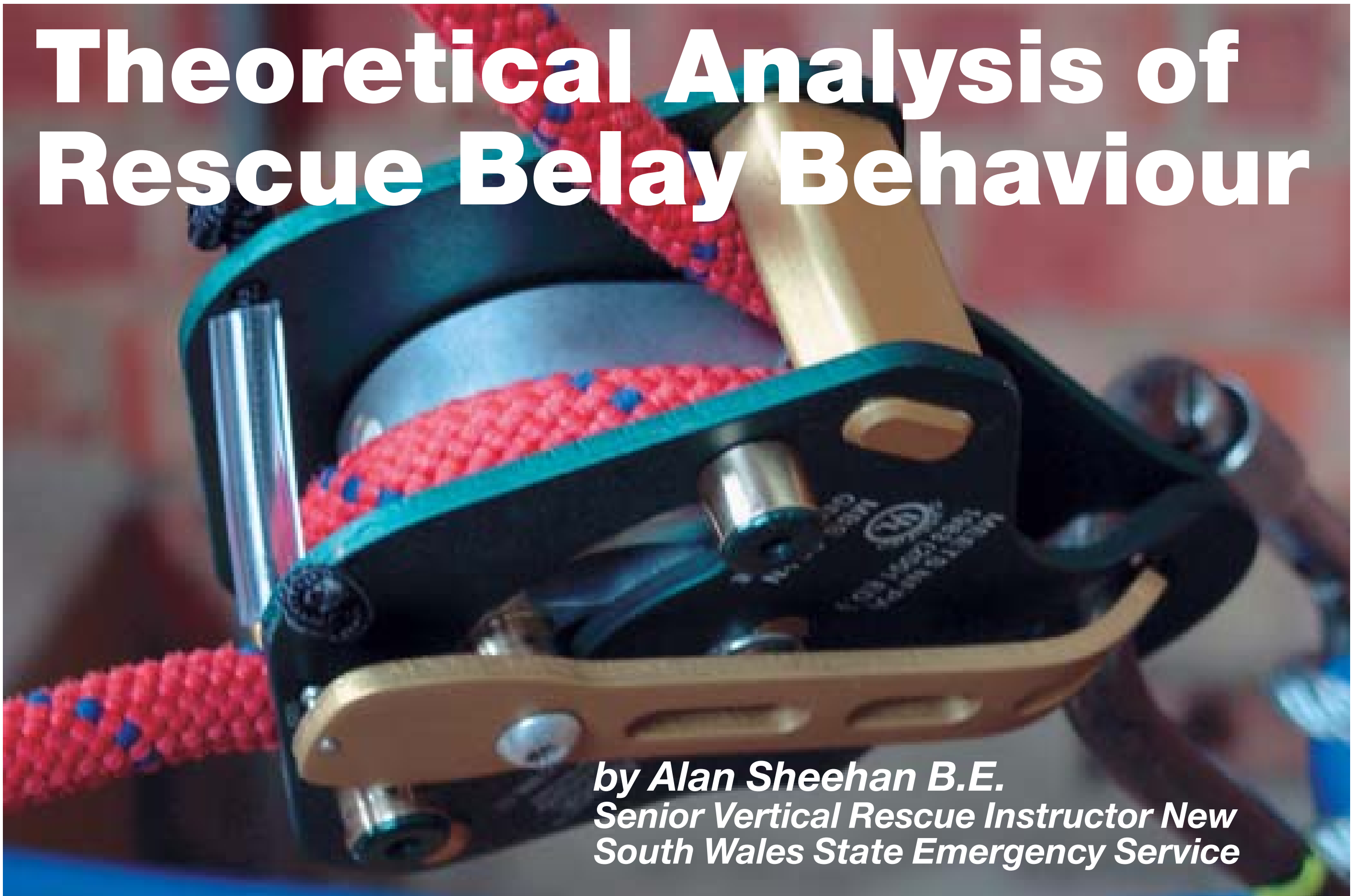

Theoretical Analysis of Rescue Belay Behaviour

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About the Author
Al Sheehan is a practicing professional mechanical engineer with a Bachelor degree in Mechanical Engineering with First Class Honours and over 20 years experience in design and mechanics (application of physics). For more than 15 years the author has been involved in recreational abseiling, canyoning, caving and vertical rescue in wilderness areas. For over 10 years, he has been a Vertical Rescue Instructor with the New South Wales State Emergency Service and the New South Wales State Rescue Board. For over three years he has been a Senior Vertical Rescue Instructor with both the New South Wales State Emergency Service and New South Wales State Rescue Board. He is the owner/moderator of the VerticalRescue and CaveRescue internet discussion groups, has judged High Angle/ Vertical Rescue Competitions in both Australia and South Africa.

