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Measuring Slope of Forestry Machines on Steep Terrain

Summary

Increasing the operating range of ground-based machines onto steep terrain has the potential to decrease harvest costs and improve safety as it removes workers from manual tasks. To better understand the true range of slopes on which forest machines are operating, a study of 22 forest machines in New Zealand and Europe was undertaken. A digital accelerometer was attached to each machine, which captured real-time measurements of machine slope. The evaluated machines were grouped into four machine types; feller bunchers, "shovel loggers", skidders and European purpose built steep terrain machines. The machine types were then analysed with respect to actual machine slope and terrain slope (predicted from machine GPS location on a digital terrain map). Results showed the four machine types experienced different machine slopes in comparison to the slope of the terrain on which they operated. All machines sampled operated on slopes that exceeded the Approved Code of Practice for Safety and Health in Forest Operations guidelines. The New Zealand machines were shown to exceed the guidelines for terrain slope much more frequently, and by a greater margin, than the European-based machines.

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INTRODUCTION

Cable yarding, the preferred method of steep terrain harvesting in New Zealand, is characterised by lower productivity and higher cost than ground-based harvesting. Cable yarding also has higher levels of manual labour undertaking hazardous tasks such as tree felling or breaking out (setting chokers), with corresponding higher safety risks. Using ground-based machinery instead of manual labour has the potential to decrease harvest costs and improve safety (Bell 2002; Raymond 2010).

The Approved Code of Practice for Safety and Health in Forest Operations (ACoP) states that as a rule equipment shall not be operated on slopes that exceed the maximum specified by the manufacturer (DoL 1999). As a guide (where manufacturer's limits are not given), subject to weather and ground conditions, wheeled machines should not operate on slopes that exceed 30% (18^{O}) and crawler tractors, feller bunchers, excavators, and other similar mobile plant should not operate on slopes that exceed 40% (22^{O}). Very few manufacturers however publish slope limits for their machinery, and anecdotal information indicates that New Zealand harvesting machines regularly exceed these guidelines.

The onus is on contracting firms (employers) and operators (employees) to take all practicable steps to ensure the safety of employees and themselves while at work. In particular to ensure that machinery and equipment is safe and that the working arrangements are not hazardous. Clearly slope is not the only factor that should be considered when assessing safe operations on steep terrain. Soil bearing capacity and the vehicle-terrain interface are also important, as is the operator skill factor (Heinimann, 1999). Limitations of steep slope harvesting technology have been considered by various groups over the last four decades. In the early 1970s ground-based extraction machines had made considerable progress, whereas mechanised felling and processing technology was only just emerging on gentle terrain. 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 initial limits had to be reduced in order to keep soil erosion within acceptable limits (Heinimann, 1999). The slope values of 30% and 40% for wheeled and tracked machines respectively therefore were related primarily to machine traction and soil erosion, and these values have since been presented and propagated in many subsequent documents and guidelines.

With new developments in steep slope machinery, many safety organisations have revised these 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

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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 per cent;
(b) crawler tractors, feller-bunchers, excavator harvesters or similar machines should not be operated on a slope which exceeds 40 per cent; and
(c) any other forestry equipment specifically designed for use on steep slopes should not be operated on a slope which exceeds 50 per cent".

Further work by European researchers expanded the considerations and understanding of steep terrain machinery and their constraints. New 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 (Figure 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-assisted" or traction winch technology.

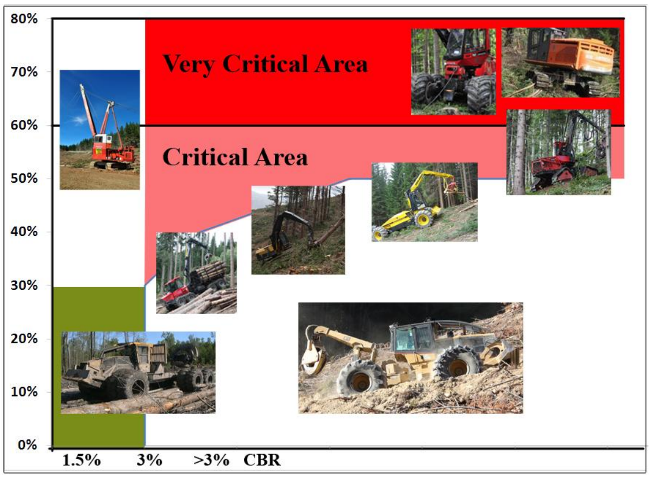

Figure 1: Safe operating range of ground-based harvesting machines related to terrain slope (%) and soil bearing capacity, as measured by California Bearing Ratio (after Heinimann, 1995).

