Session No. 617

Fall Arrest Clearance Calculations Made Easy

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Introduction

How often, before any of us start work using a Fall Arrest System, do we pause to actually figure out how far we would fall before the System stops us? When was the last time any of us actually calculated our clearance?

The following are possible reasons why we may not be evaluating our clearance:

- Required Clearance can be complex to assess. It requires knowledge about how the equipment and systems perform, spatial reasoning and some mathematical calculation. While a Fall Protection course can teach about the equipment, our students may not have the inherent skills. When exams include clearance calculation, these are the questions most frequently answered incorrectly. Nonetheless, students pass because they get enough of the other questions right, and leave the course with certificates testifying they understand Fall Protection well enough to be safe.
- When we use Fall Arrest Systems at significant heights, it is “frighteningly” obvious that we have more than enough clearance, no matter what type of Fall Arrest System we are using. We focus on having the right equipment, system and anchorage. There is truly no safety reason why we must accurately know the Required Clearance, so we may get in the habit of NOT considering it.
- As we get closer to the ground, where knowing our clearances becomes important, we also feel much more comfortable. What we are doing may be exactly the same as what we trusted at greater heights. We may be complacent when we notice that no one else around us seems concerned about clearance. Perhaps we are unwilling to admit that we cannot remember how to figure it out and simply trust that “if they feel safe then I should feel safe”. This is known as a “herd” mentality, when everyone assumes that someone else, who knows more than us, would speak up if there were a problem.

In summary…. most people neglect clearance because they probably don’t understand it well enough. It is in our nature to trust something we don’t understand when we do not have the capacity to prove it.

Available vs. Required Clearance.
When we need to determine if we are safe, we must understand two types of clearance, what is "Available" as compared to what is "Required".

Available Clearance is the room below an anchorage or platform, through which workers can freely fall, before encountering a surface or object that may injure them in stopping or deflecting the fall.

Required Clearance, also known as **Calculated Clearance,** is the greatest distance below an anchorage, or the platform a worker might fall from, before the Fall Arrest System will stop (arrest) the fall.

A safe and effective Fall Arrest System must ensure that Required Clearance is less than the Available Clearance.

Available Clearance is most easily determined through direct measurement, such as by dropping a tape measure from the platform a worker is standing on. There are few problems with knowing it accurately.

As discussed above, Required Clearance is the more difficult type of clearance to assess, since we must figure out how far we might fall according to how our Fall Protection System behaves.

The purpose of this paper is to simplify these calculations, so that more (ideally all) workers and their supervisors can efficiently and safely assess Required Clearance. The final formulae and Pictograms provided at the conclusion of this paper will hopefully be useful to Workers and the Competent and Qualified Persons who may be working with them.

Two Different Types of Fall Arrest Systems = Two Clearance Calculation Methods.

There are two distinct types of Fall Arrest Systems; those that minimize slack between the user and the anchorage (Automatic Length Systems), and those that do not (Fixed Length Systems). For the purposes of this paper, these are defined as follows:

"Fixed Length" (FL) Systems
In this paper, "FL Systems" refers to "Fixed Length Lanyard or Lifeline Systems".

These systems connect the worker to an anchorage using a fixed length lanyard or lifeline. Sometimes the length of this equipment can be manually changed, but there is no automatic adjustment to maintain the shortest possible length between the user and the anchorage. A Vertical Lifeline that uses a manual fall arrester would be classified as an FL System.

These systems generate Free Fall (explained in the next section) according to how much closer the worker is to the anchorage than the length of the lanyard or lifeline.

"Automatic Length" (AL) Systems
In this paper, "AL Systems" refers to "Lifeline Systems that automatically adjust to minimize the length of the connection between the Worker and the Anchorage". This feature minimizes the

Free Fall, to reduce the Required Clearance. Examples of AL Systems include Self Retracting Lifelines (SRLs) and Vertical Lifelines (VLLs) that use Automatic Fall Arresters (Rope Grabs).

Clearance for each type of system (FL vs. AL) is most easily calculated by a different method, with different rules about what must be included in the calculation.

Although either method may be used to calculate Required Clearance for both FL and AL Systems, this can get quite complicated when the method that is best for FL systems is used on AL Systems, and vice-versa. Qualified Persons should possess the spatial reasoning and calculation skills to be able to do this, but other people may not.

In part, because it is possible to calculate clearance using only one of the two methods, training programs sometimes choose to teach only one clearance calculation method. This leaves workers, at best, with the tools to easily determine clearance for the one type of system, but very confused if they try to apply what they learned to the other type.

It takes a bit longer to teach both clearance calculation methods, including the need to develop a clear understanding of which method is applied to an FL vs. an AL System, but the results, in my experience, have been a greatly improved ability to evaluate Required Clearance.

In this paper, we go a step further, and apply the FL and AL calculation methods to four key types of systems. We then provide Pictograms to help users identify which formulae to use, and show some examples of just how easy it can be to determine Required Clearance.

What factors must be considered in Required Clearance Calculations?

The following factors must be considered in determining Required Clearance in AL and FL Systems.

Free Fall (FF)

This is the distance the worker falls freely, with nominally no force applied to slow him or her down. Free Fall takes all of the slack out of the Fall Arrest System and includes the distance required for arresting devices, such as Fall Arresters and Self-Retracting Lifelines (SRLs) to activate or lock-up.

Unfortunately, spatial reasoning and math are required to figure this out in FL Systems.

One of the objectives of this paper is to develop clearance calculation methods that eliminate the need to determine Free Fall.

Deceleration Distance (DD)

This is the distance a worker travels while the system applies force to arrest the fall. Many parts of the Fall Arrest System can be involved in dissipating the energy generated during a fall, including deployment of Personal Energy Absorbers (PEAs), braking mechanisms on Self-Retracting devices (SRLs), and the Anchorage System itself can deflect. Each component absorbs energy as it deploys, stretches, deflects or sags. This is complex, and usually requires a Qualified Person to determine how much energy gets apportioned to each part of the system, in order to accurately determine the total Deceleration Distance.

One of the objectives of this paper is to develop clearance calculation methods that reduce or eliminate the need to determine Deceleration Distance. This is done by making conservative assumptions about how far things deflect, stretch or deploy. This is not a new idea by any means, since most people are already taught to assume full deployment of their Personal Energy Absorbers.

