the slope on which the snowpack is situated determine the shear stress on a layer boundary. The weight of each layer is determined as follows:

$$\omega = t * \rho \quad \text{.....................................(1)}$$

Where (ω) is the weight in kg/m^2 (actually weight per unit area) of layer number n; (t) is the thickness in meters; and (ρ) is the density in Kg/m^3. To determine the weight acting on layer number n, the summation of the weight of each layer, above layer (n), must be determined, i.e.;

$$\text{Total weight (W)} = \omega_1 + \omega_2 + \omega_3 + \ldots \omega_{(n-1)} \quad \text{...............................(2)}$$

As shown in figure 1, the weight acting on a layer can be represented by the vector W_g, and can be divided into two components, one normal (perpendicular) to the slope, W_c and one parallel to the slope W_s. W_s represents the weight component acting down slope while W_c represents the weight component acting in compression into the slope.

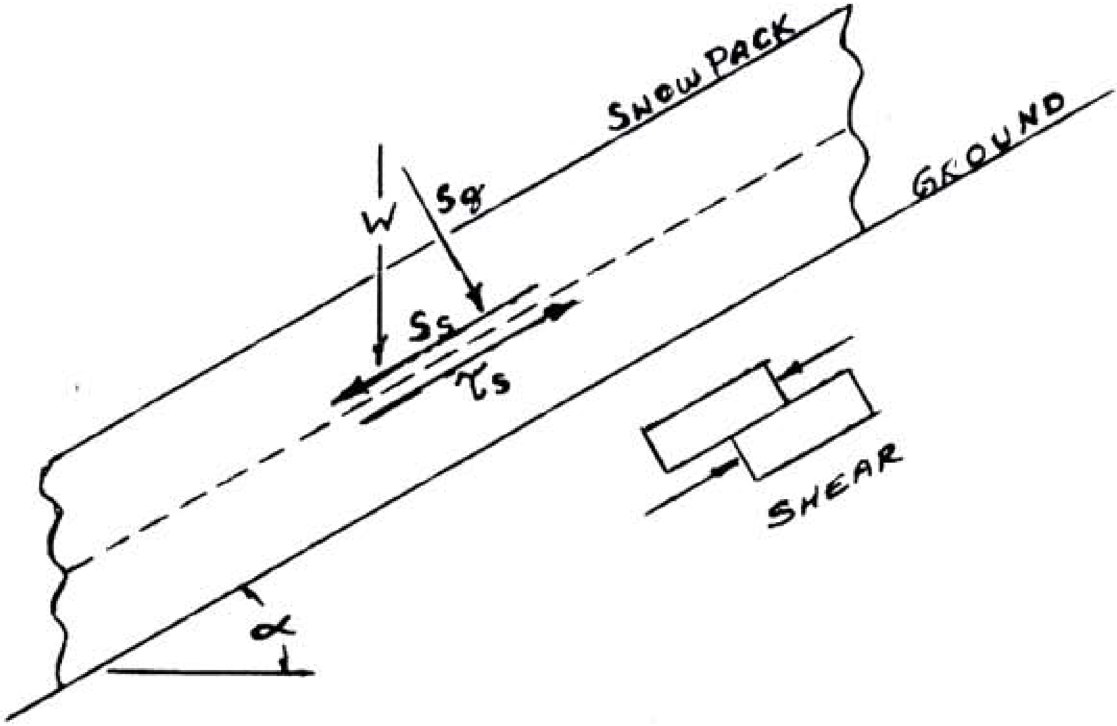

Figure 1. Stress components in a snow pack.

These two components of weight are changed into forces by Newton's second law that states:

Force, (F) = ma

Where m is the mass and a is acceleration. In this example of force determination, a = acceleration due to gravity. Therefore, to determine the force (S_s) acting downhill on a layer:

$$S_s = W * g * \text{Sin}(\alpha) \quad \text{.......................} \quad (3)$$

Where α is the slope angle and g is acceleration due to gravity. Likewise, the force acting in compression normal to the slope (S_g) is:

$$S_g = W * g * \text{Cos}(\alpha) \quad \text{.......................} \quad (4)$$

These two forces are in actuality forces per unit area and therefore referred to as stresses.

The units for shear and normal stress are "Newton's per square meter". This is arrived at through the multiplication of the units of W_t. and g, which gives:

$$kg/m^2 * m/sec^2 = kg/msec^2$$

Since 1 Newton (N) = (1) kgm/sec^2, then the unity expression:

$$\text{"}N/(kgm/sec^2)\text{"} \times \text{"}kg/msec^2\text{"} = N/m^2$$

Continuing, 1 (N/m^2) = 1 Pascal

For the sake of expediency, we will use the unit "kPa", which equals 1000 Pascals. The ratio of shear stress to normal stress is called the "coefficient of static friction", ((Tan α), or/and (f)).

Table 1, which follows, shows the use of equation (3) to compute the relationships of several variables existing at the time of fracture due to shear failure. For example, if a 1.5 meter fracture occurred on a slope of 40 degrees, where the total weight resting on the weak layer = 254 kg/m^2, (average density = 169 kg/m^3), the shear strength of the layer at failure = 1.6 kPa.

S_s (N/m^2)	α (deg.)	W (kg/m^2)	ρ_a @ h = 1 m	ρ_a @ h = 1.5 m	ρ_a @ h = 2 m
1000	30	241	241	136	102
1200	"	245	245	163	122
1400	"	285	285	190	143
1600	"	327	327	210	163
1800	"	367	367	245	184
1000	35	178	178	119	89
1200	"	213	213	142	107
1400	"	249	249	166	125
1600	"	285	285	190	142
1800	"	320	320	213	160
2000	"	356	356	237	178
1000	40	159	159	106	79
1200	"	190	190	127	95
1400	"	222	222	148	111
1600	"	254	254	169	127
1800	"	286	286	190	143
2000	"	317	317	212	159

Table 1. Relationship between Shear stress (S_s), Weight (kg/m^2), and Slope angle (α).

The two tables following (2), list the snow profile parameters from snowpit observations and (3), list typical variations in measurements. As can be seen, measurement of snowpack properties are not to be construed as data for accurate analyses of avalanche phenomenon, but rather as a guide to assist in reaching reasonable conclusions toward the evaluation of probable events.

