THE SAFETY OF VERTICAL CAVING EQUIPMENT

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Abstract

Vertical caving techniques are now widely used in caving. However, vertical caving remains a potentially hazardous occupation, because of the relative absence of any back-up devices. The person who claims the perfectly safe vertical caving system can be built is, at best, using his terms loosely, at worst, woefully ignorant of the limitations of his equipment. The task of the designer of vertical caving equipment is to develop a system where the chances of failure are reduced to an acceptable level. Up to now the philosophy has been: "if it looks okay, give it a go". Unfortunately, intuition does not produce the safest system. It is time the design of vertical caving equipment was placed on a more scientific footing. This paper explains, in non-technical language, the principles governing the safety of vertical caving equipment. It describes the factors which determine the maximum forces which can occur, and provides guidelines for the design and testing of vertical caving equipment.

Introduction

Vertical caving techniques are becoming increasingly popular. Unfortunately, knowledge of the performance and safety of vertical caving systems (i.e., devices enabling vertical movement in caves) has not grown proportionately.

The design and implementation of vertical caving systems has been accompanied by much woolly thinking. It is not unusual to hear that a certain vertical caving technique is "perfectly safe". Claims such as this are dangerously misleading.

Perfect Safety

Perfect safety in vertical caving is impossible. To use the old axiom, a vertical caving system is only as strong as its weakest link.

For example, suppose you are abseiling on a single rope. The karabiner you are using may have an ultimate load capacity of 2000 kg, the whaletail a capacity of 4000 kg, the rope a capacity of 2200 kg, and the webbing a capacity of 1400 kg. However, if the anchor for the rope has an ultimate load capacity of 250 kg, then it is the anchor that governs the load carrying capacity of the system as a whole – it is the weakest link.

Using this concept, I'll explain why perfect safety is impossible.

Suppose we had an infinite number of people and each person is abseiling using a rope tied off to a different rock projection. If we tested the ultimate strength of the rock projections we would obtain a distribution of strengths as shown in Fig. 1.

All those rock projections with a strength less than the minimum safe strength (those in the hatched area) are capable of causing an accident.

In order to make our rock projection "perfectly safe" we must eliminate the hatched area, i.e., avoid using all projections that fall within this zone. This is not easy. Some possible courses of action are:

(i) We could test all projections with our body weight before abseiling off it. This won't help us much because the minimum safe strength required is much greater than one body weight, probably at least four times one body weight.

(ii) We could tie the rope off using two rock projections. This will modify our strength distribution graph as shown in Fig. 2.

The hatched area has been reduced, but it still exists, i.e., accidents can still occur.

The vertical caver is moving in a world of many unknowns. It is not possible for him to test every item of his equipment up to a minimum safe load capacity every time he is about to use it. Every

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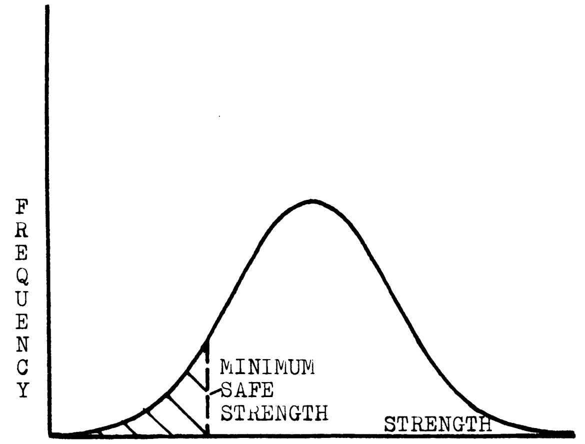

Fig. 1 Strength of rock projections.