Executive Summary
- Rescue belays have been the subject of significant research into the forces generated during a belay event, reduction of these forces and failure of belay systems.
- Rescue belays are limited in their ability to protect the rescue load by the very characteristics of the technology we use.
- There are real risks to the rescuer and casualty due to the distance travelled during the belay event, and the speed attained during the belay event. To date this has largely been ignored in rescue belay research.
- There are avenues for future research and development into effective rescue belaying methods, but a departure from current practice is required.
- Single Rope Rescue Protocols provide an effective safe alternative to belayed rescue systems if properly applied.
- Belays have their place, but they have limitations and (so far) hidden risks as well.

Introduction
Rescue Belays have been a topic of considerable debate and more recently some research. For some time various people have done tests to measure the dynamic loads developed in a belay event - usually as worst case analysis based on a minimal practical length of rope of 3 metres. More recently some testing has begun on belay devices, to find what works, what doesn't, and the device's ability to mitigate the dynamic forces involved. One aspect of research, however, that the author has yet to see any research being done on is the amount of movement of the rescue load during a belay event. The laws of physics suggest this can be very significant in long rope systems - a fact seemingly overlooked by researchers so far, with their primary concern being the forces involved in belays and the consequently short belay test rigs.

This paper theoretically analyses the amount of movement during a belay event, and discusses the implications of that movement. It is hoped this will encourage practical testing to start on this topic, increase rescuer's understanding of how belay systems work, and draw attention to the risks that so far appear to have been overlooked by many belay users and proponents.

Modeling
For the analysis, a number of rope lengths were chosen: 3m, 10m, 25m, 50m, 100m, 150m, and 200 metres.

As this is a theoretical analysis, the chosen nominal rope characteristics are based on requirements of AS4142.3 Static Life Rescue Lines as being typical. Actual ropes may vary from this. It is also assumed that Hooke's Law applies. I.e. that stress is proportional to strain (and force is proportional to elongation). It may be expected that nylon, particularly in the form of kernmantel rope is not linear, however, this deviation from linearity cannot be considered significant unless practical testing proves it to be, and does not affect the concepts that rescuers need to understand to be aware of the risks, limitations and behaviour of a belay system. Part of the purpose of this paper is to show there is a need for practical testing of long belay systems.

Based on AS4142.3 requirements for Static Life Rescue Lines, it is assumed that when an 80 kg load is applied to the rope, it will stretch 3%. Applying Hooke's Law, a 200 kg rescue load will therefore stretch the rope 7.5%.

We can calculate the amount of elongation in the rope simply by multiplying the length of the rope by the elongation (stretch) as a percentage. So from Table 1, we can see that a 200 kg rescue load on a 100metre rope will actually stretch the rope another 7.5 metres. In other words, the load line would be stretched about 7.5 metres before the load is lifted off the ground.

Fundamental to the operation and behaviour of a belay is that the belay rope does not carry any load. The load line carries the load, while the belay line is unloaded until a belay event occurs. A belay event is some failure in the load line system, which causes the load to be dropped onto the belay line. Ideally the belay should have no load and also no slack, however, in practice there is often some slack in the belay line.

Discussion

When a Belay Event occurs, the load is suddenly transferred to the belay line. This is actually a fall factor zero situation. Fall Factor is a conceptual dimensionless number calculated as the distance of free fall divided by the length of rope catching the falling object. It is a term commonly used in climbing circles, and often poorly understood and misleading. A fall factor zero situation is actually a "special case" taught in engineering courses. It is essentially the same situation as a vehicle travelling across a bridge - the weight of the vehicle is applied to the bridge relatively suddenly. As the bridge responds by deflecting to support the weight, the mass of the vehicle develops a component of velocity downwards. When the bridge has deflected enough to hold the weight of the vehicle as if it were parked on the bridge, the downward momentum carries the vehicle and bridge below the equilibrium position. This dynamic effect results in the dynamic loads and deflections on the bridge equalling twice the static load. This is a result of the laws of the Conservation of Momentum and the Conservation of Energy, and so these laws provide the key to solving the problem.

