Stability Analysis of Timber Cribbed Road Fill on a Steep Slope

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ABSTRACT - In an effort to minimize the hazard that results from traditional cut/sidecast road construction on steep slopes, forestry companies operating under the BC Forest Practices Code Act have been forced to utilize the more expensive full bench, end haul technique. Historically, roads have been successfully constructed using timber cribs braced against stumps to support the fill, but the stability of such construction has never been measured. This technique potentially offers a lower cost, environmentally less disruptive alternative to full bench endhaul construction.

In order to quantify the stability and the feasibility of a stump supported timber cribbed road fill on a steep slope, a 250 m test section of road was constructed. It was hoped that this test would identify the critical components on the support structure, provide recommendations on how to improve the technique for the construction of short-term roads, and if possible, develop a monitoring system to alert operators of movement of the crib.

There are four main components to the current project:

- Develop a model of the slope using the geometry from the site and parameters based upon geotechnical correlations and published information.
- A stump pulling exercise to measure the pull-out resistance of stumps (reported by others).
- An instrumented loading of the crib under typical yarding operations.
- Refine and analyze the model based upon the measured values from the stump pull and loading operation.

This paper will present some background information, a description of the site, and detailed results of the instrumented load test.

Keywords: alternate road construction, endhaul, factor of safety, forest road

BACKGROUND

Historically, logging roads in British Columbia were conventionally constructed by cut and sidecast construction methods. These methods were also often used on steep terrain. Less frequently, these historical haul roads were constructed using earthfill retained by logs laid between tree stumps, (herein referred to as stump crib construction). The advantage of this form of construction was cost savings by reducing the width of the required road bench as well as lessening the potential for fillslope failure (in the short term). These roads were typically constructed without an engineering analysis and often left in place after logging was complete. This has lead to failures of the fill slope due to overloading of the structural elements (logs and stumps) or due to deterioration of their strength over time as they decay.

The recently adopted Forest Practice Code Act of British Columbia addressed this issue. Current forestry regulation for logging practices on Crown land require a qualified registered professional to assess all road locations proposed on slopes of greater than 60%. On such slopes, the standard recommendation is to build using “full bench and end haul” construction methods. With this method, the entire width of the roadway is cut into the slope. The material removed is hauled away for disposal or for fill on another section of the road. This method is both time consuming and expensive, particularly in the case of logging spur roads which have a limited life (three years or less). The method has also been proven to be unsuitable in many situations because it transfers the problem for potential fillslope failure to the greater potential of cutslope instability.

Weyerhaeuser approached EBA Engineering Consultants Ltd. (EBA) to undertake an analysis of a section of road, which was to be supported, by a stump crib structure. The section under study was to be used for yarding logs uphill to the spur road L8D utilizing a Madill 044 Grapple Yarder. Cost to build this 250 m long section of road was about $40/m (Cdn) compared to a typical cost of $200/m (Cdn) for full bench endhaul construction. That is, the cost of the stump crib construction method is comparable to conventional construction methods.

It became apparent that there were several components of the analysis for which the parameters were not well known; these included:

- The loads imparted by a grapple yarder during yarding.
- The "pullout" resistance offered by stumps.
- The most critical failure mechanism.

Using available information and sensitivity analyses, it was assessed that the Factor of Safety (FoS) against fill slope failure was 1.4 for static conditions and 1.1 for dynamic conditions.

Due to the uncertainties involved in this analysis, the study which will be described herein, was undertaken with the following objectives:

- Measure the load imparted on the road fill by a grapple yarder during yarding.
- Measure the “pullout” resistance offered by Douglas-fir stumps in the area of Road L8D.
- To determine if the loads imparted by the yarder are transferred to the stump crib.
- To determine if the most critical failure mechanism can be identified.
- To establish a method of monitoring the performance of the stump crib structure during yarding.

SITE CONDITIONS

The site is located along spur Road L8D which is located in east Vancouver Island, BC. A location plan is attached as Figure 1. It is approximately 30 km west of Ladysmith, just south of Jump Lake. The road is situated near the top of an east facing slope approximately 400 m in elevation above South Fork Jump Creek, which flows to the north into Jump Lake.

The road is at an elevation of approximately 1000 m above sea level, thus it is in the snow accumulation zone. On Vancouver Island, the zone from 300 m to 800 m above sea level is susceptible to rain-on-snow events.

