Expanding Ground-based Harvesting onto Steep Terrain: A Review

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Abstract

Timber harvesting on steep terrain has always been, and will remain, a challenge in terms of economic viability, safety and environmental performance. For almost a century motor-manual felling coupled with cable yarding has been the most appropriate harvesting system, but new technologies and innovations have led to machines and systems being developed that are modernising the way we operate on steep terrain. Specifically, they provide the opportunity for the mechanisation of operations with proven improvements in both safety and cost-effectiveness. The additional development of cable-assist machines is potentially making a real step-change by expanding the operating range onto very steep slopes. This paper reviews these developments, the main engineering considerations of how cable-assist works, as well as the advances being made in terms of how such equipment is integrated into harvesting systems. The review also includes analyses of the operating guidelines that are either in place or being developed to help implement the systems.

Keywords: timber harvesting, steep terrain, cable assist, harvester, forwarder

1. Introduction

Cable yarding remains the mainstay of steep terrain harvesting operations (Samset 1985, Studier and Binkley 1974, Heinimann et al. 2001). However, cable yarding remains both expensive (Dykstra 1975, Raymond 2012) as well as hazardous relative to ground-based harvesting operations (Slappendel et al. 1993, Klun and Medved 2007). The safety issues arise from the manual activities still common in cable logging, including the felling by chainsaw and using choker-setters in the extraction phase (Kirk and Sullman 2001). A high level of risks to forest workers operating these systems provides both the need, but also the potential benefits, of mechanising the manual aspects of this system (Bell 2002, Montorselli et al. 2010).

Cable yarders can be used in many different configurations (Studier and Binkley 1974) with distinct advantages and disadvantages for each configuration (Harrill and Visser 2012). There are several options for the mechanisation and automation of existing cable yarding systems. For example, the advent of radio-controlled chokers reduces the need for the operator, and/or a separate »poleman«, to unhook the stems once on the landing (Stampfer et al. 2010). The use of video cameras increase operator visibility for increased productivity (Evanson 2013) and can also be used for advanced training (Parker 2010). The development of motorised grapple carriages can reduce, but not eliminate, the need for choker-setters (McFadzean and Visser 2013). On the landings, the opportunity to integrate processors has long eliminated the need for the use of skid-workers. Combining elements of ground-based systems into cable yarding has also shown to have benefits (Stampfer and Steinmüller 2004, Acuna et al. 2011). For example a study by Visser and Stampfer (1998) showed a 40% increase in cable extraction productivity when using mechanised versus chainsaw felling. Although the concept of carriages that can fell and extract are being investigated, no commercial success has yet been reported. As such, some work processes of cable yarding operations will remain manual and/or motor-manual.

Ground-based harvesting has benefited significantly from mechanisation and many options for fully mechanised systems are available (MacDonald 1999).