Harness Stretch

The D-ring usually flips up and slides up the webbing when a fall is arrested. The webbing in the harness also stretches, and some Harness models use highly elastic webbing, which is considered more comfortable to wear.

Depending on the model, harness stretch varies between 1 and 2.5 feet (0.3 to 0.75 m). To keep things simple, we usually specify clearance based on a conventional harness (that would stretch 1 foot (0.3 m)), and instruct workers to add in an additional 1.5 feet (0.45m) if using a "stretch" harness. It is useful to have a term defining the additional harness stretch, so this paper will use the term, "ΔX_H".

Figure 1
Comparing Harness Stretch

Worker Stretch-Out

A standing worker starts and finishes the fall in a vertical body orientation, and (nominally) does not get any longer. The torso begins the fall from a higher elevation than for someone who is kneeling on the platform. This affects the Free Fall in FL Systems, and the clearance in the AL Systems.

Workers who kneel or lie on the work surface will straighten out and hang vertically. They will elongate by 2.5 to 4 feet (0.75 to 1.2m) in the vertical direction, depending on their initial kneeling or lying position. Kneeling while working is common. Lying down is rare, and largely eliminates the risk of falling when you are close to an unprotected edge. For these reasons, our focus when teaching Worker Stretch-Out should be on the case of kneeling workers.

Figure 2
Kneeling workers need 2½ ft (0.75m) more clearance

Worker Stretch-Out must be considered when determining clearance below the platform because it is the governing case for AL Systems anchored above the worker.

For FL Systems (or AL Systems anchored behind or lower than the worker's Dorsal D-ring), standing workers will have more Free Fall than kneeling workers, generating more fall energy, requiring greater deployment of PEAs or SRLs, and thus more clearance. Thus we only need to add extra clearance for Stretch-Out of kneeling workers when using AL systems, such as SRLs and VLLs that are anchored above the worker.

Combined Worker and Harness Stretch (X_W)

It is a common practice to combine Worker Stretch-Out and Harness Stretch into a single factor, X_W.

The ANSI Z359.6 and CSA Z259.16, standards for the "Design of Active Fall Protection Systems", specify X_W as 1 foot (0.3m) for a worker falling from a standing position when wearing a regular harness.

If the worker is not standing at the start of the fall, we must add 2.5 or 4 feet (0.75 or 1.2m) respectively if falling from a kneeling or lying position, but as discussed above, this is only applicable for AL Systems anchored above the worker, such as SRLs and VLLs.

If the worker is wearing a stretch harness, we must add ΔX_H, discussed above in Harness Stretch.

Figure 3
Height of worker (D-ring to toes) at Fall Arrest is nominally 6 ft (1.8m)

Height of Worker at Fall Arrest (H_W)

At Fall Arrest, the worker is fully stretched out. In a regular Harness, we assume the worker height is 6 feet (1.8m) from Dorsal D-ring to toes.

The initial body position does not affect the Height of Worker at Fall Arrest.

If the worker is wearing a stretch harness, we must add ΔX_H, discussed above in Harness Stretch.

Swing Fall Distance (SFD)

Gravity will always pull workers to the lowest possible elevation the system will allow, directly below (or opposite) the anchorage (or a point the line deflects over). Workers who are connected to an anchorage system that is not immediately overhead will drop in elevation as they swing from the location where the system starts to apply arrest forces until they come to rest wherever gravity pulls them.

Unfortunately, figuring out the vertical drop in a swing fall also requires mathematical (geometry) and spatial reasoning skills, making it as difficult as figuring out Free Fall.

Well meaning people often offer simple rules of thumb, such as "keep your line within 30 degrees of vertical", however this does not help much with clearance calculations for a couple of reasons:

- The worker is not told how much clearance to add if they follow this rule.
- The reason the worker is not told how much clearance to add is because it actually depends on the length of the line between the worker and the anchor. At 30 degrees, a 10-foot (3m) line will create a Swing Fall of 1.34 feet (0.41m) whereas a 100-foot (30.5m) line gives a swing fall of 13.4 feet (4.1m), which is extremely dangerous for sideways impacts.

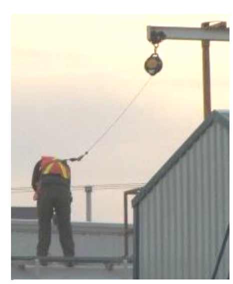


Figure 4
Swing Fall requires understanding of geometry

A good alternative to attempting to teach mathematical swing calculations is to show workers in the field how to measure or estimate the length of line between the anchorage and where they will be working, and then to measure from the anchorage to the platform or edge they may fall from. We can visualize where gravity will pull us, or perhaps experiment with a weight on a string. The swing fall distance is the difference between these two measurements, and can actually be determined without subtraction if you don't retract the tape from the first measurement and read the measurement where the tape crosses the platform or edge for the second. Not only is this easier to do, but it helps the worker visualize what is going to happen.

In FL Systems, because, by definition, the length of the lanyards or lines are fixed, the Required Clearance is calculated by following the line from where the Worker comes to rest, back to the anchor. Therefore we do not need to add in the SFD, because the worker ends up in the same place whether they fall straight down or swing to the same location. This does NOT mean that Swing Falls can be ignored in FL Systems, because sideways impacts can cause severe injuries. It only means that Swing Falls will not affect the Required Clearance.

Maximum Anchorage System Deflection (MASD)

Deflection of the anchorage system (including the stretch of a vertical lifeline, sag of a horizontal lifeline or flexing of an anchor beam) absorbs energy. It is therefore part of the deceleration distance. Discussed later, some regulators do not include MASD in their "regulated" deceleration distance. It is also happens to be easier to handle this as separate factor in our calculations.

Unless we have a Qualified Fall Protection Engineer to do the work for us, we do need some simple and conservative rules of thumb for estimating MASD.

Structural Components.

The amount that a truss, beam, or other structural component may deflect can be determined by a Qualified Person or by testing. This is done by applying a known load to the structure and measuring how far it deflects, and then apportioning the deflection according to the ratio of the Fall Arrest force to the test force.

Most large structural elements that are good places to anchor Fall Arrest Systems, such as beams, columns and trusses, are generally so rigid that their MASD is negligible and a fraction of the clearance margin if MASD is ignored. Most experienced workers should be able to judge whether or not their anchorage will deflect enough to warrant a more accurate determination (by testing or a Qualified Person).

Vertical Lifeline Stretch.