The Workers' Compensation Board of British Columbia (WorkSafeBC) 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's stability during operation."

In July 2011, the British Columbia Forest Safety Council, a not-for-profit society dedicated to promoting forest safety in the sector, developed a steep slope resource package to help manage safety of operations on slopes that exceed the BC guidelines. Part 1 of this resource package is a Steep Slope Hazard Assessment Tool, a method of evaluating site-specific and machine-specific hazards and developing 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. (BCForestSafe, 2011).

In order to better understand the types of slopes on which New Zealand tree felling and extraction machines are operating, and the impacts ground slopes have on the stability of these machines, it is necessary to measure the performance of individual machines. The aim of this research was to improve the knowledge and understanding around the conditions that forestry machines encounter on steep terrain. This information could be used to aid in appropriate harvest planning, and in machine hazard management by contractors and operators during the harvesting operation. It could also assist in reassessing the guidelines for ground-based machine operation.

DATA COLLECTION METHODS

A digital accelerometer was attached to 22 forest machines to provide real-time measurements. The machines were also tracked with a GPS unit to give machine location. The study sites were selected by the forest management company at the time of visit, with preference given to contractor operations using the selected type of machinery on steep sites. The study areas in New Zealand included Canterbury, Nelson/ Marlborough and Otago. The study areas in Europe were located in the Lillehammer region in

Norway and the states of Carinthia and Lower Austria in Austria.

Each evaluated machine was grouped into one of four machine types: feller bunchers (n=4); “shovel loggers” (n=5); skidders (n=9); and European purpose-built steep terrain machines (n=4).

The machine types were then analysed with respect to their machine slope (actual) and terrain slope (predicted), based on a digital terrain map. The calculation of terrain slope was done using 20-metre and, when available, 10-metre contour data for the New Zealand operations, and 5-metre contour data in the European sample. The raw data were screened to remove longer periods (>10 minutes) of the machine being stationary. Stationary periods were normally associated with both the machine and the terrain slope having very low values, which is consistent with the machine being parked for an operator break, maintenance or refuelling. As such the data presented is for “work only”.

Evaluation of Terrain Slope

Deriving a continuous slope surface from contour data in a Geographic Information System (GIS) such as ArcMap can be achieved in two ways; one was based on a triangular irregular network (TIN) file and the other was based on a raster file.

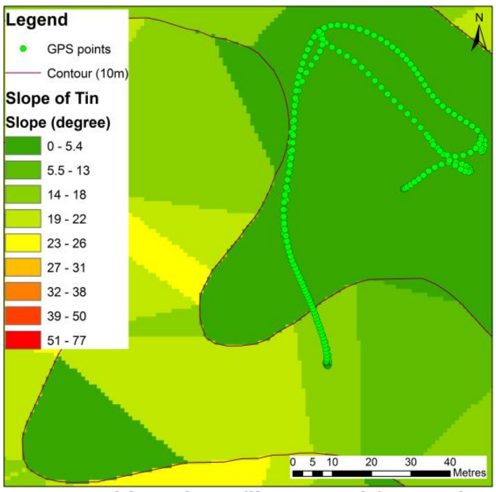

Figure 2: Resulting slope file created from Triangular Irregular Network (TIN). Where a contour curves back on itself (i.e. on a ridgeline) the TIN incorrectly assumes a flat area.

Although the TIN method is most common for calculating and presenting terrain slope, it resulted in a large proportion of zero terrain slope values. The flat areas of a TIN file result from a triangle that is formed from three points at the same elevation value (Figure 2).