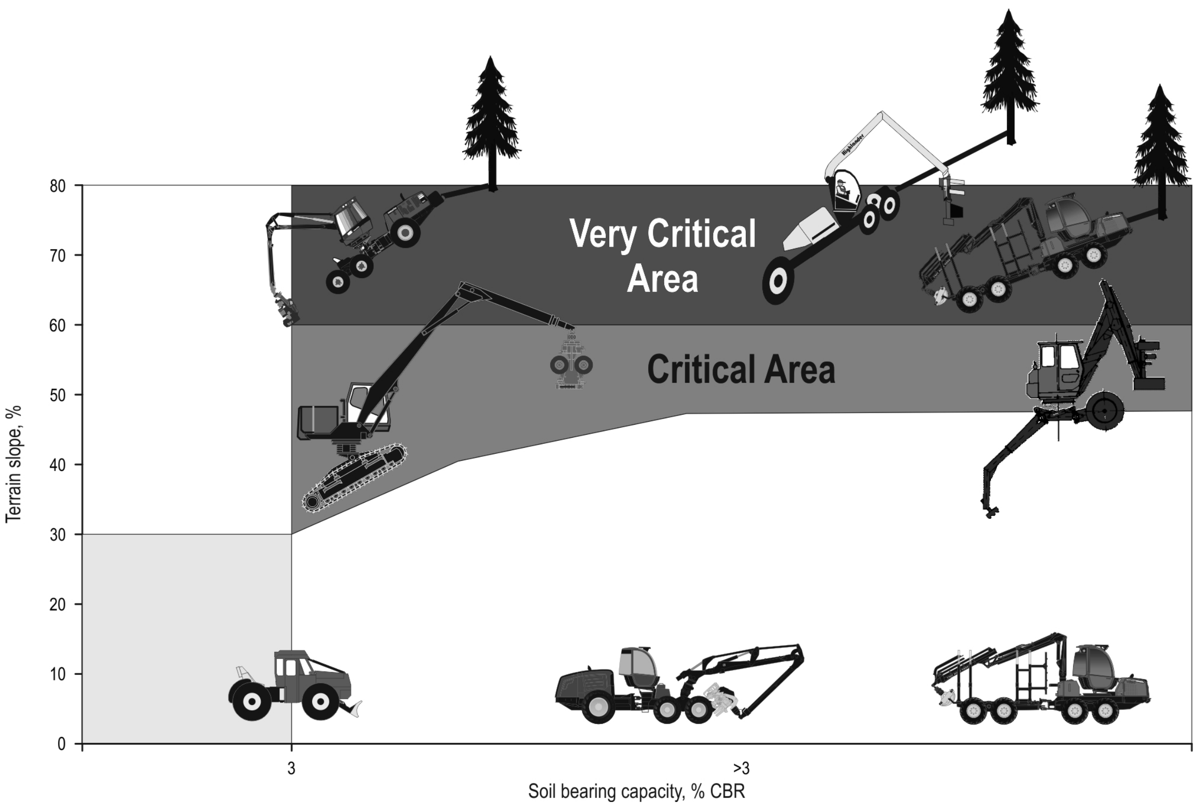

Fig. 1 Safe operating range of ground-based harvesting machines related to terrain slope (%) and soil bearing capacity, as measured by California Bearing Ratio (after Heinimann 1995)

The two most common options are the Cut-to-Length (CTL) and the Whole-Tree (WT) extraction systems. CTL, first made popular in Scandinavia, uses a combination of a harvester to fell and process the tree into logs, followed by a forwarder that will accumulate the log piles and bring it to roadside. WT relies on a felling machine to put the trees down (and possibly pre-bunch them), a skidder to extract them to a landing, and a processing machine to buck the stems into logs. Both mechanised systems have proven advantages in terms of safety (Bell 2002, Axelsson 1998, Laflamme and Cloutier 1988) and productivity (Raymond 2010).

While modern fully mechanised ground-based systems are a default option for safe and productive harvesting, they have always been limited by terrain factors such as slope (Olund 2001, Alam et al. 2013, Strandgard et al. 2014), soil strength and/or roughness (Amishev et al. 2009, Visser 2013). In the early 1970s, ground-based extraction machines had made considerable progress whereas mechanised felling and processing technology only just emerged on gentle terrain (Carson 1983). Feasibility limits were fixed for downhill skidding at a slope gradient of 50% for wheeled skidders and 60% for crawler tractors, depending on surface roughness (FAO/ECE/ILO 1971). Practical experience later demonstrated that those limits had to be reduced in order to keep soil erosion within acceptable limits (Heinimann 1999). Reported slope limits of 30% and 40% for wheeled and tracked machines, respectively, were related primarily to machine traction and soil erosion, and these values have since been presented and propagated in many subsequent reports (e.g. Arola et al. 1981) and guidelines (i.e. NZDOL 1999).

A study by Visser and Berkett (2015), recording the actual machine slope on 22 different operations (18 in New Zealand, 4 in Europe), showed that, under normal operating conditions, machines exceed established slope guidelines frequently and for extended periods of time. This, as well as anecdotal evidence from many countries, suggests that equipment advances have far outpaced operating guidelines.