Vertical Lifelines, that pass the current ANSI Z359.1 and CSA Z259.2.1 standards, are allowed to stretch 22% at a force of 1800 pounds (8 kN). Most workers use Personal Energy Absorbers (PEAs). Although slightly conservative in the worst possible case, a rule of thumb that is easy to remember is to assume that the VLL will stretch 10% for a 900-pound (4 kN) PEA and 15% for a 1350-pound (6 kN) PEA. The deployment force for the PEA is printed on its label.

It must be noted that many VLLs on the market have much less stretch than permitted by the standards. 10% or less at 1800 pounds (8 kN) is frequently the case, and both the CSA and ANSI standards are considering adopting this value in the future. When the manufacturer or a Qualified Person has certified other stretch values, these should be used so that we are not overly conservative.

The MASD for a Vertical Lifeline will be the % stretch (determined above) multiplied by the length of lifeline between the worker and the anchorage.

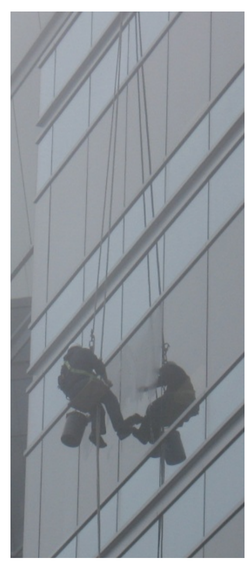


Figure 5
VLLs may stretch significantly

The amount of stretch (MASD) of a VLL can be quickly estimated in the field. At a safe elevation off the ground, lock a Fall Arrester on the VLL and put a reference mark on some adjacent structure or measure the Fall Arrester elevation from the ground. Apply your weight (hang from the Fall Arrester) and put a mark or measure the new elevation of the Fall Arrester. The stretch at Fall Arrest may be estimated as the ratio of the arresting force of your Personal Energy Absorber divided by your weight multiplied by the stretch of the VLL you just measured.

Most workers can figure out (and then remember) the ratio of their PEA deployment force to their weight (e.g., a 225 pounds worker using a 900 pounds PEA has a ratio of 4, so he/she simply multiplies the hanging stretch measured at the start of each job x 4 to have an accurate estimate of the VLL stretch at Fall Arrest)

Horizontal Lifeline (HLL) Sag.

Horizontal Lifelines typically sag 8 to 25% of the span when arresting a fall, depending on a number of factors. The determination of this sag is very complex, so the Manufacturer, Designer or Qualified Person usually provides complete information about the Required Clearance. As long as the actual use matches the specifications for the system (e.g., lanyard length, Free Fall, worker weight, etc.) the clearance is known and the user(s) do not need to determine MASD (or the clearance).

Figure 6
HLL Sag

Figure 7
Force Management Anchors add a lot of sag

In the absence of this information, it is usually safe to assume that HLLs that are sold as kits, and connected to RIGID end anchorages, will sag less than 15% of the span length.

When the HLL is anchored on deformable anchor posts (Force Management Anchors), the sag (MASD) may be as much as 25% of the span length.

Boom Lift Bounce.

In Boom lifts, the amount of deflection (bounce) that will occur when arresting a fall may be significant enough that it should be included in the clearance calculations.

Bounce can be determined by a Qualified Person, or can be estimated in the field in a similar fashion to estimating VLL stretch. Boom out to the full horizontal extension of the lift, and position the basket slightly off the ground. Measure the elevation of the basket off the ground. Apply your weight (step into the basket) and measure the new elevation of the basket. The bounce at Fall Arrest may be estimated as the ratio of the arresting force of your PEA divided by your weight, times the change in basket elevation you measured.

Figure 8
Boom Lifts may have a significant bounce when arresting a Fall

As with field estimation of VLL stretch, most workers can remember the ratio of their PEA deployment to their weight, and simply multiply it by the measured deflection of the basket.

Clearance Margin (CM)
Any determination of clearance is only an estimate. There are many foreseeable reasons why the calculated clearance won't be exact, including workers being lighter or heavier, taller or shorter, or using different manufacturer's equipment. There may also be inaccuracies in determining factors such as swing falls, harness stretch and MASD. It would be too conservative to try to account for every possible error or omission; however, a reasonable safety factor must be included to protect against foreseeable variances and minor errors.

In North America, traditional clearance calculations have included a 3-foot (0.9m) clearance margin. Europe, Australia and other metric countries have used 1m (3.3 ft). Worker and Harness stretch was not recognized as an important or variable factor, so the Clearance Margin in the past covered the omission of harness stretch.

When the CSA Z259.16 standard for "Design of Active Fall Protection Systems" was being developed, it was recognized that harness technology had changed and that stretch might significantly exceed 1 foot (0.3 m). Worker Stretch-Out in AL systems was also seen as something that needed to be included. It was decided that we could reduce the clearance margin to 2 feet (0.6m) if we accounted for Worker & Harness Stretch, X_W, as a separate factor with a minimum value of 1 foot (0.3m).

ANSI Z359.6 subsequently adopted the same criteria.

What do the Regulations and Standards say about Clearance?

Most regulations and standards establish clearance requirements in a couple of ways:

- They require a Fall Arrest System to stop the fall before the worker strikes a lower level. Unfortunately, no guidance to workers or employers is given about how to verify meeting this criteria, other than stating that workers must be trained to figure this out, or that persons designing the systems must inform the workers how much clearance is required.
- They regulate the maximum Free Fall and Deceleration Distance so that a fall will be stopped within a prescribed distance. The reasoning behind this approach is that if the total of these two factors can be less than a certain distance (such as the height of each story in a building), then meeting these requirements will protect workers from falls above that height. Unfortunately, this criterion ignores other critical factors such as Worker and Harness Stretch, Swing Fall, and MASD.

United States
The Occupational Safety and Health Administration (OSHA) regulations specify both criteria.

CFR 1910.66 Appendix C (General Industry) and CFR 1926.502(d)(16) (Construction Industry) stipulate, "Personal Fall Arrest Systems, when stopping a fall, shall …….be rigged such that an employee can neither Free Fall more than 6 feet (1.8 m), nor contact any lower level; and …… bring an employee to a complete stop and limit maximum deceleration distance an employee travels to 3.5 feet…"

Most people pay attention to the 6 foot Free Fall and the 3.5-foot deceleration distance (because they are easier to understand than clearance) and trust this will keep the worker safe. Few recognize that at the threshold height of 6 feet (1.8m) where Fall Protection becomes necessary, the total of these two factors is 9.5 feet (2.9m), which exceeds the Available Clearance by a wide margin. This is without even considering other factors that might be applicable, such as Worker/Harness Stretch, Clearance Margin, Swing Fall, and MASD.