Raster refers to a type of spatial data used by a GIS that consists of rows and columns of rectangular cells. Each cell contains values or attributes for that particular layer, e.g. if the layer is elevation, then the attributes will contain elevation values in metres. The raster method divides the map area into smaller squares and then calculates an average slope for each square. This method showed an advantage over using the TIN file as it provided a better representation of slope for the purpose of relating slope to machine location (Figure 3). More complete analyses of slopes can be found in Berkett (2012).

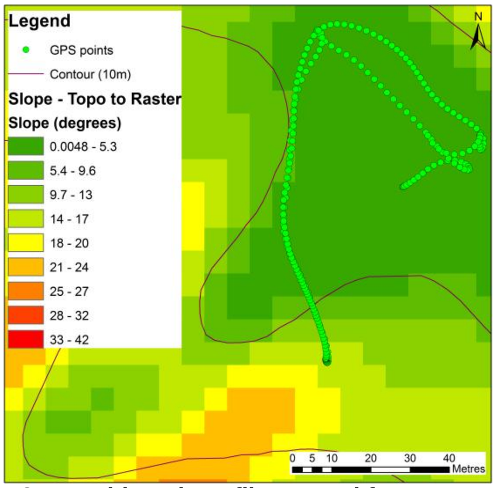

Figure 3: Resulting slope file created from raster data.

RESULTS

Machine Slope vs. Terrain Slope

Results of slope measurements are given in Table 1 overleaf. This Table shows the average and 95th percentile for each individual machine slope and terrain slopes (using the raster method), and overall averages for the four machine types. Of the four machine types measured, the felling machines were operating on the steepest slopes with regards to real-time machine slope.

The difference between the machine slope measured and the terrain slope was also determined. A positive value indicated that the machine slope was greater than the slope of the terrain on which the machine was working. Conversely, a negative difference indicated that the machine had positioned itself on the terrain to minimise its slope.

Analysis showed that there was a significant difference at the 0.05 significance level, between machine slope and terrain slope for the four machine types: felling, shovelling, skidder, or European. It was concluded that the four machine types experienced different machine slopes in comparison to the slope of the terrain on which they operated.

Table 1: Machine slope and terrain slope for each study, as well as category grouped averages. The last column presents the difference between machine and terrain slope.

	Machine slope (95th %)	Terrain slope (95th %)	Difference
Feller	22.9 (31.9)	25.0 (33.6)	-2.1
Feller	14.1 (22.0)	15.7 (19.0)	-1.7
Feller	22.4 (36.4)	16.6 (24.8)	5.8
Feller	15.2 (26.3)	10.2 (16.4)	5.0
Average	**18.6 (29.1)**	**16.9 (23.4)**	**1.8**
Shovel	23.5 (33.0)	13.7 (20.8)	9.8
Shovel	14.4 (25.6)	15.5 (18.0)	-1.2
Shovel*	14.2 (24.1)	6.8 (9.8)	7.5
Shovel*	16.3 (24.5)	15.4 (18.3)	0.9
Shovel	21.1 (33.1)	16.8 (21.4)	4.3
Average	**17.9 (28.1)**	**13.6 (17.7)**	**4.3**
Skidder	17.1 (29.1)	17.6 (33.0)	-0.6
Skidder	17.2 (26.3)	17.5 (33.0)	-0.3
Skidder	6.4 (9.5)	13.4 (26.6)	-6.9
Skidder	17.9 (29.9)	9.9 (18.4)	8.0
Skidder	14.3 (23.1)	17.9 (21.4)	-3.5
Skidder	14.4 (22.2)	12.0 (18.5)	2.3
Skidder*	11.6 (19.2)	16.2 (21.8)	-4.6
Skidder*	13.1 (21.1)	16.0 (21.8)	-2.8
Skidder	16.1 (23.9)	13.6 (16.3)	2.5
Average	**14.3 (22.7)**	**14.9 (23.4)**	**-0.5**
Harvester**	22.2 (36.5)	19.5 (21.0)	2.7
Harvester**	20.7 (35.6)	19.7 (30.1)	1.0
Forwarder**	13.8 (24.9)	21.7 (33.3)	-7.9
Harvester**	11.1 (16.8)	16.0 (23.0)	-4.9
Average	**17.0 (28.5)**	**19.2 (26.8)**	**-2.2**

(Note: Slope calculated from 10 m DTM using raster method, except *used 20 m DTM and **used 5 m DTM)