The same thing happens in a belay. Hence the theoretical dynamic loads and deflections (movement) in the belay are twice the static load and stretch. This can be practically demonstrated with a simple weight on an elastic band or piece of shock cord. Hang a weight on a piece of shock cord. Note the position of the weight under static conditions. Now lift the weight until the shock cord just goes slack and release the weight. The weight will oscillate about the static equilibrium position with initial amplitude equal to how far the weight was lifted. So from no load on the shock cord at the top, it gets stretched to twice the static weight and elongation at the lowest point. It is worth noting here, that belay devices limit the forces generated in the belay event by slipping or allowing more movement of the belayed load than theoretically calculated in this paper. So belay devices allow more movement of the belayed load in order to reduce the forces generated.

So this means, for our rescuer and casualty on the end of a 100 metre rope, if they are dropped in a belay event, that they will move 15 metres before coming to rest and being accelerated back up to oscillate around the static equilibrium point! 15 metres is a long way to drop! It may be of little concern in the ideal free hanging pitch, but how many pitches are truly free hanging? Most are against a face, across ledges, through vegetation or structures, etc. There is a lot of potential for injury to both the litter attendant and the casualty in such a belay event. The worst case would be when the rescue load was lifted exactly the static elongation above the ground or a ledge. In this case, the rescuer and casualty would hit the ground or ledge with maximum velocity. So consider a rescuer and casualty on a 100 metre rope, lifted just 7.5 metres off the ground when a belay event occurs. They will hit the ground at 8.577 metres per second, or the same speed as free falling 3.75 metres ! More than enough to seriously maim a rescuer underneath a stretcher!