The ANSI Z359.6 standard for the "Specification and Design Requirements for Active Fall Protection Systems" includes all of the factors discussed in this paper, however the clearance figures only illustrate the method that is easiest for AL Systems (this, as discussed previously, will work for FL systems, but requires a Qualified Person to figure out the free falls).

<u>Canada</u>
In Canada, each province as well as the Federal Government has their own OH&S regulations. Requirements for clearance vary from no specifications whatsoever, to specified Free Falls and Deceleration Distances, to only the fundamental requirement that the fall must be stopped within the Available Clearance.

The CSA Z259.16 standard for the "Design of Active Fall Protection Systems", cited in some jurisdictions, includes all of the factors discussed in this paper. Like the US standard that was based on it, the clearance figures only illustrate the method that is easiest for AL Systems (this method, as discussed previously, will work for FL systems, but requires a Qualified Person to figure out the free falls).

<u>Europe</u>
In Europe, the EN 355 and 360 standards for Lanyard Energy Absorbers and Retractable Fall Arresters stipulate that manufacturers must advise users of the minimum clearance below the feet of the user, defined as:

- Two times the length of the lanyard plus 1.75m (5.75 feet) (the maximum deployment of the PEA) + 1m (3.3 feet). This is very conservative when the user is connected to an anchorage higher than the platform he/she is standing on. This does not include any allowance for MASD, swing falls, or extra harness stretch.
- The arrest distance of the SRL plus 1m (3.3 feet). As above, this does not include any allowance for MASD, swing falls, harness stretch, workers falling from a kneeling position, or how to handle clearance when the SRL is not actually anchored above the worker.

Two References Points (Platform vs. Anchorage)

There are two primary locations that clearances should be referenced to. We must know which one to use in which circumstances, and how they relate to each other.

<u>Required Clearance below the platform, Cp (applicable to Automatic Length Systems)</u>
This is the best reference point for AL Systems since the elevation of the anchorage above the worker does not affect the Free Fall since the equipment automatically adjusts. Free fall is a known quantity, which then generates a known deceleration distance. Examples include SRLs and Automatic Fall Arresters on Vertical Lifelines.

<u>Required Clearance below the anchorage, Ca (applicable to Fixed Length Systems)</u>

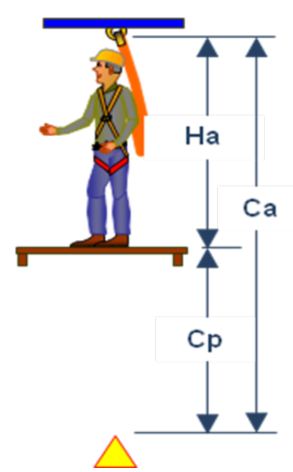


Figure 9
Illustration of Ca, Cp and Ha

For FA Systems, it is easier to reference clearance to the anchorage. We simply add up the known length of all components between the anchorage and the worker, as they would be at Fall Arrest, plus the worker length and the clearance margin.

When the anchorage is not vertically in line with the direction of fall, and may deflect the line over structures such as a roof edge, parapet or guardrail, Ca is still the distance from the worker to the anchorage, but now follows the path of the lifeline (See figure 12, Fixed Length Lanyard or Lifeline).

Height of Anchorage Above the Platform (Ha)

When there is a need to determine Cp while using a FL System, or Ca when using an AL System, it is very simple to calculate one from the other if you know the height of the anchorage above the platform, Ha (See Figure 9):

Ca = Cp + Ha or in another variation **Cp = Ca – Ha.** **(Equation 1)**

Basic Clearance Formulae

Building Clearance around the simplest cases.

Let's first work with formulae for the simplest case:

- A worker falling from a standing position and wearing a regular harness. X_W = 1 foot (0.3m) and H_W = 6 feet (1.8m)
- No swing fall. SFD = 0
- Anchored to non-deflecting anchorage systems. MASD = 0

Once we have clearance for either type of system for the simplest case, we can add in the required additions for kneeling workers, ΔXH, SFD and MASD.

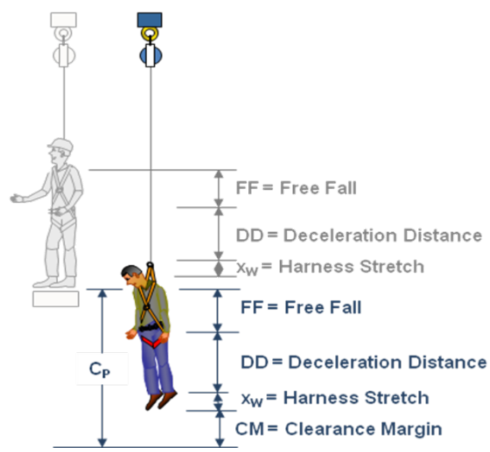


Figure 10
Determination of Clearance Below the Platform

Automatic Length Systems (Formula for Cp)

Let's start with the classic clearance formula for "Clearance below the Platform". Figure 10 shows (in Grey) the distance travelled by the shoulder blades of the worker. This equals the distance travelled by the feet (in Blue), so it is easy to see that:

Cp = FF + DD + X_W + CM **(Equation 2)**

Where: FF = the Free Fall
DD = the Deceleration Distance
X_W = the stretch out of the worker and harness = 1 foot (0.3m) in a regular harness from a standing position.
CM = the clearance margin = 2 feet (0.6m).

This calculation is very straightforward when Free Fall and Deceleration distance are known values, controlled by the "automatic" Fall Arresting equipment. We will simplify this equation further in the next section by putting in conservative known values for specific scenarios.

<u>Fixed Length Systems (Formula for Ca)</u>
Let's start with the classic clearance formula for Clearance below the Anchorage, which simply adds up the factors shown in Figure 11:

$Ca = Ly + X_{PEA} + H_W + CM$ (Equation 3)

Where: Ly = the Length of Lanyard or Lifeline between the Worker and the Anchorage.
X_{PEA} = the maximum deployment of the PEA
H_W = The height of the worker, from D-ring to Toes at Fall Arrest, 6 feet (1.8m) including 1 foot (0.3m) of Harness Stretch.
CM = the clearance margin = 2 feet (0.6m).