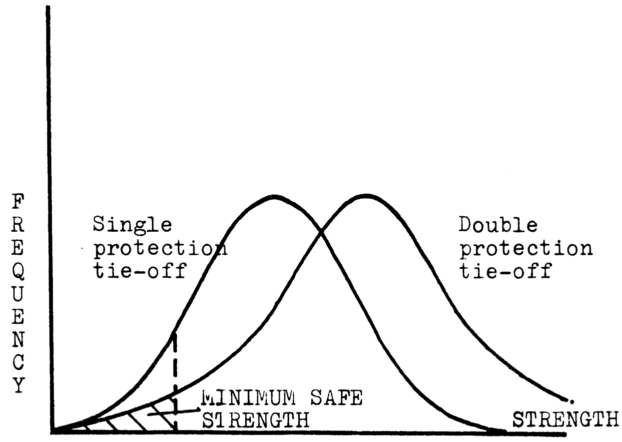

Fig. 2 Strength of double tie-offs.

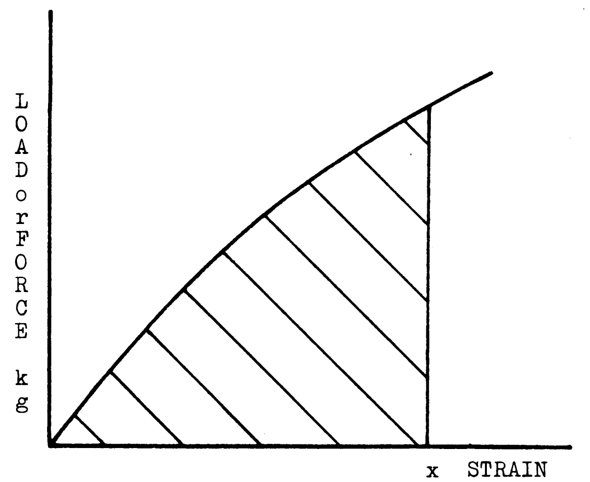

Fig. 3 Typical load vs. strain curve.

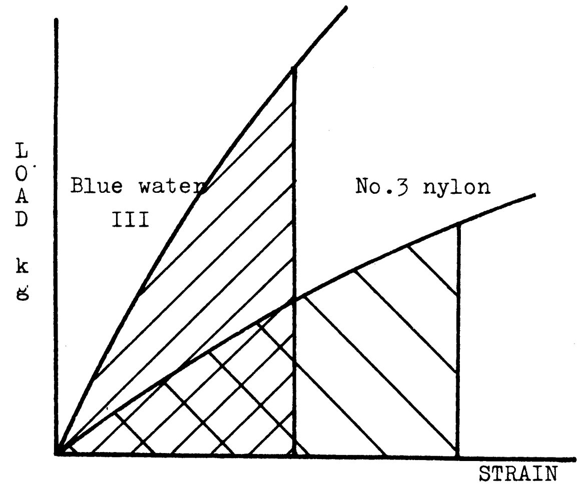

Fig. 4 Comparison of Blue water III and No. 3 nylon.

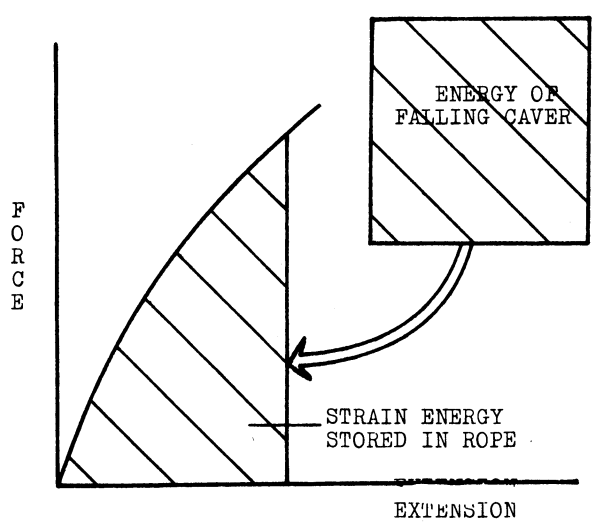

Fig.5 Conservation of energy.