	DESCRIPTION	UNITS	COMMENTS
D_i	Vertical layer thickness of the ith layer	cm	Slab-group thickness is total snow thickness above shear-zone.
H_i	Layer-parallel hand penetration hardness	N/m^2	a. Assume 10kg penetration force. b. Normalized to "fist" hardness.
X_{ui}	Unmetamorphosed snow grains	D.L.	Scaled by degree of riming: 1 = +, 2 = +R, 3 = ✱
X_{di}	Destructive-metamorphosed snow grains (ET)	D.L.	Scaled by degree of rounding: 1 = λ, 2 = ϕ, 3 = •
X_{ci}	Constructive-metamorphosed snow grains (TG)	D.L.	Scaled by degree of building: 1 = □ , 2 = Δ, 3 = Λ,V.
X_{wi}	Wet-metamorphosed snow grains (MF)	D.L.	Scaled by degree of sintering: 1 = O, 2 = ∿∿, 3 = ∿∿∿, 4 = ▬
C_i	Average grain diameter	mm	Disaggregated grains.
ρ_i	Layer density	kg/m^3	Density averaged in slab-group
T_i	Layer temperature	°C	Least squares fit from 10 or 20cm profiles.
∇T_i	Temperature gradient across the snow layer	°C/cm	Least squares fit. Positive=cold down.
τ_g	Slope-parallel stress component	N/m^2	$\tau_g = \rho_i\, g \sin\theta \left(\sum_{i=1}^{n} D_i \cos\theta\right)$. g = accel. of gravity. θ = slope angle. n = no. of layers in the slab-group
σ_g	Slope-normal stress component	N/m^2	$\sigma_g = \rho_i\, g \cos\theta \left(\sum_{i=1}^{n} D_i \cos\theta\right)$.
f	Coefficient of static friction	D.L.	$f = \frac{\tau_g}{\sigma_g}$.

Table 2. Snow profile parameters from snowpit observations. (Ferguson, S.A. 1984)

	Source of Uncertainty		
	Measuring Instrument	Observer Technique	Natural .Variations
D	$\pm .5\ cm$	$\pm 1-10\ cm$ [1]	$\pm 1-100\ cm$
H	$\pm 5 x 10^3 \frac{N}{m^2}$	$\pm 5 x 10^3 \frac{N}{m^2}$ [2]	$\pm 5-500\ x\ 10^3 \frac{N}{m^2}$
X	$\pm$ 1 *category*	$\pm$ 1 *category* [3]	$\pm$ 1 *category*
G	$\pm 1\ mm$	$\pm 1\ mm$ [4]	$\pm 1\ mm$
ρ	$\pm 1 \frac{kg}{m^3}$	$\pm 10 \frac{kg}{m^3}$ [5]	$\pm 10-50 \frac{kg}{m^3}$
T	$\pm .5°C$	$\pm .2°C$ [6]	$\pm 1-5°C$

[1] Measures depths along line other than vertical.

[2] a. Varies penetrating force.
b. Varies penetrating instrument (*e.g.*, ungloved to gloved hand).

[3] Is either unfamiliar with categories or cannot see the shapes.

[4] a. Does not disaggregate grains.
b. Does not distinguish between range or mean size.

[5] Compresses or disturbs sample upon extraction.

[6] Does not allow thermometers to equilibrate with environment.

Table 3. Typical variations in snowpit measurements for three sources of uncertainty. D = layer thickness, H = hand-hardness; X = grain type; G = grain size; p = layer density; and T = temperature. (Ferguson, S.A. 1984).

There are many ongoing efforts to enhance the state-of-the-art of avalanche hazard forecasting such the work of Buser (1983); Buser, et al, (1984); Obled and Good, (1980); Judson and Erickson, (1973), to list a few. Most of the ongoing work tends toward statistical approaches utilizing past and current meteorological and avalanche event data. With the capabilities of current computer technology, these methods of forecasting using statistical models appear to have a definite application in the forecasting of avalanche events. Another form of avalanche hazard forecasting model is based on physical occurrences within the avalanche environment and constitutes a number of sub-models. These sub-models each have the potential to cause or contribute to instability in the critical zone of an avalanche path.

Examples of logical sub-models are:

Snow-load Model: This is the very basic phenomenon of an increase in load on the existing snowpack caused by new snow or wind transported snow. The weak point in this model is the requirement to quantify the shear strength of each discernible layer in the snowpack. A study is needed to define the categories of possible sliding surfaces, i.e., sun crust, surface hoar, kinetic growth crystals, etc., and assign a validated range of shear strengths to each surface.
The following examples demonstrate the possible applications of the basic snow load model. Snow pit data from actual field observations is shown below:

Location:	Miller Country	Sky:	Overcast
Observer:	WLH	Wind:	5kts @ 315
Date:	21Jan 86	Air Temp:	-5 deg C
Time:	1530	Pit Slope:	25 deg
Elevation:	6200 ft	Precip:	Lt Snow
Aspect:	135	Total Depth:	3.55 m

Layer #	thickness (m)	density (kg/m^2)	hardness	T_s (kPa)	T_s (kPa)	shovel	crystal type	temp (deg C)
1	0.30	120	4F	0.3	24.5		des	- 8
2	0.50	200	4F	0.7	24.5		des	- 6
3	1.00	335	1F	2.5	96.0	easy	rnd	- 5
4	0.05	200	1F	2.0	16.3		facet	- 5
5	0.65	340	P	3.5	87.0		rnd/facet	- 4
6	0.55	200	P	3.8	90.0	mod	rnd	- 3
7	0.35	255	P	4.9	80.0		facet	- 2

Where:

T_s = Shear Strength measured at <u>bottom</u> of layer (kPa).
T_t = Tensile Strength of each layer (kPa).

The length of the avalanche track (crownface to stauchwall) is a distance of 50m.

Using equations (1), (2), and (3), determine the shear stress at the bottom of each layer:

layer 1: (.30 * 100) * (9.8 * Sin(25) /1000) = .124 kPa
layer 2: (.50 * 200) * (.00414) + .124 = .538 kPa
layer 3: (1.0 * 335) * (.00414) + .538 = 1.93 kPa
layer 4: (.05 * 200) * (.00414) + 1.93 = 1.97 kPa ..., etc.