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Length of rope, m:	**3**	**10**	**25**	**50**	**100**	**150**	**200**
Spring Stiffness of Rope, k, N/m:	8720	2616	1046.4	523.2	261.6	174.4	130.8
Characteristics of a Single Person (80 kg) Belay - No slack in Belay (Fall Factor 0):							
Percentage Static Strain @ 80 kgs load, %:	3%	3%	3%	3%	3%	3%	3%
Static Elongation (Stretch) @ 80 kgs, m:	0.09	0.3	0.75	1.5	3	4.5	6
Percentage Dynamic Strain @ 80 kgs load, %:	6%	6%	6%	6%	6%	6%	6%
Dynamic Elongation (Stretch) @ 80 kgs, m:	0.18	0.6	1.5	3	6	9	12
Maximum Dynamic Force in Belay Rope @ 80kgs, zero slack, kN:	1.5696	1.5696	1.5696	1.5696	1.5696	1.5696	1.5696
Maximum Dynamic Force in Belay Rope @ 80kgs, zero slack, kgf	160	160	160	160	160	160	160
Dynamic Multiplier @ 80kgs, zero slack:	2	2	2	2	2	2	2
Maximum Velocity of Fall for 80kgs, zero slack, m/s:	**0.939628**	**1.715517**	**2.712471**	**3.836014**	**5.424942**	**6.64417**	**7.672027**
Maximum Velocity of Fall during Belay Event, kph:	3.382659	6.175863	9.764896	13.80965	19.52979	23.91901	27.6193
Equivalent Fall Height @ 80kgs, zero slack, m:	**0.045**	**0.15**	**0.375**	**0.75**	**1.5**	**2.25**	**3**
Characteristics of a Rescue Load (200 kg) Belay - No Slack in Belay (Fall Factor 0):							
Percentage Static Strain @ 200 kgs load, %:	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
Static Elongation (Stretch) @ 200 kgs, m:	**0.225**	**0.75**	**1.875**	**3.75**	**7.5**	**11.25**	**15**
Percentage Dynamic Strain @ 200 kgs load, %:	15%	15%	15%	15%	15%	15%	15%
Dynamic Elongation (Stretch) @ 200 kgs, m:	**0.45**	**1.5**	**3.75**	**7.5**	**15**	**22.5**	**30**
Maximum Dynamic Force in Belay Rope @ 200kgs, zero slack, kN:	3.924	3.924	3.924	3.924	3.924	3.924	3.924
Maximum Dynamic Force in Belay Rope @ 200kgs, zero slack, kgf:	400	400	400	400	400	400	400
Dynamic Multiplier @ 200kgs, zero slack:	2	2	2	2	2	2	2
Maximum Velocity of Fall for 200kgs, zero slack, m/s:	**1.485682**	**2.712471**	**4.288794**	**6.06527**	**8.577587**	**10.50536**	**12.13054**
Maximum Velocity of Fall during Belay Event, kph:	5.348454	9.764896	15.43966	21.83497	30.87931	37.81928	43.66994
Equivalent Fall Height @ 200kgs, zero slack, m:	**0.1125**	**0.375**	**0.9375**	**1.875**	**3.75**	**5.625**	**7.5**
Length of rope, m:	**3**	**10**	**25**	**50**	**100**	**150**	**200**
Spring Stiffness of Rope, k, N/m:	8720	2616	1046.4	523.2	261.6	174.4	130.8
Characteristics of a Single Person (80 kg) Belay - 1m Slack in Belay Rope:							
Fall Factor	**1/3**	**1/10**	**1/25**	**1/50**	**1/100**	**1/150**	**1/200**
Potential Energy at Start of Fall (zero slack reference), J:	784.8	784.8	784.8	784.8	784.8	784.8	784.8
Velocity when Belay Slack = 0, m/s:	4.429447	4.429447	4.429447	4.429447	4.429447	4.429447	4.429447
Kinetic Energy when Belay Slack = 0, J:	784.8	784.8	784.8	784.8	784.8	784.8	784.8
Maximum Velocity for @ 80kgs, 1m slack, m/s:	**5.369075**	**6.144964**	**7.141918**	**8.26546**	**9.854389**	**11.07362**	**12.10147**
Maximum Velocity of Fall during Belay Event, kph:	19.32867	22.12187	25.71091	29.75566	35.4758	39.86502	43.56531
Equivalent Fall Height @ 80kgs, 1m slack, m:	**1.469264**	**1.924597**	**2.599745**	**3.482051**	**4.94949**	**6.25**	**7.464102**
Elastic Energy at Maximum Elongation, J:	1195.804	1672.144	2500.483	3760.203	6178.717	8560.855	10930.85
Dynamic Elongation (stretch) @ 80 kgs, m:	**0.523705**	**1.130662**	**2.186141**	**3.791288**	**6.872983**	**9.908327**	**12.9282**
Max Distance Travelled @ 200kg, 1m slack, m:	1.523705	2.130662	3.186141	4.791288	7.872983	10.90833	13.9282
Maximum Dynamic Force in Belay Rope @ 80kgs, 1m slack, kN:	4.566707	2.957813	2.287578	1.983602	1.797972	1.728012	1.691009
Maximum Dynamic Force in Belay Rope @ 80kgs, 1m slack, kgf:	465.5155	301.51	233.1883	202.202	183.2796	176.148	172.376
Dynamic Multiplier @ 80kgs, 1m slack:	5.818944	3.768875	2.914854	2.527525	2.290994	2.20185	2.154701
Characteristics of a Rescue Load (200 kg) Belay - 1m Slack in Belay Rope:							
Fall Factor	**1/3**	**1/10**	**1/25**	**1/50**	**1/100**	**1/150**	**1/200**
Potential Energy at Start of Fall (zero slack reference), J:	1962	1962	1962	1962	1962	1962	1962
Velocity when Belay Slack = 0, m/s:	4.429447	4.429447	4.429447	4.429447	4.429447	4.429447	4.429447
Kinetic Energy when Belay Slack = 0, m/s:	1962	1962	1962	1962	1962	1962	1962
Maximum Velocity for 200kgs, 1m slack, m/s:	**5.617992**	**6.599424**	**7.860482**	**9.281663**	**11.29152**	**12.83373**	**14.13388**
Maximum Velocity of Fall during Belay Event, kph:	20.22477	23.75793	28.29773	33.41399	40.64946	46.20143	50.88196
Equivalent Fall Height @ 200kgs, 1m slack, m:	**1.608656**	**2.219796**	**3.149193**	**4.39089**	**6.498387**	**8.394733**	**10.18178**
Elastic Energy at Maximum Elongation, J:	2844.9	4905	9319.5	16677	31392	46107	60822
Dynamic Elongation (stretch) @ 200 kgs, m:	**0.932549**	**2.186141**	**4.570482**	**8.393544**	**15.94097**	**23.45912**	**30.96872**
Max Distance Travelled @ 200kg, 1m slack, m:	1.932549	3.186141	5.570482	9.393544	16.94097	24.45912	31.96872
Maximum Dynamic Force in Belay Rope @ 200kgs, 1m slack, kN:	8.131824	5.718944	4.782553	4.391502	4.170158	4.09127	4.050709
Maximum Dynamic Force in Belay Rope @ 200kgs, 1m slack, kgf:	828.9321	582.9708	487.5181	447.6557	425.0926	417.0509	412.9163
Dynamic Multiplier @ 200kgs, 1m slack:	4.14466	2.914854	2.437591	2.238278	2.125463	2.085255	2.064581