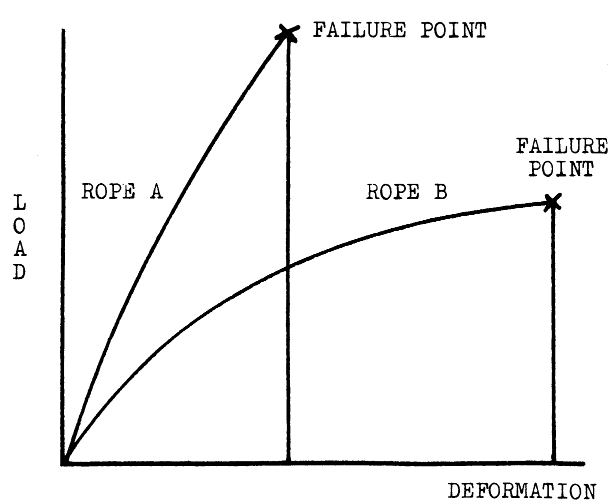

Fig. 6 Comparison of load vs. deformation curves.

time he uses an item, its strength may be reduced by abrasion or chemical attack.

The vertical caver must reconcile himself to the fact that he is playing a risk game, and approach his sport accordingly.

Safety Factors

Rather than dream about perfect safety, the designer of vertical caving equipment should direct his efforts to attaining an acceptable level of safety. But, what is acceptable safety?

Technicians love to talk about safety factors. A safety factor is a non-dimensional number obtained by dividing the ultimate strength of a device by the maximum load that you intend to put on the device.

For example, suppose we wanted to design a device to carry a maximum load of 100 kg. If we wanted the device to have a safety factor of 2, then we would design it to fail at not less than 200 kg. For a safety factor of 3, it would need to fail at not less than 300 kg.

The actual safety factor that we choose will depend upon:

(i) the certainty with which the maximum working load can be determined;
(ii) the consequences of the ultimate load carrying capacity being exceeded.

As an illustration of the second point, consider a steel bridge, held together by a large number of bolts. If one bolt snaps then usually the load that was being carried by that bolt, will be distributed to the numerous bolts surrounding it, and the bridge will continue to stand. Contrast this with a caving situation where you are using just one bolt as a tie-off for your abseil rope. The consequences of the bolt failing in the latter case are obviously more disastrous.

If the bridge engineer uses safety factors in the range 1.4 to 2.0, it is obvious that the caver should be using safety factors of at least 2.0.

Forces in Vertical Caving

The safety factor tells us by what factor to increase our maximum anticipated loads to obtain an ultimate load capacity. Hence, before we can design our equipment we need to have some idea of what our maximum anticipated loads are going to be.

As an illustration I will outline two potentially dangerous situations that could arise in vertical caving. Both situations involve a caver weighing 70 kg (The technical calculations are contained in Appendix C.)

Situation A:

A caver is climbing a ladder. The belay rope is a number 3 nylon, and belaying is done by means of a jumar at the top of the pitch. The pitch, which is free-hanging, is in excess of 80 metres. Forty five metres from the top the climber stops for a rest and then starts climbing again. The belayer is inattentive and does not recommence taking in the belay rope. Thirty metres from the top the climber loses his grip and falls 15 m vertically before the slack in the belay rope is taken up. The maximum force in this fall will be 330 kg.

Situation B:

A caver is jumaring on Bluewater III, a low stretch nylon rope. Unbeknown to the caver, the rope is caught on a small projection at the top of the pitch. When he is 0.9 m from the top of the pitch the rope comes free from the projection and he falls 0.3 m vertically before the slack in the rope is taken up. The maximum force in this fall will be 570 kg.

How did these forces arise? Why is the force in Situation B much greater than that for Situation A?

Two factors interact to govern the maximum forces arising in a fall, they being

(i) the fall factor, and
(ii) the stretch factor.

Fall Factor

The fall factor is the height of the fall divided by the length of the rope above the falling body. For a given rope, the greater the fall factor the higher the force in the rope. (An analytical proof of this hypothesis is given in Appendix B.)