Or to find the stress at the top of layer (4), the weak layer:

T_S = (.3*100 + .5*200 + 1.0 * 335 + .05*200) * 9.8 * .4226/1000 = <u>1.97 kPa</u>

Question: <u>At what slope angle will shear failure occur?</u>

Using equation (3) and the measured value of shear strength, (T_s) in place of (S_s):

$\alpha = \text{Sin}^{-1} (T_S/(W_t{*}9.8) = \text{Sin}^{-1} (2.0{*}1000/(475{*}9.8)$ = <u>25.45 deg.</u>

Question: With the current snowpack conditions, how much new snow at a density of 80 kg/m3 will cause the slope to become unstable due to shear stress? Using equation (3) and the measured value of shear strength, (T_s), solve for W:

$W = T_S / (g * \text{Sin}\ \alpha) = (2.0 * 1000)/(9.8 * \text{Sin}\ 25)$ = <u>482.9 kg/m^2</u>

The net between the existing (W) and the (W) required for failure is:

482.9 - 475 = <u>7.9 kg/m^2</u>

Since $W = (t * \rho)$, (equa.1), t = 7.9 / 80 = <u>0.99m</u>, or 10cm.

To calculate the tensile strength (T_t), of a particular layer, it is necessary to know the length of the slope that will fracture due to tensile failure. This is usually taken as the distance between the crownface and the stauchwall. For the example shown above, this distance was estimated to be 50 meters.

In order for a slope to fail in tension, the slope must have failed in shear and is supported by the tensile strength of the layer(s) above the weak layer. Figure (2) shows a schematic (not to scale) of the volume of snow whose weight must be determined as acting on the area of the crownface.

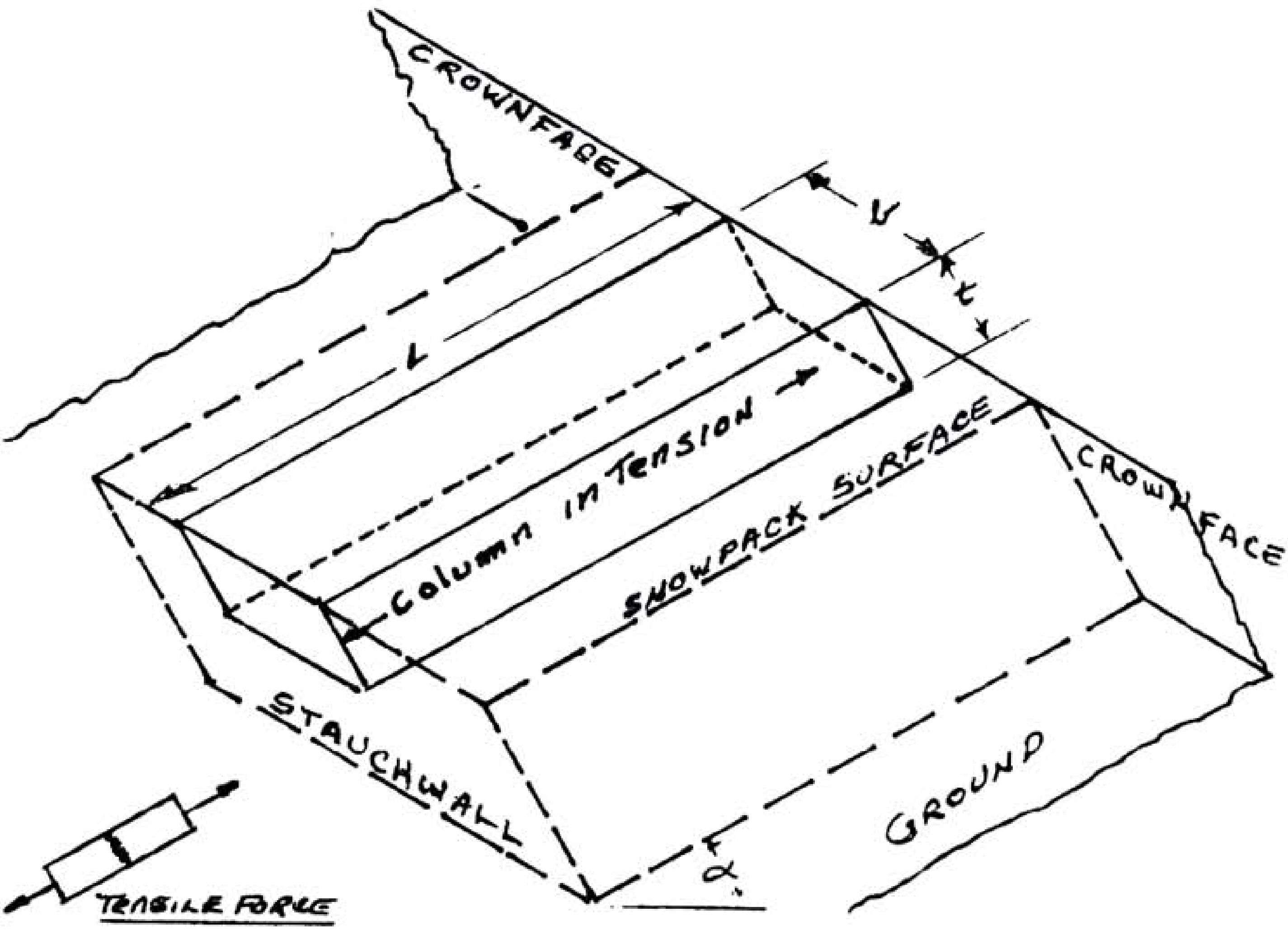

Figure (2). Schematic of a unit column of snow acting in tension.

To determine the tensile stress (S_t):

$$S_t = (\text{Volume} * \text{density} * g * \text{Sin}(\alpha)) / \text{cross sectional area}$$

Therefore, $S_t = (L * b * t * \rho_a * g * \text{Sin}(\alpha) / (b * t * \text{Cos}(\alpha))$; by canceling b and t,

$$S_t = (l * \rho_a * g) * \text{Tan}\,\alpha \qquad (5)$$

Assuming that layer (3) is the strongest above the layer most likely to fail in shear, the tensile stress in layer (3) is:

$$S_t = (50 * 258 * 9.8 * \text{Tan } 25)/1000 = \underline{59 \text{ kPa}}$$

Theoretically, since the measured tensile strength is greater, (96 kPa), the slope will not fail. Realistically any ski cut, weak spot (tree, rock, etc.) could cause the slope to fail.