Actual guidance on slope limits, based on either science or experience, is rare. Many guidelines refer to manufacturer's specifications, yet few of the major forestry equipment manufacturers provide slope and/or operating limits for their purpose built machinery. Komatsu has recently published operating guidelines that indicate a slope limit of 55% when using winch assist (Komatsu 2015). Cavalli (2015) surmised that wheeled machines with chains or bands might have an upper limit of 45%, integral track machines up to 60%, and that tethered machines should be able to operate up to a range of 75 to 85% slope.

Work by European researchers expanded the considerations and understanding of steep terrain machinery and their constraints. Charts were developed to help indicate safe operating zones for ground-based harvesting machines related to terrain slope (%) and soil bearing capacity, as measured by California Bearing Ratio, or CBR (Fig. 1). This shows the need for low ground pressure machines (e.g. using high flotation tyres) for any soil less than 3% CBR, but with increasing CBR operating up to 50% slope is acceptable with any ground-based machine. Operating from 50% to 60% slope is a critical zone where purpose-built steep terrain harvesters are required, but operating above 60% is considered very critical and requires additional securing systems such as »cable-assist« or traction winch technology.

Slope is not the only factor that should be considered when assessing safe operations or system productivity on steep terrain (Strandgard et al 2014). Soil bearing capacity and the vehicle-terrain interface are also important (Horn et al. 2007), as is the operator skill factor (Heinimann 1999). Visser and Berkett (2015) demonstrate that ground roughness and stumps can have a larger impact on the slope of the actual machine than the underlying terrain slope. Operating machinery on steep terrain can also increase the impact on soil disturbance (Horn et al. 2007). It can be assumed that cable-assist system will reduce soil disturbance through reduced slippage of the wheel and/or tracks. However, few studies (e.g. Wratschko 2006) have actually quantified the level of disturbance associated with cable-assist machinery on slopes where previously no machine had travelled.

2. Machine improvements for steep terrain

Improvements to allow machines to operate on steeper areas are two-fold: the need for increased stability of the base machine on the slope itself, as well improving the ergonomics for the operator. The latter has proven to be the easiest to resolve. With the goal of rationalising timber harvesting in steep terrain, early developments in North America included tracked machinery equipped with processors, feller-buncher or harvester heads. Empirical studies showed a reduced productivity and operability when operating the machine without a self-levelling cab (Schiess et al. 1983). Based on such results, many new steep slope purpose built machines were equipped with self-levelling cab and boom. The greater the ability to self-level the cab and boom, the steeper the terrain that could be operated on (Peters 1991).

In the early 1980s these steep-terrain tracked machines were studied to assess the operational slope limits (Arola et al. 1981, Schiess et al. 1983). The results indicated that manual-mechanical machine controls are not suitable for difficult terrain conditions. The machines were operated on slopes up to 70%. More recently improved control systems, and swivel seats, 360 degree windows and/or rear facing cameras provide for greater visibility and improved operator performance. Modern self-levelling machines also redistribute the center of gravity uphill to improve overall stability (Fig. 2).

There have been some significant advances in equipment design in Europe with machines working successfully on slopes over 65% (33 degrees) not uncommon (Stampfer and Steinmüller 2001, Bombosch et al. 2003, Stampfer and Steinmüller 2004). Successful felling on steep terrain is mainly due to the machines having new under-carriage design. One of these concepts is demonstrated in the development of the Komatsu 911 X3M (initially developed as the Valmet 911 »Snake«) (Stampfer and Steinmüller 2001) that is fitted with four independently suspended »high-drive« tracks (Fig. 3). This improves traction and stability, as one track can negate an obstacle such as a tree stump, while the other three are still firmly flat on the ground. Other developments include machines such as the Menzi-Muck A91 (www.menzimuck.com; Fig. 4) and the Kaiser S3 Spyder (www.kaiser.li). They have increased stability and maneuverability with wheels on

Fig. 2 Tigercat steep terrain feller-buncher shows that self-levelling cab feature is also used to redistribute the weight uphill for increased stability