Consider the following example:

Case 1: Caver falls 10 m on 30 m length. The fall factor is $^{10}/30 = {}^{1}/3$.
Case 2: Caver using same rope falls 2 m on 4 m length. The fall factor is $^{2}/4 = {}^{1}/_{2}$;

Case 2 will generate a greater force in the rope.

However, if we look at our two situations we obtain

Situation A: Fall Factor = $\dfrac{15}{30 + 15} = {}^{1}/3$

Situation B: Fall Factor = $\dfrac{0.3}{0.3 + 0.9} = {}^{1}/4$

We would expect that Situation A would give the highest force, but we already know that it does not. Hence, there must be second factor affecting the forces arising in the rope.

Stretch Factor

The stretch factor can be stated as follows: for a given fall factor, the stretchier the rope, the lower the force.

Consider the following example.

Case 1. A 7.6 m fall on a 30 m rope length above the falling body. For a number 3 nylon, the maximum force will be 295 kg.
Case 2. If the same fall occurs on Bluewater III, the maximum force will be 570 kg.

The relevance of the stretch factor can be explained graphically.

For any rope, we can obtain a load versus strain graph as shown in Fig. 3. The strain is a non-dimensional value obtained by dividing the extension of the rope by its length, i.e., it is the extension of the rope per unit length. (The terms "load" and "force" are synonymous in this paper.)

The hatched area under the curve is a measure of the energy stores in the rope per unit length, when it has a strain of x.

In Fig. 4, the load versus strain curves for both number 3 nylon and Bluewater III have been plotted on the same axes. For the same fall factor on each rope the area under each curve must be the same. Hence, the Bluewater III rope must carry a higher force.

The Failure Criterion

The ultimate criterion for failure of every vertical caving system can be stated simply as follows: the system will fail when the energy input, (i.e., the energy of the falling caver) exceeds the capacity of the system to absorb energy.

Using this criterion it can be shown that the breaking strain, (a misnomer, it should be called the ultimate tensile load) when quoted without supportive data is almost meaningless.

A falling caver tied to a belay rope will have a certain energy (kinetic and potential) indicated by the square hatched area in Fig. 5. If the caver is to be stopped by a rope, then virtually all of his energy must be converted to strain energy stored in the stretched rope. The maximum force in the rope will be reached when the energy of the falling caver is equal to the hatched area under the curve in Fig. 5.

The total area under the curve when a rope is loaded to failure is the energy absorption capacity of the rope. Different ropes have different load versus deformation curves, and different energy absorption capacities. Consider two ropes with load versus deformation curves, as shown in Fig. 6. Rope A has a "breaking strain" approximately twice that of rope B. However, rope B has a greater energy absorption capacity than rope A and, hence is a safer rope. The "breaking strain", by itself, tells us little about a rope. What we really want to know is the energy absorption capacity.

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Equipment Design

Anyone who designs vertical equipment is shouldering a heavy responsibility.

It is not intuitively obvious what the worst loading conditions are going to be. Sometimes, seemingly innocuous events can lead to a heavy load being placed upon an item of equipment. It is the duty of the designer to foresee what the maximum loads on his equipment might be and to design his gear to withstand these loads with an adequate safety factor. If the equipment cannot withstand certain types of loading with an adequate safety factor, then it is the designer's responsibility to ensure that these loading conditins can never be applied to the equipment.

Experimental evaluation of equipment performance is not a simple matter. The strength of every item of equipment is approximately normally distributed as shown in Fig. 1. It is the responsibiity of the designer to develop, where possible, a testing procedure which will eliminate every item having less than the minimum safe strength.

The development of proper testing procedure should be the province of a skilled technician. Too often I hear of testing procedures which consist of taking one or two specimens from a large batch, and testing them to destruction under one type of load, in conditions which barely duplicate the field conditions. Using this scanty data, sweeping claims are then made about the performance of the entire batch. This sort of procedure is far from adequate.

A good procedure includes proper sampling techniques and multiple testing across a wide range of loading conditions, duplicating the field conditions as nearly as possible. Where relevant, mean values and standard deviations should be determined.