Wind Transport Model

This model would determine the amount of loading on the existing snowpack of a particular avalanche slope caused by blowing snow. The model would be based on wind velocity, direction, length of wind event (kilometers of wind per unit of time) slope aspect, snowpack surface in the fetch area, and probably other geometric features of the fetch area and avalanche path.

Solar radiation model:

The primary function of this model will be to determine the effect of solar heat on layer strength(s); by water percolation due to surface melting (Springtime) and the creation of sun crusts throughout the winter-spring season prior to the next storm.

Mass heat transfer model:

This model combines the effects of relative humidity, wind velocity, and temperature on the snow surface and on layers beneath the surface. One example of the effect of mass heat transfer occurs when a layer of warm air, with high relative humidity, and moderate winds moves over a deep layer of new snow. This snow layer which is still in the stages of destructive metamorphism has a granular structure and is subject to point releases at most. Assuming a slope angle of sufficient magnitude, the mass heat transfer condition described above can cause a rapid bonding of the grains in the upper part of the new snow layer creating a coherent soft slab. This condition will generate the capability of fracture propagation if disturbed (for example by a ski cut) and the added weight, as the slide progresses down slope, can cause a significant avalanche.

The effect of mass heat transfer on the strength of buried layers is another requirement for extensive study. It is known that a sudden warming after a cold spell can cause a weakening of buried layers but there are no quantitative analyses, to date .

Temperature, and temperature gradient model.

Throughout the winter season, temperature variations generally follow a pattern of starting near 0 deg. C and dropping to some minimum level for a period before moderating towards 0 deg. in the late winter - early spring. Superimposed upon this seemingly straightforward trend are the daily rise and fall of temperatures (Temperate and Sub-Arctic zones), all which have an effect on snowpack structure. Again, there are few if any validated quantitative models relating temperature and avalanche hazard levels. There are guidelines, for instance, for alerting the practitioner to the conditions leading to kinetic growth crystals. for example, a gradient of 10 deg. per meter of depth. However, if the temperature gradiency exists between -1 and -15 deg. C, the results will be quite different than if the same gradiency exists between -20 and 40 deg.C. So the temperature model presents yet another area requiring intensive study.

An interesting set of temperature related equations and conditions leading to avalanche slope instability was presented by B.N. Rzhevskii, based on research conducted in the USSR (reference not available at time of printing). The report is titled " Avalanches caused by sharp temperature fall". A summary of the work follows:

Equations: °C/hour

if U < .17 °C/per hour avalanche activity is minimum
• minimum conditions
→ t_i minimum is 6 hours
→ t_d max is 50 hours

T_i = U / (0.123U - 0.0183) ....(6)

T_d = (15.359 - 2.81U) / (U - 0.44) ....(7)

Where t_i = time of commencement of avalanche danger after the beginning of temperature drop, and t_d = duration of danger. (t_i) and (t_d) are in hours. (U) is the intensity of temperature drop in degrees per hour.

Conditions:

1) Increase in intensity U, decrease in t_i and t_d.
2) At U less than 0.17 deg. per hour, probability of activity is minimal.
3) Minimum t_i is 6 hours.
4) Maximum t_d is 50 hours.

Maximum period of danger (but not minimum) is from hour 6 to hour 50 after intensity "U" of 0.17 or greater has been recorded.

About 20% of all natural avalanches are caused by sharp temperature fall, while 3% are caused by sharp temperature rise.

Pertinent remarks:

Observations recorded a decrease of shear strength, from 20 gm/cm^2 to 7 gm/cm^2, with a sharp temperature fall from -9 C to -18 C. Layer depth was 0.45m (important!).

A rise in temperature from -19.4 C to -7.2 C over a 7-hour period caused a decrease in shear strength from 25 gm/cm^2 to 3 gm/cm^2. (!!)

Most favorable time for decent of "temperature rise avalanches" is 11 to 14 hours mean solar time. Minimum "U" value = 0.29 degrees per hour.

No equations exist for temperature rise avalanches. (?)

Wet avalanches: Minimal danger after 21 hours of commencement of temperature rise. 60% of the avalanches descend within 9 to 15 hours after commencement of temperature rise.

Since this article was a translation from Russian to English, there is no certainty that the equations are as stated by the author. An important factor is that the work was performed in an avalanche area in the USSR (Siberia) where the climate was perhaps of the Arctic - Sub-Arctic regime.

Of more importance to this discussion is that a model of this nature, thoroughly validated for a particular region would be a valuable tool to the avalanche hazard forecaster.

There is hope that with the capacities of current desktop computers, sufficient local weather stations, adequate monitoring of snowpack conditions, and validated comprehensive models as described above, the forecasting of avalanche hazard will reach a much higher confidence level.

This is not to say that avalanche hazard forecasting will approach the level of an exact science since the variability of all physical aspects of the snowpack and the associated terrain features which form the avalanche scenario will never permit a degree of accuracy approaching exactness.

The proper use of models, such as proposed above, and models such the "Expert Systems" model by McClung and Schearer, (1993), will provide the practitioner with yet, additional tools for increasing the confidence level of forecasting avalanche hazard levels.