Fig. 3 Komatsu 911.5 X3M, for example, can be fitted with four independently suspended »high-drive« tracks (photo from Komatsu Forest)

Fig. 4 Menzi Muck A91 as an example of a harvester with wheels on hydraulically actuated »arms« that can lower its centre of gravity to improve stability (photo from Raffaelle Cavalli)

Fig. 5 Ponsse ScorpionKing (photo retrieved from Ponsse.com)

hydraulically actuated »arms« (Hempill 1983). This allows the machine to rise over obstacles such as stumps, but more importantly it can lower itself on to the ground when felling larger timber in a difficult position.

Increasing the number of axles and providing independent suspension for those axles increases the number of contact points with the ground. The new purpose built Ponsse ScorpionKing provides four axles on two bogeys (Fig. 5). Another significant difference between the CTL type harvesters and the tracked felling machines is that a significant proportion of the weight is carried directly on the under-carriage. That is, only the weight of the cab, and/or the cab and the boom, need to self-level. In contrast, the WT felling machines carry the engine, pumps, fuel, hydraulics above the turntable raising the relative centre of gravity, as well as creating significant swing momentum when working. Another purpose built feature on the Ponsse ScorpionKing is the ability for the front and rear frames to tilt to the terrain, with the resulting pivot point for the cab being low. It also has an active stabilisation system based on detecting the direction and position of the crane, and then pressing the rear frame in the direction of work.

While points of contact, as well as distribution of weight on the ground affect the amount of traction a machine can gain, on tracked machines longer »cleats« can cut through a softer soil surface and also increase the level of traction. Wheeled machines can use chains (see also Fig. 3) or belts to successfully extend the operating range. The machine then develops the maximum amount of traction by ensuring the failure is between soil layers, and not between the tracks and the soil. While these options invariably extend the operating range, they can be expensive, cumbersome, increase fuel usage and increase the level of soil disturbance.

While equipment modifications have increased the operating range, not all forest operations can employ such technology. Difficulty to access areas by machine is not the only limiting factor; larger diameter trees, and/or smaller crews that cannot support the high capital cost of such a machine within their system, can also limit mechanised options (Raymond 2008). As such, chainsaw felling is still common in some countries and is still the highest risk in terms of fatalities in the industry.

3. Cable assist system

Cable assist machinery for forest operations have been commercially available in Europe since the 1990s (Sebulke 2011), with a number of different companies

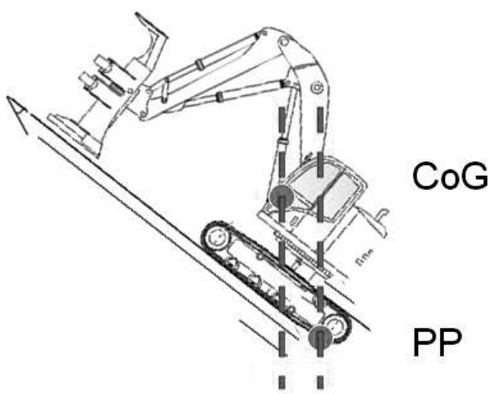

Fig. 6 Forestry machines can be stable on very steep slopes if the weight and centre of gravity are well managed (from McLean and Visser 2011)

offering cable winch products that are either integrated onto the machine or a separate attachment (Sutherland 2012). Initially they were mainly used on forwarders (e.g. Bombosch et al. 2003, Wratschko 2006), but now there are numerous commercial options to extend that technology to harvesters (Sebulke 2011).

There is a limit with regard to the physical feasibility of operating machines on steep slopes (Hunter 1993). The loss of traction will prevent the machine from moving up and down the slope, but in terms of »failure«, the real safety concern is the risk of machine roll-over. The slope associated with static roll-over is relatively easy to calculate as shown in Fig. 6. If the machine Centre of Gravity (CoG) is on the uphill side of the Pivot Point (PP), then the machine will not roll. Most forestry machines have relatively low CoG and are technically very stable in their intended direction of drive, both uphill and downhill. However, McLean and Visser (2011) showed that the machines with a higher centre of gravity traversing across the slope, such as a loaded forwarder, can easily become statically unstable on very low slopes (Fig. 7). Machines with boom attachments, such as felling machines, can also become unstable if the boom is swung to the downhill side. The weight, but also the force from the momentum, can affect stability (Eger and Kiencke 2003).