These techniques are not quick, nor are they cheap. However, they are a rational method of attaining an acceptable level of safety when playing the risk game of vertical caving.

APPENDIX A

DERIVATION OF MAXIMUM FORCE ARISING IN A FALL

It is possible to derive an equation for the forces arising in a rope when it is required to hold a falling caver.

Let W = weight of caver

L = unextended length of the rope between tie-off point and caver

d = vertical distance the caver falls before the slack in the rope is taken up (i.e., before the rope starts stretching)

x = extension of the rope

x_{max} = maximum extension of the rope

k = stiffness of the rope, which is defined as the force required to cause a unit extension of a length L of the rope. Hence stiffness has units of force/distance.

F = the force in the rope

F_{max} = the maximum force in the rope

The energy equation for a falling caver is,

Potential energy of caver about to fall = Strain energy stored in the rope at its point of maximum extension 1

Equation 1 ignores the small amounts of energy which are lost through heat, sound, etc.

In the absence of any firm data to the contrary, we assume that rope obeys Hooke's Law, i.e.,

$$F = k.x \qquad \text{..... 2}$$

The strain energy stores in the rope under extension x is

$$S.E. = \tfrac{1}{2} . F . x$$
$$= \tfrac{1}{2} . k . x^2 \qquad \text{..... 3}$$

Using as datum the level the caver reaches when $x = x_{max}$,

Eq. 1 can be expressed as

$$W(d + x_{max}) = \tfrac{1}{2} . k . x^2_{max} \qquad \text{..... 4}$$

Solving Eq. 4 we obtain

$$x_{max} = \frac{W + \sqrt{W^2 + 2kWd}}{k} \qquad \text{..... 5}$$

Substituting in Eq. 2

$$F_{max} = W + \sqrt{W^2 + 2kWd} \qquad \text{..... 6}$$

APPENDIX B

PROOF OF THE FALL FACTOR HYPOTHESIS

It can be proved, that, for a given rope, the maximum force in the rope is a function of the fall factor.

Using the Notation of Appendix A, consider two lengths L_1 and L_2 cut from the same rope. Under the action of a body weight, W, the extension for each rope will be

$$x_1 = cL_1\ 100 \qquad \ldots\ldots 7$$

$$x_2 = cL_2\ 100 \qquad \ldots\ldots 8$$

where c is the stretch of the rope expressed as a percentage of its length.

The stiffness of each rope will be

$$k_1 = \frac{W}{x_1} = \frac{100W}{cL_1} \qquad \ldots\ldots 9$$

$$k_2 = \frac{W}{x2} = \frac{100W}{cL_2} \qquad \ldots\ldots 10$$

Rearranging 9 and 10 we have

$$100W = k_1\ L_1 = k_2L2 \qquad \ldots\ldots 11$$

Hence for a given rope, kL is a constant.

Equation 6 of Appendix A can be rewritten in the form,

$$F_{max} = W + \sqrt{W^2 + 2(kL)\ .\ w.\frac{d}{L}} \qquad \ldots\ldots 12$$

Terms W and kL are constant, hence F_{max} is a function of $(^d/L)$ alone. The term $^d/L$ is the Fall Factor.

APPENDIX C

CALCULATION OF MAXIMUM FORCES

SITUATION A

Assume that number 3 nylon has approximately 5% stretch under a load of 70 kg.

Using the notation of Appendix A:

$W = 70$ kg

$d = 15$ m

$k = 70/(45 \times 0.05) = 31.1$ kg/m

$$F_{max} = W + \sqrt{W^2 + 2kWd}$$

$$= 70 + (70^2 + 2 \times 31.1 \times 70 \times 15)$$

$$= 330 \text{ kg}$$

SITUATION B

Assume that Bluewater III has approximately 1% stretch under a load of 70 kg.

Hence

$W = 70$

$d = 0.30$ m

$k = 70/(1.21 \times 0.01) = 5785$ kg/m

$$F_{max} = 70 + /(70^2 + 2 \times 5785 \times 70 \times 0.30)$$

$$= 570 \text{ kg}$$