A failure of the fill from Road L8D is likely to reach South Fork Jump Creek and introduce sediment to Jump Lake, which is part of the water supply system for the Regional District of Nanaimo.

The slope in the area of L8D is typically 30° to 35° (58% to 70%). The subsurface conditions include a veneer of well drained, gravelly colluvium in a silty sand matrix overlying granitic bedrock, which is exposed in places.

The vegetation, in the area, consists of old-growth Douglas-fir and some hemlock with an average breast height diameter of 1.2 m and an average rooting depth of 1.0 m to 1.5 m.

Road L8D is a short-term road, which was constructed in the autumn of 1999 and was permanently deactivated in the autumn of 2001.

A typical section through the completed road is given on Figure 2. It includes a 3 m to 4 m wide rock bench with sidecast rockfill supported on logs. The rockfill, which has been placed on the surficial organic layer and colluvium, forms a 1 horizontal to 1 vertical (1H:1V) slope. The cut slope varies in height up to 4 m and the fill slope varies in height up to 4 m.

PROJECT TEAM

This study involved input (of time and money) from several sources. The main participants are:

- Weyerhaeuser Nanaimo Woodlands, who coordinated the study.
- Weyerhaeuser South Island Timberlands, who provided funding, manpower and equipment.
- FERIC, who undertook the stump pull component and assisted with data collection.
- EBA Engineering Consultants Ltd., who completed the stability analyses and did data interpretation.
- RST Technical, who supplied and installed the instrumentation and assisted with data collection.