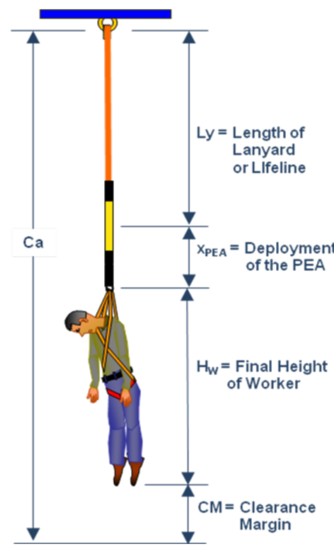


Figure 11
Determination of Clearance Below the Anchorage

Notice that this calculation does not require an estimate of Free Fall. A Qualified Person would need to know FF to determine how much the PEA would actually deploy. Since we don't know how to calculate PEA deployment, and prefer to avoid determining Free Fall, we are taught to assume full deployment of the PEA, making this method of calculating clearance very easy.

Clearance Formulae for Specific Scenarios

Now that we have spent so much time understanding the complications of clearance, we are ready to come up with the promised simple formulae and rules that could be printed onto a single page card, for quick and easy reference by people who need to figure out clearances.

<u>Formula 1: Self-Retracting Lifelines Anchored Above the Worker</u>
Let's develop the values for the four factors in equation 2, for Cp.

FF = the Free Fall varies according to the design of the SRL. These devices typically lock-off after Free Falls between about 4 inches and 1.5 feet (0.1 to 0.45m). Let's be conservative and use 1.5 feet. Our conservatism will be discussed later.
DD = the Deceleration Distance also depends on the model. For a 310 pounds (140 kg) worker falling into a clutching SRL (or one with an external PEA), the deceleration distance after a 1.5 ft Free Fall is usually somewhere between 1.5 and 3 feet (.045 to 0.9m). Let's be conservative and use 3 feet (0.9m). Our conservatism will be discussed later.
X_W = the stretch out of the worker and harness = 1 foot (0.3m) for a standing worker in a regular harness, for the simplest case.
CM = the clearance margin = 2 feet (0.6m).

Putting these values into the formula for Cp:

$Cp = FF + DD + X_W + CM$
$Cp = 1.5\text{ ft} + 3\text{ ft} + 1\text{ ft} + 2\text{ ft} = 7.5\text{ ft}$ or, $0.45m + 0.9m + 0.3m + 0.6m = 2.3m$

The 7.5 feet (2.3m) is our conservative worst-case, but we could ask if we are being *too* conservative? Let's look at some reasons we may want to reduce this a bit:

- Most of the smaller SRLs lock-off in much less than 1.5 feet (0.45m). Only the larger SRLs generate this much Free Fall, and then only when the worker is close to the SRL at its anchorage. As the worker gets further away, these SRLs lock-off faster (typically less than 1 foot (0.3m) and thus also have smaller deceleration distances (say 2 feet). It is unlikely that we would use a large SRL anchored a short distance off the ground. Thus at the six foot (1.8m) threshold height, we likely will have FF + DD of 3 feet (0.9m) or less, instead of 4.5 feet (1.35m) as conservatively calculated above.
- OSHA does not require any clearance margin, only that we prevent the worker form impacting the ground. If we deduct the clearance margin and have controlled the other factors not included in this calculation properly, even in the worst case of using a large SRL anchored a short distance off the ground, we should actually stop the worker 0.5 feet (0.15m) above the ground at the 6 foot (1.8m) threshold height
- Even if the worker somehow manages to impact the ground, the system will have slowed them considerably, and they would impact at a speed equivalent to a much lower fall height, probably equivalent to jumping off the bottom step on a stairway.

With this rationalization, I believe it is safe to work with 6 feet (1.8m) of clearance to get a very simple and easy to remember rule, requiring no calculations, and that provides a system to stop the fall at the US OSHA threshold height of 6 feet (1.8m).

Self Retracting Lifeline (SRL) anchored above the worker: Cp = 6 feet (1.8m) (Formula 1)

Don't forget we need to add 2.5 feet (0.75m) if the worker is kneeling, plus 1.5 feet (0.45m) if using a stretch harness, plus any applicable Swing Fall Distance and MASD.

Formula 2: Self-Retracting Lifelines Anchored Behind the Worker in a Leading Edge Fall

The leading edge fall clearance equation we are developing here is applicable where the device is anchored at least 6 feet (1.8m) back from the edge, so that the device will have time to retract the SRL line so that it locks up quickly after the worker falls past the edge. Because there is a risk of the line cutting at the edge, SRLs used in this way should meet ANSI Z359.13 Class LE, or the worker must otherwise have a proper PEA between his harness and the SRL Snaphook.

Let's develop some values for the four factors in equation 2 for Cp.

FF = the Free Fall comes from a worker stepping or falling off the edge of the working platform. The worker's Harness Dorsal D-ring will start off nominally 5 feet (1.75m) above the edge, and the SRL will not begin to deploy cable until the D-ring passes the edge of the platform, so the Free Fall will be 5 feet (1.75m) plus the distance taken for the SRL to lock-off once cable starts to be pulled from the device. Let's assume it locks quickly so that the total Free Fall will be 5.5 feet (1.7m) including the lock-off.

DD = The Deceleration Distance depends on the clutching force of the SRL plus friction of the line bending over the edge as well as the deployment force of the PEA, both of which are higher than the basic clutching force of the SRL. Therefore, deceleration distance for a 310 lbs (140 kg) worker is conservatively about 1.2 times the Free Fall, or 6.6 feet (2.0m) for the 5.5 feet (1.7m) free fall assumed above.

X_W = the stretch out of the worker and harness = 1 foot (0.3m) for a standing worker in a regular harness, for the simplest case.
CM = the clearance margin = 2 feet (0.6m).