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Quantitative Methods

of

Snow Strength Measurements

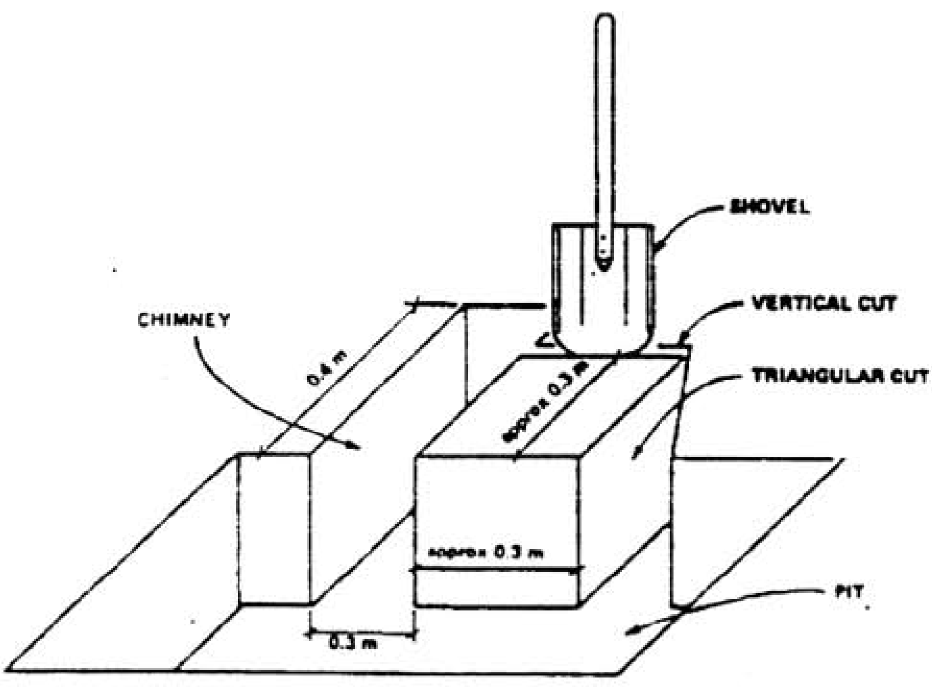
SHOVEL SHEAR TEST

The shovel shear test supplements snow profile observations with information about the location where the snowpack could fail in shear. It is best applied for identification of deep unstable layers and does not usually produce useful results in layers close to the snow surface.

Although many backcountry travelers use this test to determine hazard levels in avalanche terrain based on subjective feel, i.e., "easy", "moderate", and "hard" shear forces applied to the shovel handle, it's original purpose was not intended as a guide for determining the safety of a particular slope for skiing. On the other hand some experienced practitioners who have perfected the art of conducting the shovel shear test and relating the results to many seasons of avalanche observations find it to be a useful tool. It is a quick test and can be repeated in several locations on the slope of interest in a short period of time.

The procedure for performing the test is as follows:

Isolate a column in the snow pit by excavating a chimney about 0.3m wide by 0.4m deep as shown in the figure below.



SHOVEL SHEAR TEST

Mark a square with sides of 0.3m starting at one side of the chimney.

Make a triangular or rectangular cut on the other side of the square about 0.4m deep.

Make a vertical cut at the back of the column about 0.2m deeper than the length of the shovel ensuring that the cut extends below a suspected weak layer.

Carefully insert the shovel at the back of the column holding the handle with both hands and pull gently.

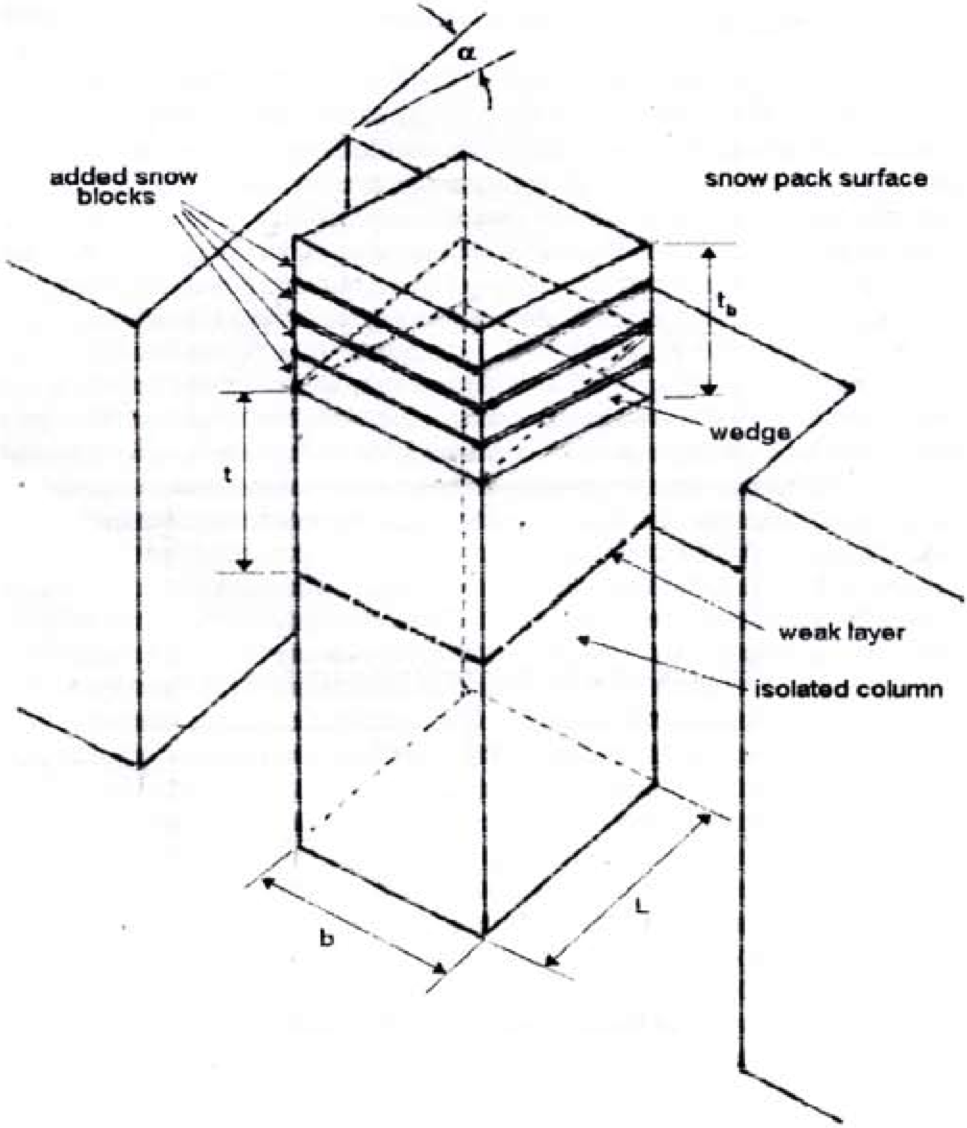
When the column breaks in a smooth shear plane above the low end of the cut, measure the location of the shear plane from the snow surface and turning the block upside down, inspect and record the snow crystal characteristics of the shear plane.