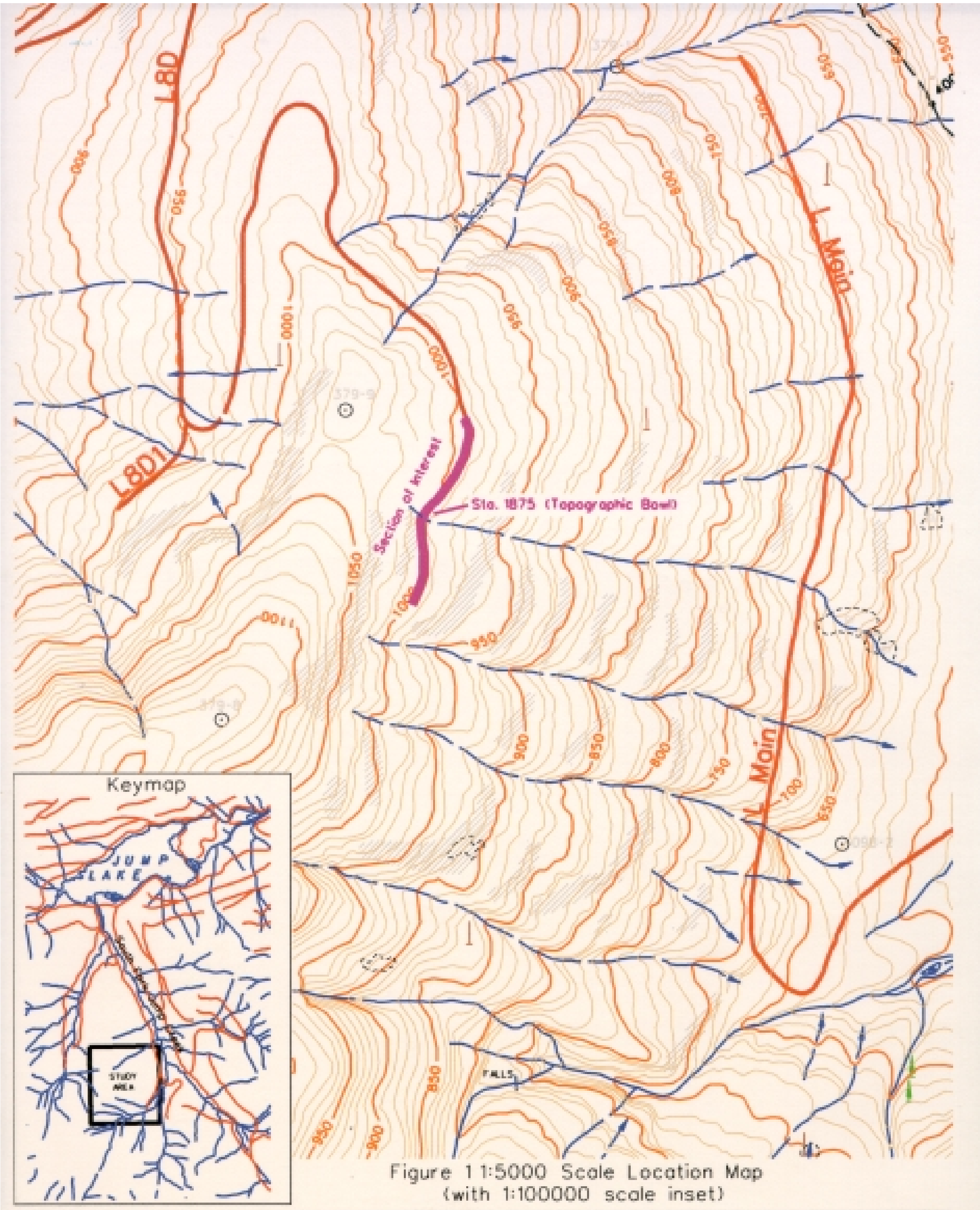
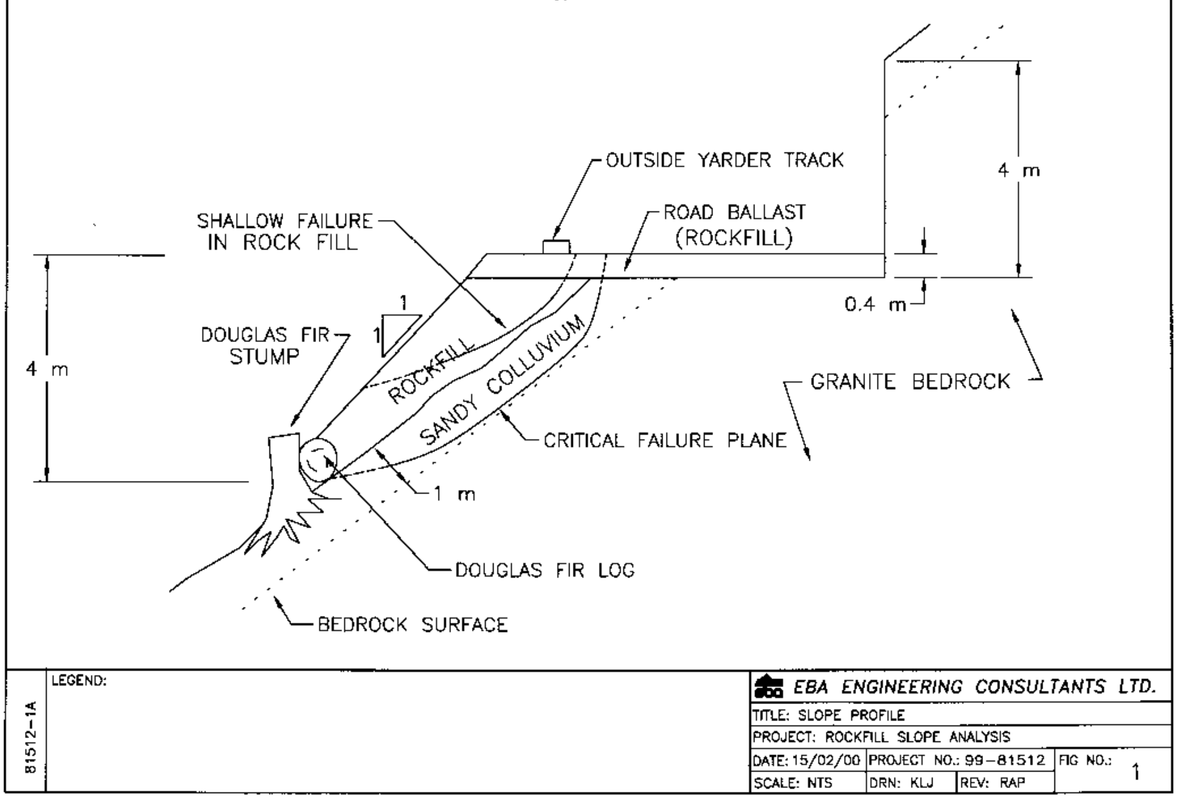


Figure 1 1:5000 Scale Location Map
(with 1:100000 scale inset)

Figure 2 Typical Section



INITIAL ANALYSIS

It became evident that several of the key parameters required for the analysis were not readily available. A typical section, as shown in Figure 2, was used in the stability model and soil parameters derived from published information *(J.E. Bowles, T.M. Leps, US Department of Agriculture)* and experience with similar materials.