This means that a belay system is not as safe as most people consider them to be unless the pitch is entirely free hanging and the rescue load is more than twice the static stretch in the rope above the ground. So the bottom 15% of any pitch is the danger zone where the belay may not provide adequate protection. A corresponding danger zone exists above every ledge or obstacle that could cause injury in the event of the rescue load being dropped.

While presenting a talk on this very subject at a recent cave rescue training weekend, it was suggested to the author that the only safe way to belay on a long rope was on a continuous high angle face so the litter attendant could keep his/her feet on the wall and maintain control during the belay event. One only needs to look at the velocities generated during a belay event to realise this is a fanciful idea! Our rescuer on the 100 metre line would have to run backwards down the face for distance of 15 metres at 40 kilometres per hour with the casualty and stretcher across his lap! For a 200 metre rope this speed increases to 50 kilometres per hour for 30 metres! Imagine sitting on the back of a truck with your legs hanging over the back, and a stretcher and casualty across your lap. When the truck reaches 40 or 50 kph, you jump off (facing backwards!)… You can probably imagine it getting fairly untidy very quickly! This is very similar to what happens in a belay event.

So what options are available to eliminate this risk in belays?

Option 1: Limit the Maximum Belay Length

Current OH&S legislation (in Australia at least) requires that persons working more than 2 metres off the ground wear fall prevention equipment. So lets assume a 2 metre free fall is the maximum allowable.

From the calculations we can see that a belay length of 50 metres corresponds to an equivalent free fall of 1.875 metres. So if we limit the maximum length of a belay, using these assumptions, we must limit the length of our belays to no more than 50 metres .

But keep in mind, in the work environment, when someone falls 1.8m without fall protection that they do not have a stretcher and casualty across their lap!

If you never have to work on a pitch bigger than 50 metres, this solution may be acceptable, however, for those of us who must operate in pitches of greater than 50 metres this is clearly unacceptable!

Option 2 Use Low Stretch Belay System

This is a controversial solution!

Say for example we were to use a steel wire rope cable for the belay rope. As long as the belay remains a fall factor 0 situation, i.e. no slack, everything will be fine - the force will be limited to two times the static load. With Steel wire rope cable, the amount of movement and hence the velocity achieved during the belay event will also be greatly reduced.

However, if ANY slack gets into the system, the forces will rise dramatically - in proportion to the difference in stiffness of static rope against steel cable!

Now all is not lost - this may still be a viable alternative IF a belay device can be developed to allow slip and limit the high forces generated in a belay event with slack. This is the current focus of most researchers on kernmantel rope belay systems - it would simply need development for steel cable.

But even the use of steel cable is not suitable for everyone, such as wilderness, remote area and mountain rescue units because of its considerable weight.

Perhaps an alternative rope solution will be developed in the future where the stiffness of steel is combined with light weight and the toughness required to absorb shock loads.

Option 3 Eliminate the Need for a Belay

This is the principle all single rope rescue protocols must work on.

It is interesting to note that few, if any, organizations that do long vertical rescues use belays. Typically the big, long pitch rescues are done by wilderness rescue groups and mountain rescue organizations. The primary reason they don't use belays is likely to be due to weight. Carrying 2 long ropes into a remote location places additional physical requirements on those crews, and in some situations would adversely affect their own safety, survivability, risk of injury, and likelihood of a successful rescue. So they have learned to work safely without a belay - with single rope systems. Interestingly, if a belay was employed in many of these situations, the benefit might well be negligible!