Putting these values into the formula for CP:

$Cp = FF + DD + X_W + CM$
$Cp = 5.5\text{ ft} + 6.6\text{ ft} + 1\text{ ft} + 2\text{ ft} = 15.1\text{ ft}$ or, $1.7\text{m} + 2.0\text{m} + 0.3\text{m} + 0.6\text{m} = 4.6\text{m}$

Let's round down (consuming a bit of the clearance margin) so that we get some easy to remember numbers:

Leading Edge SRL anchored behind the worker: Cp = 15 feet (4.5m) (Formula 2)

Don't forget we need to add 1.5 feet (0.45m) if using a stretch harness, plus any applicable Swing Fall Distance and MASD. In this case, because the SRL is behind the worker, a kneeling worker would have less Free Fall so the governing case is for a standing worker. We do not need to consider the kneeling worker in our clearance calculations.

Formula 3: Vertical Lifeline with an Automatic Fall Arrester

Let's develop some values for the four factors in equation 2 for Cp.

FF = The Free Fall is the distance it takes the Fall Arrester to lock onto the VLL plus the distance it takes for the rope grab to switch from being supported by the worker to supporting the worker (so the worker falls 2x the lanyard length, "Ly" relative to the Fall Arrester). The distance the Fall Arrester moves before locking onto the rope varies, but 2 feet (0.6m) is a conservative assumption. Therefore FF = 2 ft (0.6m) + 2Ly
DD = If the worker is using a personal energy absorber (PEA) in his linkage to the Fall Arrester, we should assume full deployment. (X_{PEAmax})
X_W = the stretch out of the worker and harness = 1 foot (0.3m) for a standing worker in a regular harness for the simplest case.
CM = the clearance margin = 2 feet (0.6m).

Putting these values into the formula for CP:

$Cp = FF + DD + X_W + CM$
$Cp = (2\text{ ft} + 2Ly) + X_{PEAmax} + 1\text{ ft} + 2\text{ ft} = 5\text{ ft} + 2Ly + X_{PEAmax}$
$= (0.6\text{m} + 2Ly) + X_{PEAmax}\ 0.3\text{m} + 0.6\text{m} = 1.5\text{m} + 2Ly + X_{PEAmax}$

Let's use a bit of the clearance margin so that we get some easy to remember numbers:

Vertical Lifeline (without stretch/MASD): Cp = 5 ft (1.5m) + 2Ly + X_{PEAmax} (Formula 3)

Remember that we need to add 2.5 feet (0.75m) if the worker is kneeling, plus 1.5 feet (0.45m) if using a stretch harness, plus any applicable Swing Fall Distance and MASD. Note that in a VLL, MASD (stretch of the VLL) is usually very significant and must always be included in the calculation of Required Clearance.

Formula 4: Fixed Length Lanyard or Lifeline

This time we must use equation 3 for Ca. Let's review values we should use for the four factors.

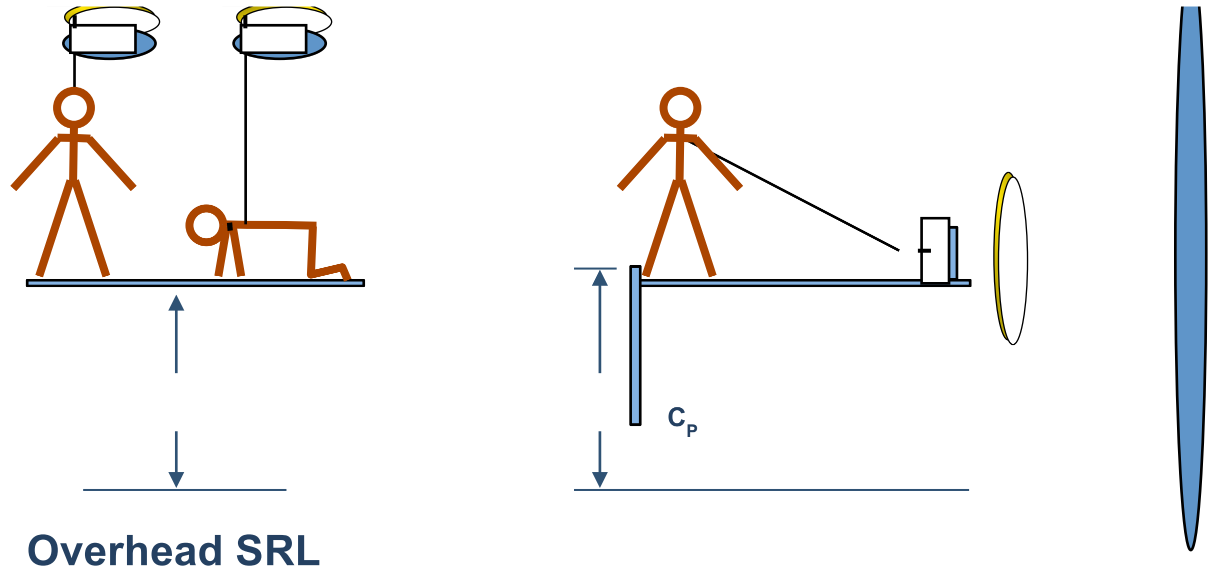
Ly	=	The length of the lanyard or lifeline between the worker and the anchorage.
X_{PEA}	=	X_{PEAmax} if we assume complete deployment of the PEA (this is printed on the label).
H_W	=	The height of the worker, from D-ring to Toes at Fall Arrest, Including 1 foot (0.3m) of Harness Stretch = 6 feet (1.8m)
CM	=	the clearance margin = 2 feet (0.6m)

Putting these values into the formula for Ca:

$$
\begin{aligned}
Ca &= Ly + X_{PEA} + H_W + CM \\
&= Ly + X_{PEAmax} + 6\text{ ft} + 2\text{ ft} = 8\text{ ft} + Ly + X_{PEAmax} \\
&= Ly + X_{PEAmax} + 1.8\text{m} + 0.6\text{m} = 2.4\text{m} + Ly + X_{PEAmax}
\end{aligned}
$$