Table 1

Material	**Cohesion kPa**	**∅’ Degrees**	**Unit Weight kN/m^3**
Rockfill	0	55	21
Colluvium	10	35	20
Colluvium/Rock Interface	0	26	N/A
Bedrock*****	N/A	N/A	N/A

*****It was assumed that the failure surface would not penetrate the bedrock.

During the static load condition, it was assumed that the load from the grapple yarder was the weight evenly distributed on both tracks, equating to a line load of approximately 200 kN/m (365 kN/m^2 on 0.6 m wide track) at a location 1 m from the edge of the road (for these analyses, the line load was used).

For the dynamic case, it was assumed that all the weight was on one track, creating a line load of 400 kN/m (666 kN/m^2 on 0.6 m wide track).

Extrapolating the work by M.R. Pytes, J.W. Anderson and S.G. Stafford as reported by Mike Wise for the larger stump diameters at L8D, the stump resistance was taken to be 400 kN using an average stump spacing distance of 4 m.

The analysis indicated the critical failure surface ran along the colluvium bedrock interface before emerging near the stump. The resulting Factors of Safety (FoS) for the static and dynamic conditions were 1.4 and 1.1 respectively.

This analysis was used to design the L8D field testing. The critical parameters to be established were the grapple yarder loading and the stump resistance. To a lesser degree, the soil strength parameters and location of the failure place were to be investigated.

STUMP PULL

As part of a Forest Renewal British Columbia funded research project in 1999, Forest Engineering Research Institute of Canada (FERIC) completed a literature search for the results of stump pull testing. FERIC referenced work by M.R. Pyles, J.W. Anderson and S.G. Stafford (1991) which included testing of Douglas-fir stumps rooted in sandy silt on 37% slopes. The trees tested had diameters of 180 mm to 420 mm and the measured pullout resistance was 50 kN to 275 kN.

These tests were completed by pulling the stumps in a direction parallel to the ground surface and failure was by rotation.

FERIC developed a cable and pulley system, which could be used to pull on stumps in the area of L8D. The details and results of this testing are provided in a companion paper by FERIC.

Eight Douglas-fir stumps ranging in diameter from 280 mm to 810 mm were tested. Displacement of the stumps was measured using an extensometer connected to a data logger. Figure 3 shows the results of the testing. The ultimate strength is plotted against stump diameter. When the ultimate strength was recorded, the stumps had undergone significant deformation, 300+ mm in some instances.

The 'elastic' resistance of the stumps ranged from 150 kN to 425 kN. The 'elastic' resistance is defined for the purposes of this analysis as the load at which there is negligible permanent displacement once the load is removed.

Also of interest is the shape of the load deformation curve, Figure 4. After a near vertical 'elastic' section, there is a yielding or 'plastic' deformation during which there is deformation (10 mm to 15 mm). Beyond this, there is deformation without any significant increase in resistance. The ‘elastic’ resistance is typically 40% to 50% of the ultimate resistance.

LOADING FROM GRAPPLE YARDER

The grapple yarder to be used on this road was a Madill 044 which has a total weight of approximately 1070 kW (120 tons) and rests on tracks which are 0.6 m wide by 4.9 m long. During actual yarding conditions, very occasionally the yarder rests on one track, a load of approximately 365 kN/m^2. In addition to this, there will be dynamic loading during yarding.

No case studies where the actual loading from a yarder had been measured could be found; therefore, a program was developed which included burying three total earth pressure cells in a line under the edge of the road where the outside track would rest.