While static roll-over slope limits are relatively easy to calculate, a dynamic factor will reduce the slope limit where a roll-over can occur. As such, loss of traction can become a significant factor and it can be deduced that most roll-over accidents result from an initial loss of traction. It results in an uncontrolled gain in momentum and if followed by hitting an object, such as a stump, or a change in terrain slope, can readily result in a roll-over. The basic physics with regard to a retaining traction on a slope is that the gravity force pulling the machine down (Wg) should not exceed the traction force (T) that the machine is able to develop on the ground. The benefit of cable-assist system is that the tension force provided by the cable (C) will add to the traction force (T) and thereby greatly increase the operating slope of the machine without it reaching its traction limit (Fig. 8).

In terms of calculations, Wg is simply the product of the downward force (W) by the sine of the angle of the slope. Wg will be 0 when on flat terrain, and in-

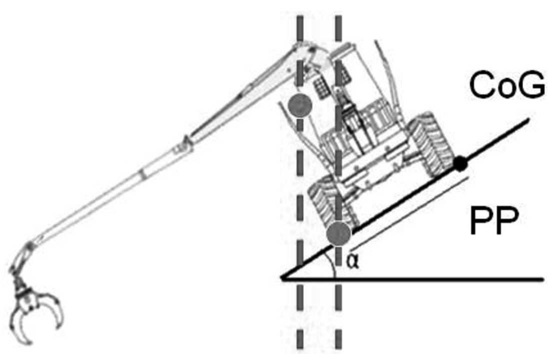

Fig. 7 A loaded forwarder typically has a high CoG, and if traversing across the slope or with the boom reaching out to the downhill side, it will be very unstable even on low slopes (from McLean and Visser 2011)

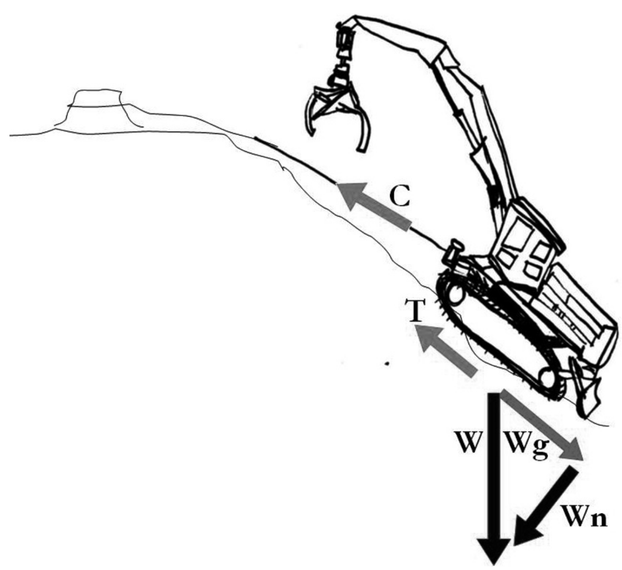

Fig. 8 Schematic diagram of forces of a cable assisted machine on a slope, where the cable assist force (C) is summed with the available traction force (T) to overcome the gravity down the slope (Wg) (from Visser 2013)

crease up to the full weight of the machine when on a vertical slope, that is fully suspended by the rope. The traction force (T) is the product of the normal force of the machine on the ground (Wn) with the Coefficient of Friction (cof). As such, the normal force Wn is defined by the product of the machine weight (W) and the cosine of the slope and will decrease with increasing slope.