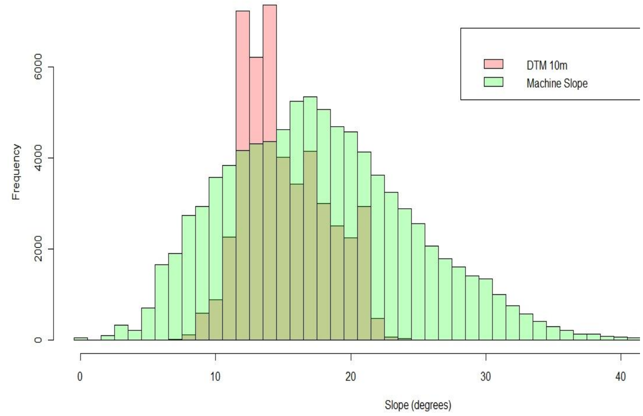

Figure 4: Histogram showing machine and terrain slope data for all shovel machines.

An example histogram illustrates this point for the shovel logging machines (Figure 4). The green bars show the distribution of all the machine slope data points, ranging from 0 through to 40 degrees. The corresponding terrain slope data derived from 10-metre DTM data points are however clustered mostly between 12 and 20 degrees with a maximum slope of 24 degrees. In this case the average machine slope of 17.9 degrees exceeded the average terrain slope of 13.6 degrees significantly.

Machine Slope Relative to ACOP Limits

Analysis was carried out to determine the percentage of time each machine spent exceeding the limits based on the ACOP guidelines applicable to each respective machine type (Table 2). This was done under the assumption that none of the machines in the study had manufacturer's specifications regarding their maximum slope. The percentages are based on the number of recordings when the machine was in excess of the ACOP slope limits, relative to the total time the machine type was working.

The major causes of the disparity between the percentage of time spent in excess of the limit for the machine slope and the terrain slope is a result of differing machine operators and operator techniques and the digital terrain model (DTM) poorly predicting actual terrain slope. Other factors may have influenced the result as well. The maps generated, on which the terrain slope was based, do not show any skid trails that the machines were operating on. In fact nearly all data sets showed that on very steep terrain machine slope was lower, indicating that the operator was more careful with machine placement and movement or that the machine was on a skid trail.

Table 2: Proportion of time spent operating in excess of ACOP guidelines based on machine slope and the raster method of DTM-based terrain slope calculation

	Machine slope	Terrain slope - Raster
Feller 1	59%	70%
Feller 2	6%	0%
Feller 3	46%	38%
Feller 4	18%	0%
Feller Average	**32%**	**27%**
Shovel 1	58%	0%
Shovel 2	11%	0%
Shovel 3	11%	2%
Shovel 4	12%	0%
Shovel 5	41%	2%
Shovel Average	**27%**	**1%**
Skidder 1	43%	34%
Skidder 2	51%	32%
Skidder 3	0%	36%
Skidder 4	51%	14%
Skidder 5	29%	61%
Skidder 6	33%	20%
Skidder 7	46%	0%
Skidder 8	14%	40%
Skidder 9	21%	37%
Skidder Average	**32%**	**29%**
Harvester 1	82%	96%
Harvester 2	38%	46%
Forwarder 1	31%	82%
Harvester 3	4%	33%
European Average	**39%**	**64%**

While the overall averages for each machine type were within the ACOP guidelines for terrain slope, individual machines were exceeding these limits for a large proportion of operating time. This was true for most machines. There were also a number of extreme events involving very steep machine slopes, up to 45 degrees (100 percent). Eight New Zealand machines spent more than one-third of operating time in excess of the respective ACOP limits.

One concern is the disparity between the percentage of time spent in excess of the associated machine slope limit based on DTM-derived terrain slope and the actual machine slope recorded. Based on actual machine slope all three types of New Zealand forestry machines had, on average, spent a higher proportion of time exceeding the ACOP limits. Although the data are variable, this suggests that the machines were experiencing a higher slope than would have been expected from the influence of the terrain alone. This has implications for overall machine stability of New Zealand forestry machines.