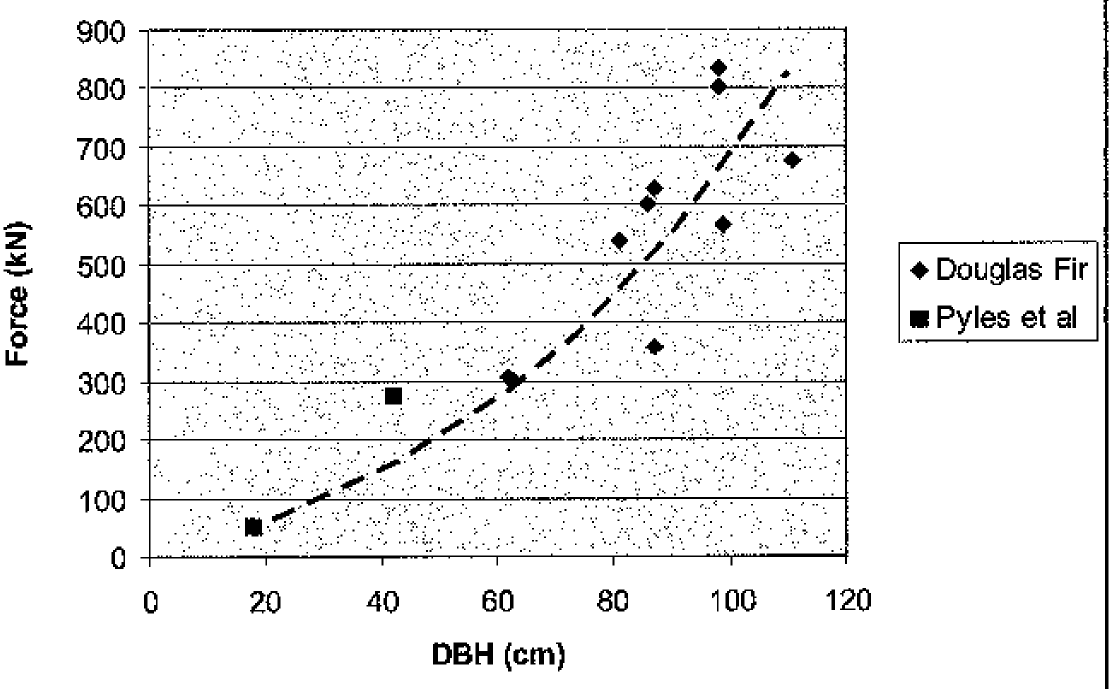


Figure 3: Relationship of Ultimate Strength with Estimated DBH

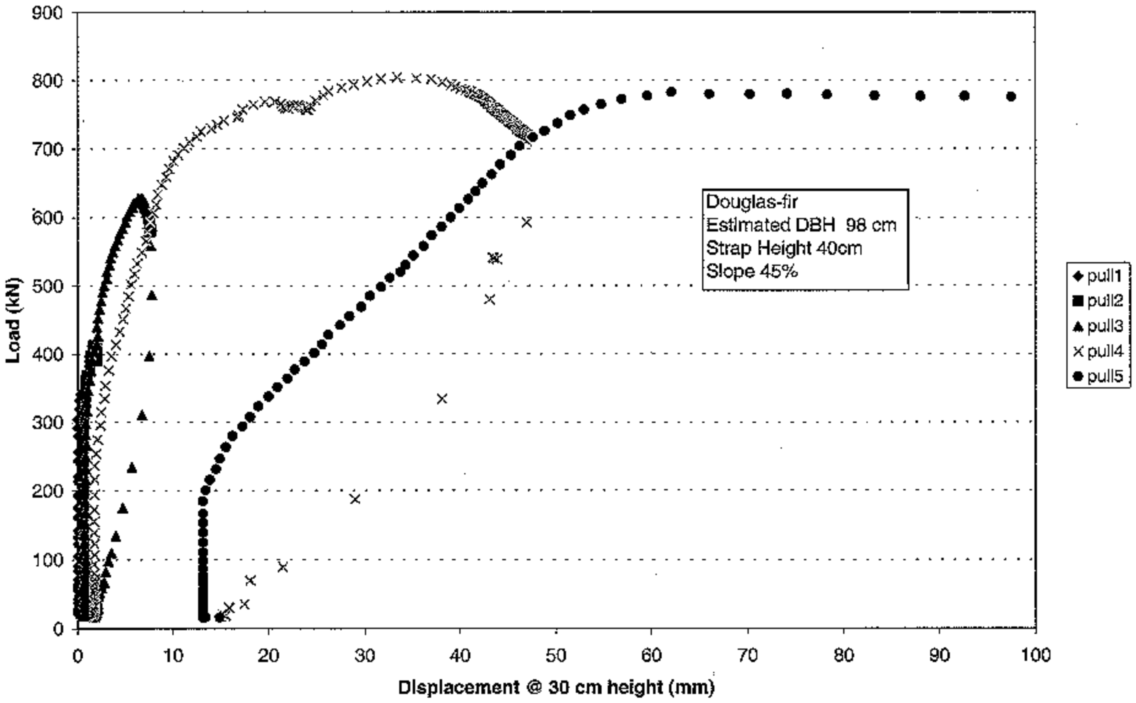
A 0.7 m deep excavation was made, the base leveled using fine to medium silica sand. The 9” diameter cells (RST Technical Model TP-101-P) were placed approximately 2.2 m apart, then covered by 50 mm of silica sand and the remainder infilled with granular fill from the initial excavation.