The cof is the relationship of the tractive force that can be developed between the tracks and the soil. This is both dependant on the machine (i.e. tracks can typically develope higher traction coefficients than tyres), as well as the inherent strength of the soil (in shear). It is a complex relationship but a typical range for cof is from 0.4 on wet, soft or weak soils, up to 1.0 for a tracked machine operating on dry firm soil. Fig. 9 shows the effect of slope angle on a range of traction coefficients from 0.4 to 1.0, overlaid on the gravity force using a 37 tonne machine, where the lines intersect represents the theoretical slope limit for the machine. For example, for a cof of 0.7, the maximum machine slope is 34 degrees. The graphic also shows the potential benefits of cable-assist system. The short black lines represent a cable tension of 10 tonnes. For the previous example of cof of 0.7, it moves the traction limit from 34 to 48 degrees. Under all scenarios, it can be seen that a cable assist system with 10 tonnes will greatly increase the operating range.

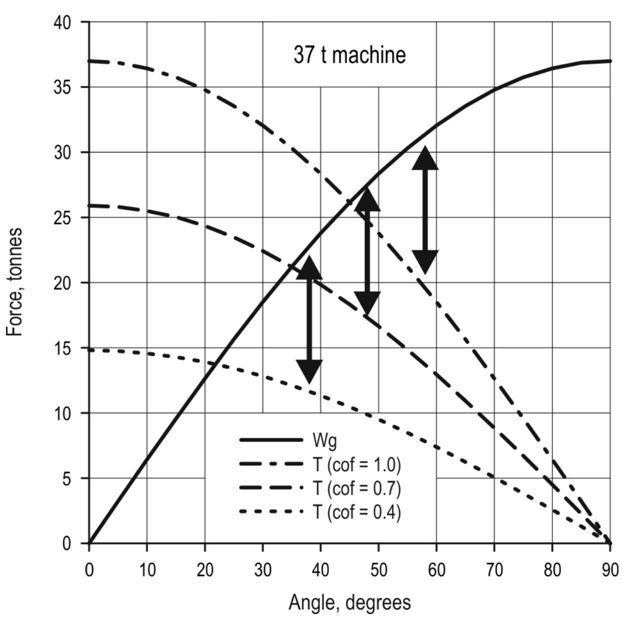

Fig. 9 Chart showing the relationship between Wg and the slope using the example of a 37 tonne machine, and the effect of differing traction coefficients and cable-assist tension on slope limit shown for different soil strength factors (cof). The intersection of the effect of gravity (Wg) and the different soil strength factors (cof) indicate the slope limit (shown in degrees). Adding a cable-assist system with 10 tonnes of tension, as illustrated by the black arrows, significantly increase the operating range. (from Visser 2013)

4. Cable-assist design options

While the cable-assist concept is simple enough, adding it to machines is not without its complications and has led to different design concept options. Consequently, two options have emerged. The most common is to mount the winch onto the chassis of the primary machine, whereby a number of manufacturers have preferred the »bolt-on« option to accommodate the opportunity to remove the unit when not required. The second uses a secondary machine to house, and provide power to the winch.

For the integrated system, adding a winch system to the machine itself adds both weight and increases power requirements (Fig. 10). In addition to the winch itself, modifications are required in terms of integrating the control system as well as some fairlead to ensure that the cable is not dragged over the ground or subjected to bending fatigue. In Europe, it is typical to connect the cable to suitable standing trees, whereas most countries in the Southern hemisphere prevent any anchoring to live trees, and instead stumps, deadmen or machines are used as anchors. An operational consideration is that the expected utilization of the cable-assist system is typically not high compared to conventional felling machines. The effort required to connect the system, and the subsequent movement limitations, means that an operator would not use the cable-assist option unless required.