After a failure, or when no break occurs remove the column to the depth of the back cut and repeat the above procedure.

THE LOADED COLUMN TEST

This test is performed by isolating a column in the snow pit of a known dimension, usually about 30cm square, to a depth sufficient to expose layers of concern. Blocks of known density are cut from the snowpit excavation material or some other expedient source, to a dimension of 30cm square. These blocks are placed on top of the column, which has been leveled at the top, until shear failure occurs. By recording the height of the placed blocks and knowing their density, the shear force at failure can be determined.

A handy pocket graph can be drawn for field use to calculate the centimeters of new snow at a given density required to cause the slope to fail in shear.



Loaded Column Test

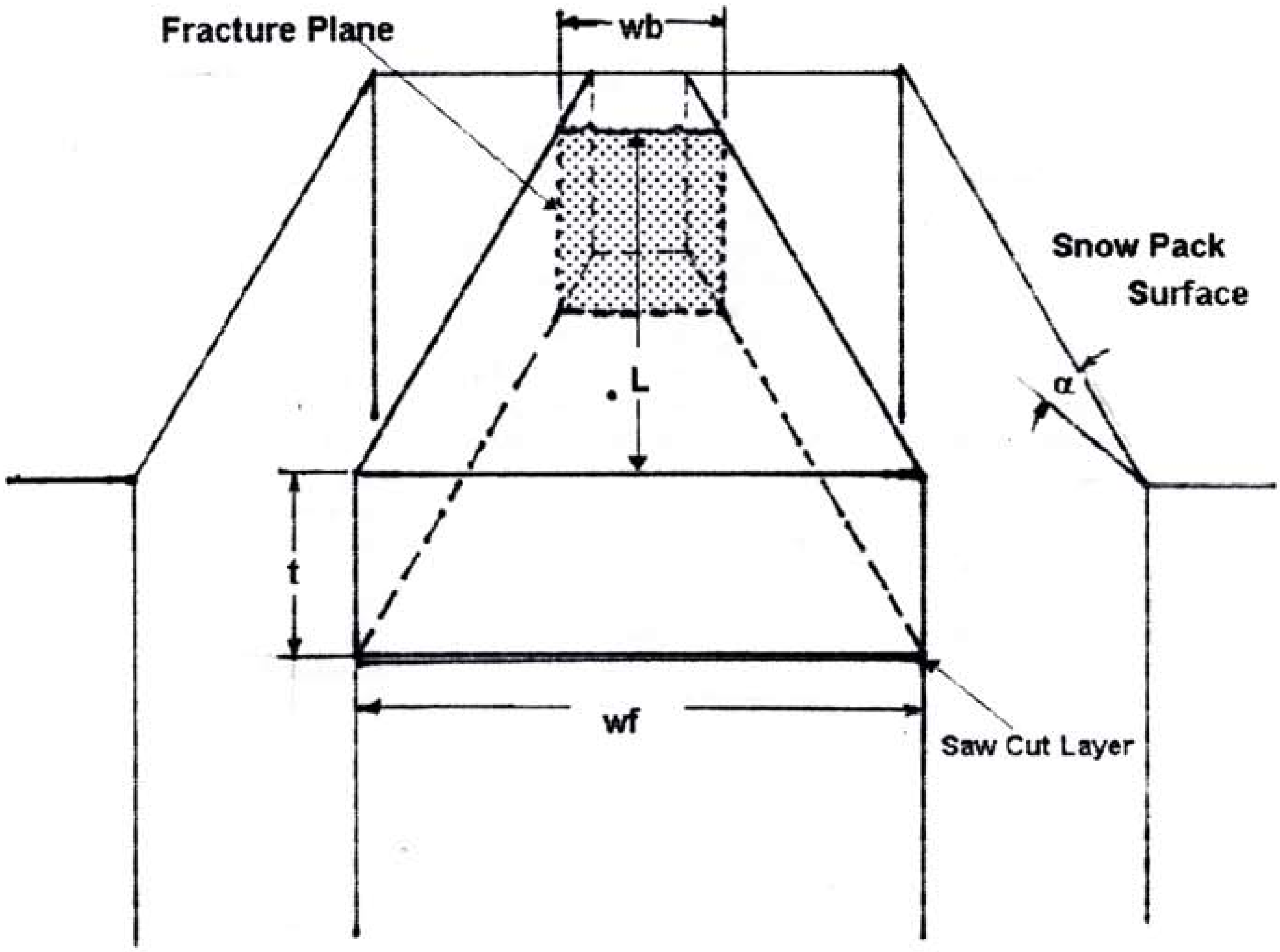
Shear Strength, $T_s = \left(W + bL\rho_a(t - (L\tan\alpha)/2)\right) \times g \sin\alpha$

Where, W = weight of added blocks in kg/m^2, and ρ_a = the average density of the snow pack to depth "t".

The blocks added for weight-to-failure are generally cut from the same layer in the snow pack thereby having the same density. The weight then becomes:

$$W = t_b \times L \times b \times \rho$$

In summary, the shear strength is the slope parallel vector of the gravitational force at failure.



Trapezoidal Tensile Test [1]

Tensile Strength, $T_t = (L*\rho_a*g*(w_f+w_b)*(\sin\alpha - \mu\cos\alpha))/2w_b$

where "ρ_a" is the average density of the layer above the saw cut, "μ" is the coefficient of friction between the snow and the sheet inserted into the saw cut, and "α" is the slope angle.