Cables from the earth pressure cells were buried to protect them from the yarder and logging truck traffic and connected to a multi-channel data logger.

During yarding operations over a two-day period, the highest loads were measured at the middle earth pressure cell, refer to Figure 5. Static loading at the load cell was approximately 120 kPa (18 psi). During yarding, the loading typically reached 345 kPa (50 psi) and peaked to near 480 kPa (70 psi). These peak loads occurred when the cables supporting the yarder were slackened and initial lift of a log was occurring. These correspond to loads at the road surface of:

	Track Pressure	Line Load
Static	240 kPa	400 kN
Dynamic	700 kPa	1170 kN
Peak	960 kPa	1600 kN

Figure 4 Load Displacement Curve



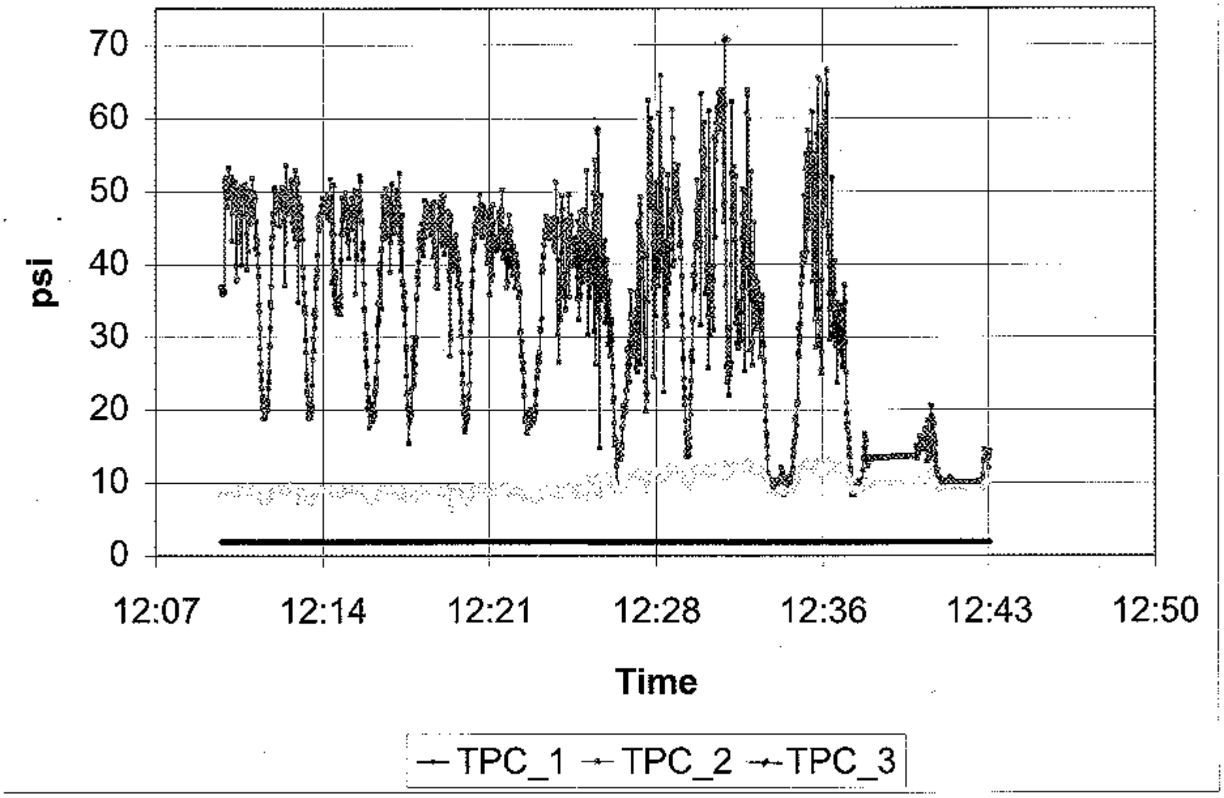
STUMP MOVEMENT

A stump, located immediately downslope of the grapple yarder during the testing and part of the stump crib structure, was equipped with an X, Y axis tiltmeter (RST Model #IC6505) to determine if the loading from the operation translated to the crib stump (Figure 6). The tiltmeter was fastened to the top of the stump such that it measured tilt in the downslope (Y axis) and cross-slope (X axis) movement. The output was recorded by the data logger.

Very little movement, refer to Figure 7, 0.68° tilt in the Y direction (downslope) was recorded at one point during the yarding. Typical movements were much less than this, in the range of 0.1°. Although it was difficult to correlate the downslope movement at the stump with the timing of the loads applied by the grapple yarder, there was definitely some deformation in this axis. In order to correlate the loads imparted on the stump with those measured in the stump pull, the tilt can be used to predict the movement of the stump. For a 1.5 m high stump, this would be a downslope movement of less than 1 mm at a height of 300 mm.

This is well within the 'elastic' resistance range and may indicate that the stump was being loaded by the yarding operation. As well, there is a very minor permanent displacement, 0.02°, which indicates that the resistance provided by the stump may not be completely elastic.

Figure 5 Dynamic Loading by Grapple Yarder during Yarding Activities



SLOPE MOVEMENT

An effort was made to measure the deformation of the fill supported by the stump crib structure during yarding. A tank drill was used to bore a 76 mm diameter hole through the fill and overburden and into the rock. A 70 mm diameter slope inclinometer casing was placed in the hole. The hole encountered 1.2 m of rock fill overlying 3.2 m of overburden.