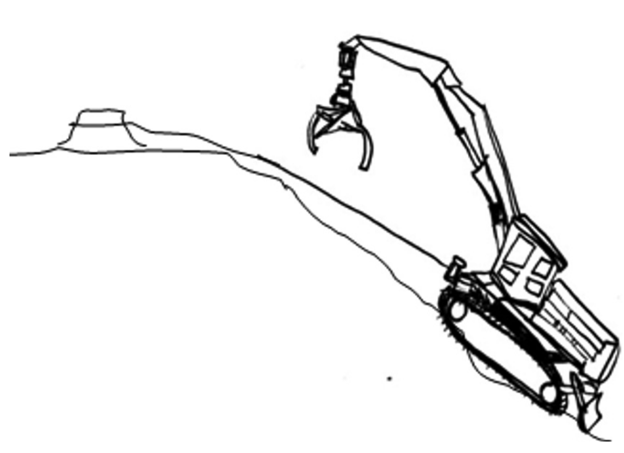

Fig. 10 Schematic diagram of cable-assist machine configuration with winch integrated onto the machine

The other design option is a two-part system with the winch mounted on and powered by a second machine, typically either a bulldozer or excavator (Fig. 11). In addition to removing the weight and power requirements from the machine on the slope, this option provides flexibility in that the machine can be used in an ad hoc basis for multiple steep terrain machines. For example, first a felling machine is tethered, and subsequently a more standard excavator with grapple is used to pre-bunch or shovel the wood up or down the slope. The anchor machine is mobile and can readily be moved.

There are also other variations of both options. Two examples include an Austrian small purpose built mobile tracked winch system (T-Winch) with significantly lower power and fuel requirements compared to converting a conventional bulldozer or excavator (Ecoforest 2013), and Summit Manufacturing in Canada have built a cable assist unit that is mounted at the base of a yarding tower, that in turn is mounted on the boom of an excavator.

While cable-assist systems are becoming common, few studies have been published to sustain indications that such systems actually have productivity, cost-effectiveness, environmental or safety benefits. A number of operational studies indicate that it is very feasible to operate on slopes not achievable otherwise, and productivity levels are acceptable once the system is set up in place (Evanson and Amishev 2010, Evanson et al. 2013). However, no long term studies have been made to establish mechanical or operational delays, but given the more extensive and set up time and machine complexity they are expected to be higher. With regard to safety, consideration of the actual tension in the rope becomes critical if the machine is not stable on the terrain without the cable. Brief studies in both Austria and New Zealand have indicated that actual tensions regularly exceed the expected, and this is consistent with tension monitoring studies in cable logging (Hartsough 1993, Harrill and Visser 2014). Operators are also going through a steep learn-curve with regard to successful implementation, but digital onboard navigation tools are being developed to support operator decision making (Marshall 2012). Engineering modification are also possible: for example most New Zealand based operations prefer the use of a chain for the first 15–20 meters to minimize the wear and tear, or eliminate the risk of breaking the rope when felling or pulling trees across it (Fig. 12).

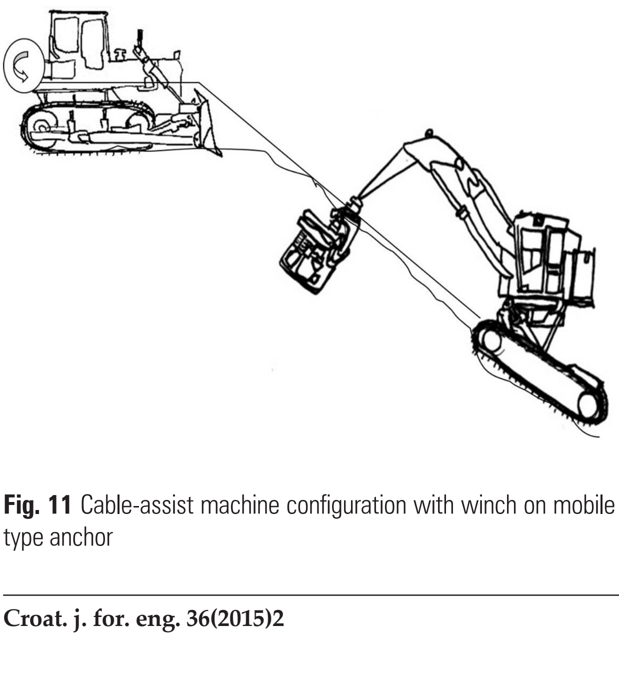

Fig. 11 Cable-assist machine configuration with winch on mobile type anchor

Fig. 12 Chain used for last section to prevent wear and tear on cable (photo from Hamish Berkett)