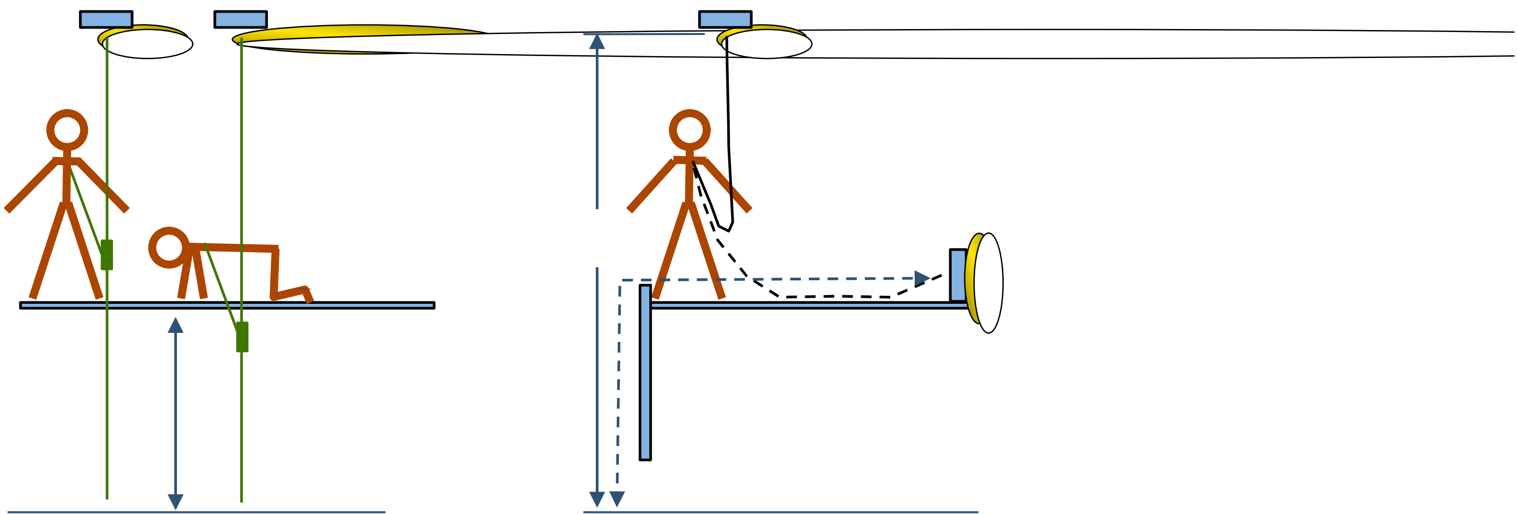
Lanyard or Lifeline System: $\mathbf{Cp = 8\ ft\ (2.4m) + Ly + X_{PEAmax}}$ **(Formula 4)**

Remember that we need to add 1.5 feet (0.45m) if using a stretch harness, plus any applicable MASD. Unless using a wire rope VLL, there should always be a lot of MASD (stretch of the VLL).



Overhead SRL

(+ MASD, SFD & ΔX_H)



Automatic Fall Arrester on Vertical Lifeline

(+ MASD (VLL Stretch), SFD & ΔX_H)

Easy Formulae for Clearance Calculations

We have now eliminated the need for workers to calculate Free Fall and to know which of the two general equations for clearance are applicable.

These simple formulas are applicable to four cases that cover a wide variety of scenarios a worker may encounter.

The two “formulas” for SRLs do not require any calculation whatsoever if the simplest case applies (regular Harnesses, no swing fall and no MASD).

To make it easy for workers to select the correct formula, the best approach is to summaries the information in a series of pictograms illustrating when each formula is to be used.

To avoid confusion about when to account for a kneeling workers, Swing Falls and MASD. These are marked on or below the Pictogram cases where they are applicable.

The four pictograms in Figure 12 can easily be included in a training manual, or printed on a quick reference card.

Additional Information to accompany the Pictograms

There needs to be definitions of the terms shown in the pictograms, as well as the rules about how to deal with situations other than the simple case (addressing stretch harnesses, Swing Fall Distance, and MASD). The following information could be printed on the backside of the Pictogram card or included in a facing page of a training manual:

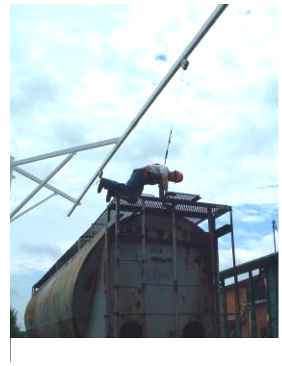
Where:	Cp	=	Required Clearance below the Platform = Ca - Ha
	Ca	=	Required Clearance below the Anchorage = Cp – Ha
	Ha	=	Height of the Anchorage above the platform
	Ly	=	Length of Lanyard or Lifeline from the worker to the Anchorage (or Fall Arrester)
	XPEAmax	=	The maximum deployment of the Personal Energy Absorber

The following factors, when applicable, must be added to the basic clearance determined in accordance with the Pictograms

ΔX_H	Add 1.5 feet (0.45m) when using a stretch harness.
SFD:	Add the difference between the length of line and the distance from the anchorage to the platform edge where gravity will pull you.
MASD:	(Maximum Anchorage System Deflection):
Structural Components	If structures appear flexible, test or check with a Qualified Person.
VLL stretch	Unless you have reliable information otherwise, assume 10% stretch for a 900-pound (4 kN) PEA or 15% stretch for a 1350 pound (6 kN) PEA. Alternatively, determine how much the VLL stretches under your weight. Multiply that stretch by the ratio of the deployment force of your PEA divided by your weight.
HLL Sag	If clearance information is not provided by the Manufacturer, Designer or Qualified Person, Assume 15% of span length for rigid end anchorages or 25% of span length for deformable anchorages.
Boom Lift Bounce	Determine how much the basket drops under your weight. Multiply that drop by the ratio of the deployment force of your PEA divided by your weight.

We have only developed simplified methods for four specific cases that hopefully cover most what workers will encounter. The SRL scenarios bracket the extreme scenarios (e.g., an SRL overhead vs. one that is behind the worker's feet). Other Pictograms can be developed as needed.

Example Calculations



Let's see how the pictograms and methods included in this paper can be used to evaluate Required Clearance in some real world examples.

Example 1: SRL on a Rigid Anchorage

A worker on top of a rail car is connected to an SRL on trolley that rolls along a rigid rail system above his head. He is wearing a stretch harness.

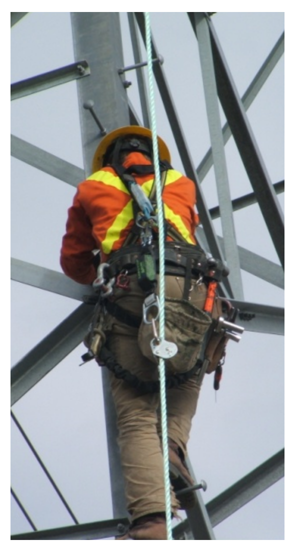
Assume the Rigid Rail anchorage system will not deflect appreciably, and that there is negligible possibility of a Swing Fall (since the trolley will track the SRL above the worker along the length of the car, and the worker cannot move very far perpendicular to the car).