1. Russo, Robert S., Alta Ski Lifts Co., Alta, Utah

The Flatjack Shear Test

Robert S. Russo, Alta Ski Lifts Inc., Alta, Utah

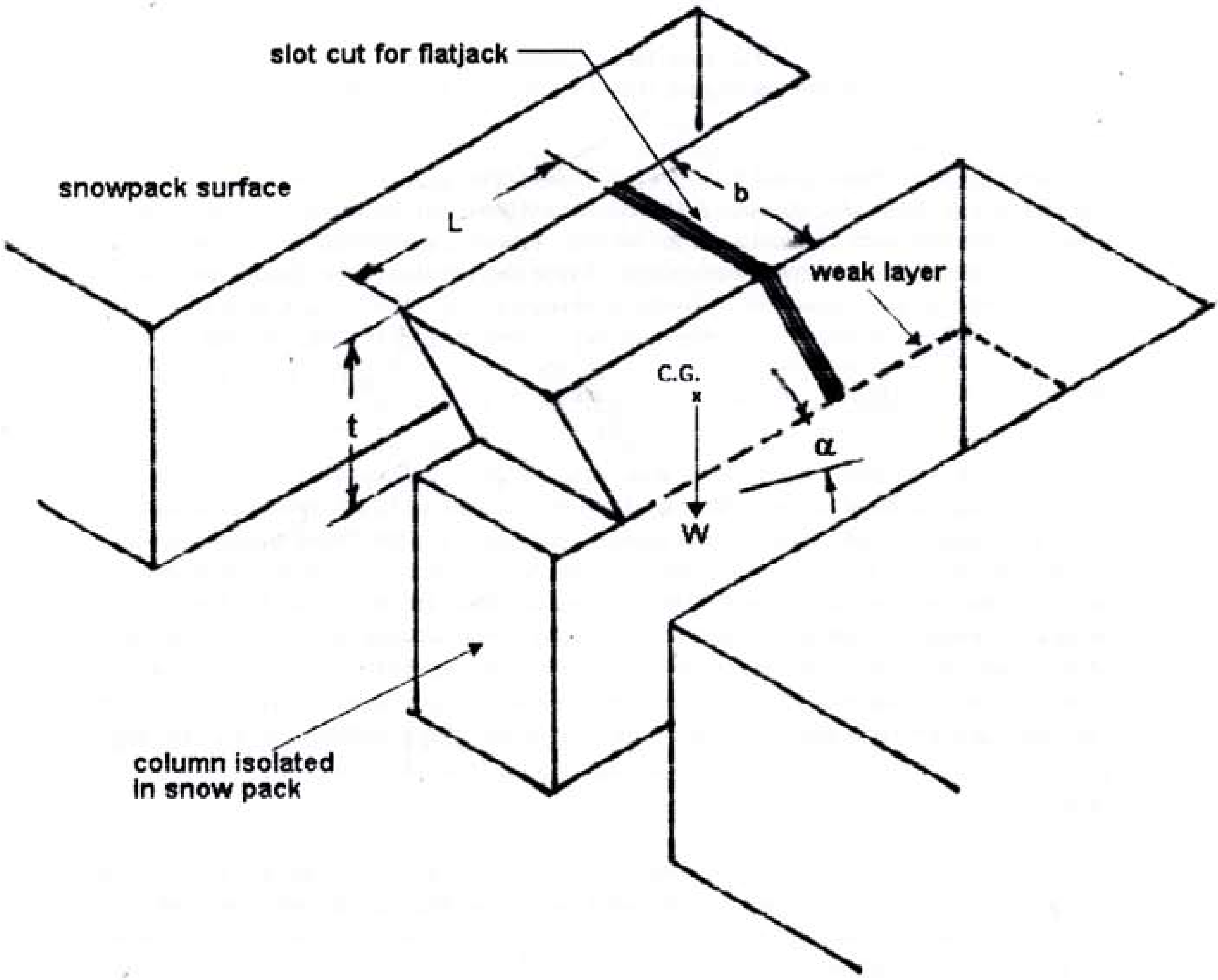
"Flatjacks have been used in experimental geology to measure changes in the earth's stress and to apply stress for experimental purposes to large in-situ rock masses (Swolfs, et al. 1975). Their application to snow mechanics required a total redesign of the technique for a media where much lower stress must be applied and measured. A flatjack is a flat slender fluid-filled bladder, which when inserted into a slot, can be pressurized to apply stress to the material surrounding it. The pressure of the fluid in the flatjack can be related to the stress in the surrounding material. For the technique discussed here, a common sphygmomanometer of the type used by medical personnel to measure the blood pressure of a patient was used. The rubber bladder was removed from the fabric "cuff" and a new nylon case was made. Fiberglass cards were inserted on each side of the bladder to maintain a uniform plane to apply stress to the snow and prevent the bladder from taking on the round shape of a balloon or from taking on some other shape dictated by regions of different hardness in the snowpack. A small nylon bag was also tied around the rubber bulb hand pump to prevent snow and ice from affecting the operation of the check valve. The pressure gage, calibrated in mm-Hg was not modified but the readings need to be interpreted to calculate the correct stress applied.

After identifying the weak layer with a shovel shear test, a block should be cut slightly wider than the bladder and long enough to assure that the block's center of gravity is behind it's front edge, With the snow removed on booth sides of the block, a saw cut can be made down the back of the block perpendicular to the slope and down to the weak layer. The bladder is then inserted in the slot made by the saw and positioned so the bottom edge of the bladder is just above the weak layer. The bladder is now pumped up slowly while the pressure gage is watched closely. As the pressure increases, some compression of the snow will take place causing slight drops in pressure but eventually the pressure will increase and shear failure along the weak layer will take place. The maximum pressure reached, and the bladder-slot thickness just before failure must be recorded". A diagram of this test is shown on the following page.

Calibration Of The Flatjack

"The relationship between the pressure in the bladder and the force applied to the block of snow should depend simply on the area of the bladder; however, as the bladder expands it stretches and some of the pressure is resisted by the tension in the bladder". This needs to be considered when calculating the true force applied to the snow block.

The curves on page 20 are the results of calibration tests performed by Robert S. Russo.