The European machines showed the opposite trend to the New Zealand machines, whereby the proportion of time exceeding the ACOP limits based on machine slope was lower, on average, than that based on terrain slope. Given the higher resolution of the DTM, some inferences about the individual machines can be made. All four of the machines showed a higher frequency of “over limit” values based on DTM terrain slope than machine slope. The two Norwegian-based machines showed a very large difference, with over 30% more time “over limit” for terrain slope than machine slope. The Austrian machines showed a lesser difference in proportion of time “over limits”. The key difference between the two European countries, the machines being almost identical, was that the use of skid trails was permitted in Norway and not in Austria.

DISCUSSION

The New Zealand forestry sector has largely adopted the North American style of forest harvesting regarding machine types, with a large population of skidders and excavator-based loaders. This is a very different approach to forest harvesting in comparison to Europe, where forwarders and purpose-built forestry machines designed for steep slopes are common. The adoption of purpose-built forestry machines into the New Zealand forestry sector has been minimal, mainly for cost reasons.

New Zealand’s harvesting machines are typically based around modified excavators for tree felling and shovel logging. Excavators are designed for heavy construction, demolition and excavation work from a stationary position. These machines have a high centre of gravity, and the ability to swing a large mass around a central point (slewing) results in large changes in load distribution, and they are rigid across the track base. When applied to a tree felling role, this track rigidity causes the machine to experience a large amount of vehicle sway and tilt as a result of travelling over uneven terrain. Although the velocity of slope change or the effect of dynamic changes in load was not included in this study, these are considered to be key factors that affect machine stability (Eger and Kiencke, 2003).

Figure 5: Komatsu 911 Snake harvester showing the advantage of passive bogie quad tracks.

In contrast, European machines utilise a front bogie wheel in the case of the six-wheeled harvesting machines, and rear bogie wheels on the six-wheeled forwarders. The Valmet Snake harvester (Figure 5) uses four trapezoidal rigid tracks mounted in the same way as the bogie wheels (passive bogies). Note in Figure 5 that the front visible track is on a different plane to the two rear tracks, but all four tracks remain in full contact with the ground surface enabling the machine to remain stable.

In wheeled forwarders the use of the passive bogie wheels allows for the machine to manoeuvre over obstacles (Figure 6), without the whole machine swaying.

Figure 6: Showing the advantage of a passive bogie wheel as the vehicle negotiates over a boulder.

When a rigid track moves over an obstacle the whole machine is forced up and over the obstacle, resulting in very rapid changes in machine slope (***Figure*** 7).

Another major difference is that New Zealand's forest excavators tend to zigzag up and down a slope, felling trees to one side as the machine moves slowly across the slope. This is in part due to the clear felling nature of New Zealand forestry, as well as the minimal advantage the rigid track system provides to stability when orientated down slope. European machines tend to operate directly up and down the slope, and almost exclusively down slope in the case of forwarders. The longer, more slender, machine (relatively) is much more stable when operated down slope than cross-slope.

Figure 7: Showing a rigid track machine experiencing excessive slope due to an obstacle.

CONCLUSION

This study showed that some machines sampled operated on slopes that exceeded the ACoP guidelines of 30% and 40% slope for wheeled and tracked machines respectively. It also showed that these machines exceeded the guidelines often and for long periods of time (over one third of operating time in some cases). Managing stability of ground-based machines will become of greater concern to forestry companies and contractors as the harvest moves on to steeper terrain over the next few years.

This study showed that there was a significant difference between terrain slope and machine slope, and that using a 20- or 10-meter contour map to predict machine slope is erroneous. Although 5-meter contour maps improve predictability, consideration should be given to investigating LiDAR-based topographic data for sub-metre contour maps. The reality is that the roughness of New Zealand's terrain, the use of skid trails on steeper slopes, and the nature of conventional harvesting operations can

cause machines to behave relatively independently of the slope on which they are working.

There appears to be a clear advantage in the European-type undercarriage that was used by all four machines studied in Europe. Independent axles with bogie wheels or tracks aided machine stability, enabling each machine to operate on very steep terrain while keeping the actual machine slope within a safe level.

The new international standards for operating machinery on steep slopes, as well as the empirical data presented in this report could give rise to a review of our ACOP and the stated limits. Finally, management plans for machinery operating beyond ACOP guidelines should be developed.

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