The Pictogram for a kneeling worker using an overhead SRL indicates that Cp = 8.5 feet if he falls from a kneeling position.

Because the worker is wearing a stretch harness, he must add 1.5 feet to the clearance calculation for a total of 10 feet.

Therefore, total clearance below the top of the rail car is required to be at least 10 feet (3m) for this worker.

A more accurate determination by a Qualified Person may recommend a bit less than this for the specific scenario, particularly the weight of the worker, lock-off distance and clutching force of the SRL. If, for instance the worker weighs 200 lbs, the SRL locks off in one foot and clutches at an average force of 500 lbs, the recommended clearance would be 8.67 ft (2.6 m).



Example 2: Vertical Lifeline.

A worker is using a vertical lifeline to protect himself while climbing a transmission tower. The worker has a 0.5m lanyard that deploys a maximum of 1.2m at a force of 4 kN between his regular harness and the automatic Fall Arrester. The length of the line is 19m between him and the anchorage at the top of the tower.

The Pictogram for a standing worker using vertical lifeline indicates that $Cp = 1.5m + 2Ly + X_{PEAmax}$.

$Ly = 0.5m$ and $X_{PEAmax} = 1.2m$.

Therefore $Cp = 1.5m + 2 \times 0.5m + 1.2m = 3.7m$

C_a

We must include the MASD (stretch of the VLL). Assume 10% stretch at 4 kN = 10% x 19m = 1.9m.

Therefore the total Required Clearance below the worker's feet should be 3.7m + 1.9m = 5.6m (18.4 ft.).

As a comparison, a more accurate determination by a Qualified Person (for example, if the PEA has an average force of 3.2 kN and the worker weighs 140 kg), following the CSA Z259.16 design code would determine a required clearance of 16.5 ft.

Example 3: Fixed Length Lanyard anchored in a Boom Lift.

A 225 lbs worker using a boom lift has a 6 foot long, ANSI Z359.13 "6 ft FF" Lanyard. The label states that the PEA deploys a maximum of 4 feet at an average force of 900 pounds. The guardrail on the basket is 3.5 feet high, and the anchor point that the worker connects to is 1.5 feet below the guardrail on the inside of the basket. The worker has climbed out of the basket, as shown in Figure 15.

C_a

Before starting work, the worker boomed out horizontally just above the ground so he could measure how much the basket may deflect under his weight. When he stepped into the basket, it lowered about 3 inches.

The Pictogram for a Fixed Length Lanyard or Lifeline indicates that Ca = 8 ft + Ly + X_{PEAmax}.

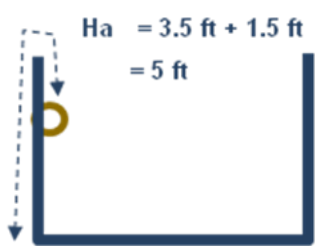
Ly = 6 ft and X_{PEAmax} = 4 ft.

Therefore Ca = 8 ft + 6 ft + 4 ft = 18 feet

But we should include the MASD (Bounce of the Boom Lift). The ratio of the Worker's weight to the deployment force of the PEA is 900 pounds / 225 pounds = 4. Therefore we would expect a 900 pound impact to cause 4 x 3" = 12" = 1 foot of bounce.

Therefore the total Required Clearance should be Ca = 18 ft + 1 ft = 19 feet.

But what does clearance below the anchorage, "Ca", mean in this case? The worker's lanyard is going to deflect over the guardrail. So it may be hard to picture what this really means. It would be more useful to convert the Required Clearance to Cp, which is referenced at the platform (floor of the manlift). We can use equation 1 to determine:



Cp = Ca – Ha

Figure 16 shows how Ha is determined, when the top of the guardrail is 3.5 feet above the platform and the anchorage is 1.5 feet below the guardrail, for a total of 5 feet.

Therefore, Cp = 19 feet – 5 feet = 14 feet.

This worker will not have enough clearance until the floor of his basket is 14 feet (4.3m) above the ground or other level or object he does not want to land on.

For comparison, a more accurate determination by a Qualified Person (assuming that the top of the chimney is 5.5 feet above the floor of the basket, and that the true deployment force of the PEA is 700 pounds), could recommend a clearance of 13.36 ft (4.1m).

Conclusions & Recommendations

Clearance Calculation is not an easy topic to understand and teach. This paper recommends more thorough instruction of our workers and Competent Persons so they can more reliably determine and their clearances.

This paper also categorizes systems into 4 broad classifications that represent or bracket most Fall Arrest scenarios workers may face, and develops some simple pictograms for to make it visually easy for workers to select the scenario they are dealing with, to know what equations to use and additional factors to consider.

In order to simplify the calculations, the methods shown in this paper are arguably conservative than the typical scenario. They assume a maximum 310 pound worker weight; full deployment of energy absorbers; and provide conservative MASD rules. A Qualified Fall Protection Engineer, following the processes in ANSI Z359.6 or CSA Z259.16 may often be able to recommend less Required Clearance if there is information to allow more accurate prediction of energy absorber deployments and MASD.

However, as seen in the three examples, the Pictograms and their applicable formulae seem to get us, very easily, within a couple of feet (half a metre) of the more accurate predictions by a Qualified Fall Protection Engineer.

Bibliography

ANSI Z359.1-2007, "Safety Requirements for Personal Fall Arrest Systems, Subsystems and Components", American Society of Safety Engineers, 2007

ANSI Z359.6-2009, "Specifications and Design Requirements for Active Fall Protection Systems", American Society of Safety Engineers, 2009

CSA Z259.2.1-98, "Fall Arresters, Vertical Lifelines and Rails", Canadian Standards Association, 1998

CSA Z259.16-04, "Design of Active Fall Protection Systems", Canadian Standards Association, 2004

CFR 1910.66 Appendix C, United States Occupational Safety and Health Administration

CFR 1926.502(d)(16), United States Occupational Safety and Health Administration

EN 355:2002 (E), "Personal Protective Equipment for Falls from Height – Energy Absorbers", European Committee for Standardization (CEN), 2002

EN 360: 2002 (E), "Personal Protective Equipment for Falls from Height – Retractable Type Fall Arresters", European Committee for Standardization (CEN), 2002