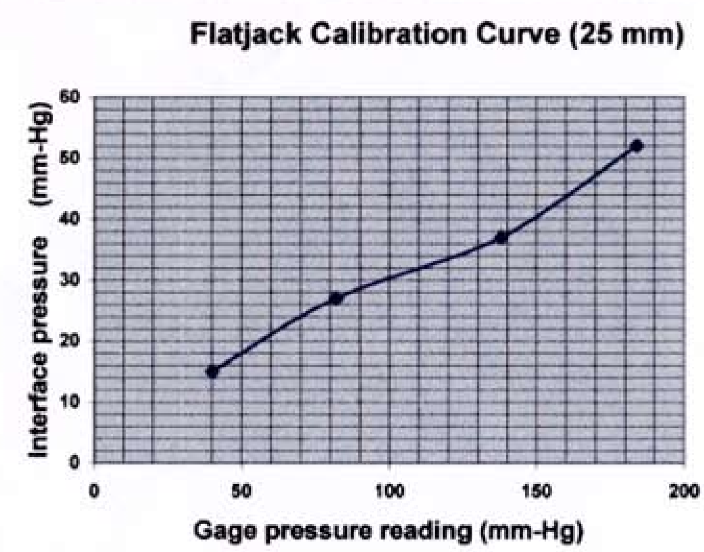
Flatjack Shear Test

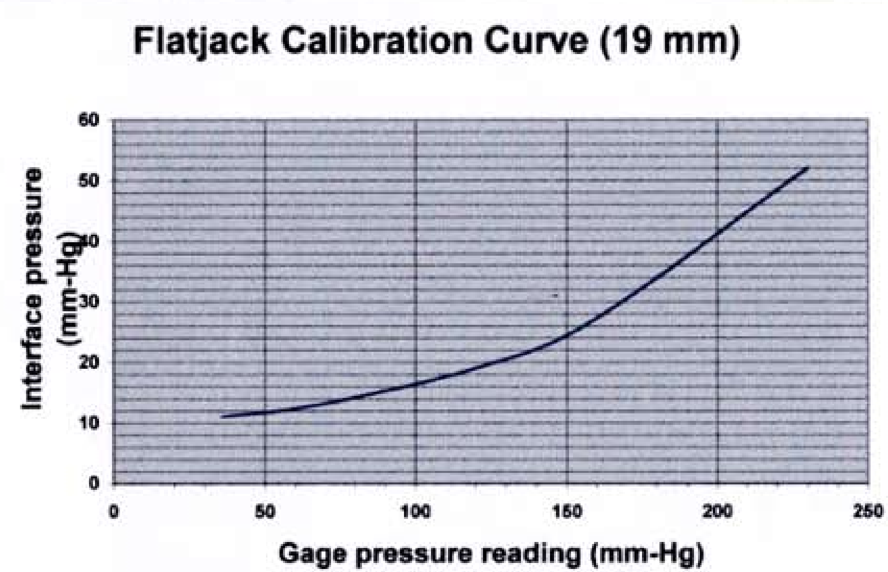
Shear Strength, $T_s = P_i \times C_{Hg} \times A_{FJ} / (b \times L) + t(\rho_a)g \times (\mathrm{Sin}\ \alpha)$

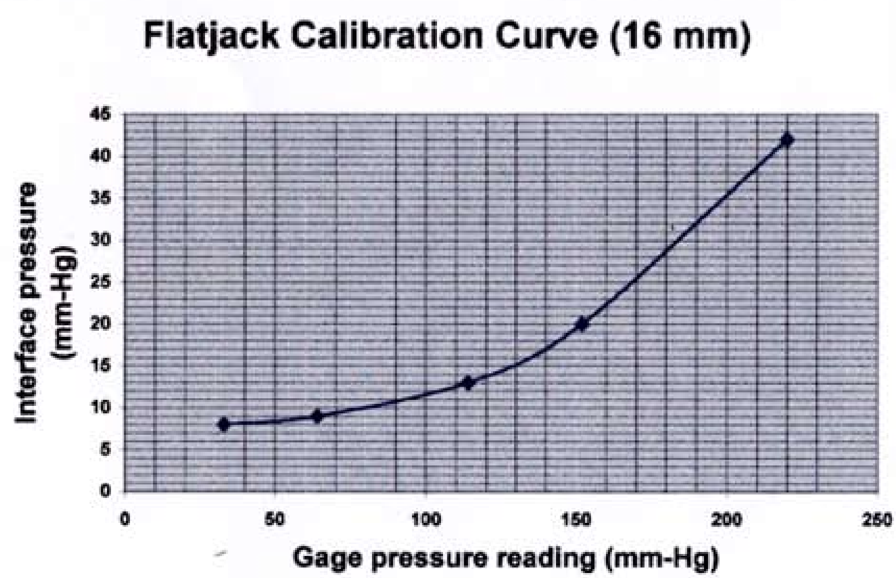
where, "P_i" is the interface pressure exerted by the flatjack, "A_{FJ}" is the area of the flatjack, and C_{Hg} is the conversion factor from mm-Hg to N/m2.

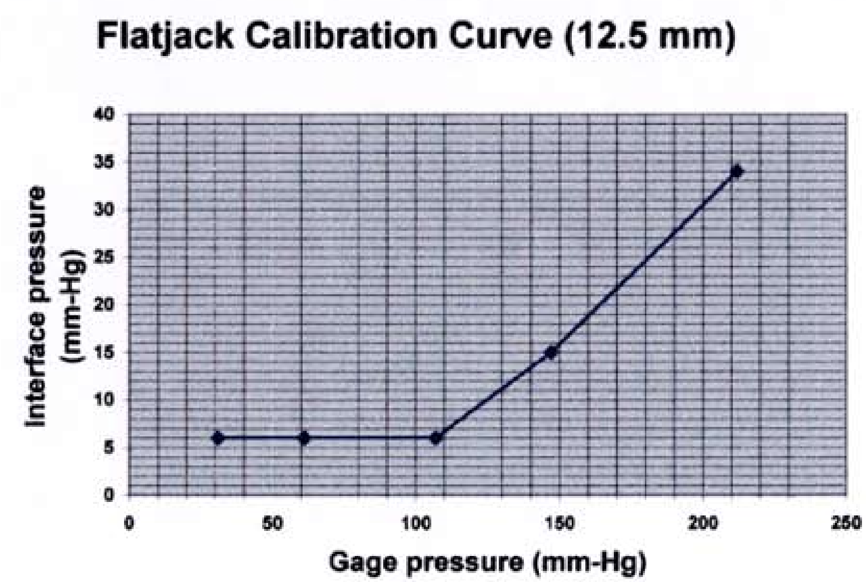
"P_i" can be selected from the charts following by measuring the thickness of the flatjack bladder when shear failure is induced.

* The faces of the block to be placed in shear are cut normal to the slope.
* The test block must be long enough for the center of weight to pass within the area in shear, as illustrated above.
* "ρ_a" is the average density from the surface to the weak layer.









CALIBRATION CURVES FOR BLADDER THICKNESS AT SHEAR FAILURE