5. Rules and guidelines for cable-assist system

In terms of commonly available and referenced harvesting manuals (Liley 1983, OR-OSHA 2009, WorkSafeBC 2006, FITEC 2000, Safe Work Australia 2013), none have been updated to include cable-assist guidance. However, with the new developments in steep slope machinery, many safety organisations have revised references to slope limits. For example the latest »Safety and Health in Forestry Work« published by the International Labour Office (ILO 1998) stated: »mechanised harvesting should not be carried out in site conditions where the stability of the machine cannot be assured«. Equipment should not be operated on slopes exceeding the maximum gradient specified by the manufacturer or exceeding that which has been assessed as safe by a competent authority or a competent person. Where the above specifications have not been made:

(a) rubber-tyred skidders or forwarders should not be operated on a slope which exceeds 35%;

(b) crawler tractors, feller-bunchers, excavator harvesters or similar machines should not be operated on a slope which exceeds 40%;

(c) any other forestry equipment specifically designed for use on steep slopes should not be operated on a slope which exceeds 50%.

The Workers' Compensation Board of British Columbia (WorkSafeBC 2006) has updated its Occupational Health and Safety Regulations and the stated slope limits are the same as those presented by the ILO (quoted above), except the word »should« is replaced by »must«. The regulations state that logging equipment must not be operated in a particular location or manner if its stability cannot be assured during that operation. Subject to this rule »… logging equipment may be operated beyond the maximum slope operating stability limits specified … if, (a) a qualified person conducts a risk assessment of that operation, and (b) written safe work practices acceptable to the Board are developed and implemented to ensure the equipment stability during operation.«

The British Columbia Forest Safety Council developed a steep slope resource package to help manage safety of operations on slopes that exceed the BC guidelines (BCForestSafe 2011). Part 1 of this resource package is a Steep Slope Hazard Assessment Tool, a method to evaluate site-specific and machine-specific hazards and develop a plan to implement practices to mitigate machine stability risks. It recommends companies develop site specific slope management plans for their operations when exceeding slope limits.

In New Zealand, the revised Approved Code of Practice for Safety and Health in Forest Operations (MBIE 2012) contained a section for winch-assisted harvesting on steep slopes and references to specific slope limits have been removed. Specifically, it requires »All mobile plant using the assistance of a wire rope and/or winch shall be specifically designed, tested, demonstrated to be safe« and that »The tension on the wire rope shall be restricted to 33% of its breaking load at all times«. As such, they have aligned the safety requirements with that of cable yarding, where a factor of safety of 3 is common for most skyline applications.

Conversely, no European country has yet implemented specific cable-assist rules, although machine manufacturers have started to develop their own guidelines. Common to nearly all is the fundamental principle that the machine must remain stable and have traction without the cable, and as such the cable is only a traction assist and no additional rules need be incorporated. Only a few manufacturers are providing slope limits, such as Komatsu noting a limit of 55%. In their operating manual, Ritter (2015) provides the following guidance for operation:

⇒ The operation and maintenance of the winch may only be carried out by suitable, reliable person familiar with this work and over 18 years of age;

⇒ Working alone is only allowed when wireless emergency communication exists;

⇒ Before use, but at least every working day, check on your proper operating condition of the winch.

While such recommendations are direct, they do not address specific slope and/or stability limitations of cable-assist machinery. As cable-assist operations become more prevalent, it would be rational to develop standardised operating guidelines.

6. Conclusion

Many developments have increased our ability to successfully harvest on steep terrain using ground-based equipment. Improvements have included additions such as self-levelling cabs for operator comfort, and more recently significant modifications of carrier bases to improve traction and stability. A possible major step-change has been the development of cable-assist technology. Cable-assist system can significantly increase the ability to operate on steep slopes and avoid soil damaging slip, but the actual implementation, and understanding of its limitations, is in their infancy.

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