So why are these risks in rescue load belaying not more obvious? Partly, it is because the organizations that use belays are working on relatively short pitches, probably less than 50 metres in height. It is also partly because the frequency of rescues is relatively low, and the incidences of load line failures resulting in belay events even lower! It is interesting, if not ironic, that the reliability of the single rope system is largely what prevents the hazards of the belay system from being recognised!

So how do you make a Single Rope Protocol Safe?

Firstly it must be designed logically, from the ground up on a needs basis. There should be nothing in the system that does not have a specific purpose. This means it must be as simple as possible, which is a good thing! The fewer the number of links in the system: the less that must rigged, the less that must be checked, and the less that can fail or go wrong. Remember the KISS principle - Keep it Simple Stupid!

Secondly, all equipment must be in top condition. This means discipline is required to check and maintain every bit of gear after every job before it is stowed, to check every bit of gear as it is used or rigged, to continuously monitor rigged systems to ensure nothing is going awry during operation, and to have sound protocols for what to do when a problem is found. It may need a paradigm shift in discipline, but it is worth it!

Thirdly, all operators need appropriate and recent training. Technical knowledge is commonly believed to have a half-life of 6 months. That is, if vertical rescue skills are not practiced within 6 months, half of what was known will be forgotten, after 12 months just 1/4 of the original knowledge will remain, etc. Training must be appropriate to the vertical hazards in question - training in the shed is of little value for a multi-pitch big wall rescue. Training should take place on as many of the different vertical hazards that must be responded to as possible - if you have a big gnarly multi-pitch canyon waterfall in your patch, that's where you should be training.

Fourthly, edge management in a single rope system is paramount. As there is only one load line, protection of that load line from damage and failure is key. The use of effective edge management machines, devices and methods is fundamental to protection of the rope. Edge management should be considered to extend right down the face of the pitch, so selection of the appropriate work position is included and methods for dealing with obstacles down the face must be understood and practiced. As part of protecting the rope, and also training, it is important to protect the rope from overloading. It will be necessary to limit the mechanical advantage and the number of haulers that can be used to prevent overloading of the rope. If the required haulers and mechanical advantage can't haul the load, there is a problem to be solved, not simply provide more grunt!

Finally, just because a single rope technique is used, doesn't mean you have to toss redundancy theory out the window. Load sharing anchors provide redundancy with minimal shock load risk compared to self equalising and back up anchors. The use of a fixed or preferably a reversible safety during hauling operations protects against any failure in the haul system or the haul system to load line attachment.

Conclusion

Single rope systems can be made safe with technology available now, and are suitable to long pitch work. With everything we do there is a risk. Even with a belay, there is a risk that the belay will fail when it is required, but more importantly, as the author has shown in this paper, there are inherent limitations to belays that few rescuers are aware of. There are real risks to the rescuer and casualty even if the belay works! These limitations are the result of applying belay theory developed from climbing to the rescue arena, and as yet we as rescuers are still trying to come to terms with how to make belays work for rescue.

To date much of the belay research has been on the forces generated, but there are other factors revealed in this paper that are just as important and threatening which are in urgent need of research, development and solutions.

In the meantime, Single Rope Rescue Systems are currently in use and can be used safely with proper development, discipline and training.

Despite considerable discussion being devoted to the (so far) hidden hazards of using belays in rescue systems, and discussion about single rope rescue systems, the author acknowledges that belays do have a place in rescue! It would be a fool indeed that suggests there is never a need for a belay. There are many situations, however, where single rope techniques can be safely used - and what is important here is that the rescue operators are skilled and experienced at using sound single rope techniques!

Fortunately, there is no legislative requirement to rescue. Whether you use a single rope protocol, or a load line and a belay, or a full double rope system, as rescuers it is always necessary to weigh up the risks. If the risk of doing the rescue is too high, it's a case of finding a safer way, or not proceeding with the rescue. Just as single rope proponents may sometimes find a belay is a good thing, there are others when twin rope proponents may find a single rope solution is better. As rescuers, the wider the range of options you have, the more adaptable you can be. The aim of this paper has been simply to highlight the inherent risks associated with belays - belays that work, by the way! - so that rescuers can be better informed and prepared.