One in-place inclinometer was installed in the casing, near the overburden fill interface. The leads were connected to the data logger.

Very little movement (0.04°) was recorded and it could not be correlated with the timing of the yarder loading.

These results are inconclusive and deformation may be disguised by the fact that the movement is lateral and not tilting; therefore, the inclinometer may not measure it.

STABILITY ANALYSIS

The results of the field trials were used to re-evaluate the stability. As no further information was gathered regarding the soil strength parameters or critical failure surface, these were not altered from the initial analysis.

FIGURE 6: Views showing stump crib construction on L8D

A) Area of stump crib construction on spur Road L8D is shown by the red box.

C) Location of instrumentation at Sta. 1875 (as shown in Fig.1). Three load cells are located below the circled grapple yarder tracks; inclinometer is the circled red standpipe located in the fillslope just below the yarder tracks; and the tiltmeter located on the circled stump on the left hand side of the photograph.

B) View south showing the log crib structure shortly after construction in Fall 1999.

D) View of the stump on which the tiltmeter was ultimately installed.

E) View south showing the grapple yarder and loader yarding logs to the stump crib constructed section of road. This is the same section of road shown in (B) and (C).

However, the loading from the grapple yarder was increased from a line load of 200 kN to 400 kN for the static case and from 400 kN to 1170 kN for the dynamic case. An analysis of the peak dynamic load of 1600 kN was also carried out.

Based on the results of the stump pull tests, and a stump diameter of approximately 900 mm, an ultimate resistance of 150 kN/m was estimated.

The results of the stability analysis are provided below:

Load Condition	Factor of Safety (FoS)
Static	1.35
Dynamic	1.16
Peak	1.02

It should be noted that these FoS are based on the ultimate resistance of the crib stump structure and will involve some downslope movement.

The analysis was also performed assuming the soil was drained.

To assess the effect of a water table, the dynamic condition was analyzed with a water table. The dynamic condition was analyzed with a phreatic surface at the top of the colluvium. This resulted in the FoS dropping below 1.0 to 0.85.

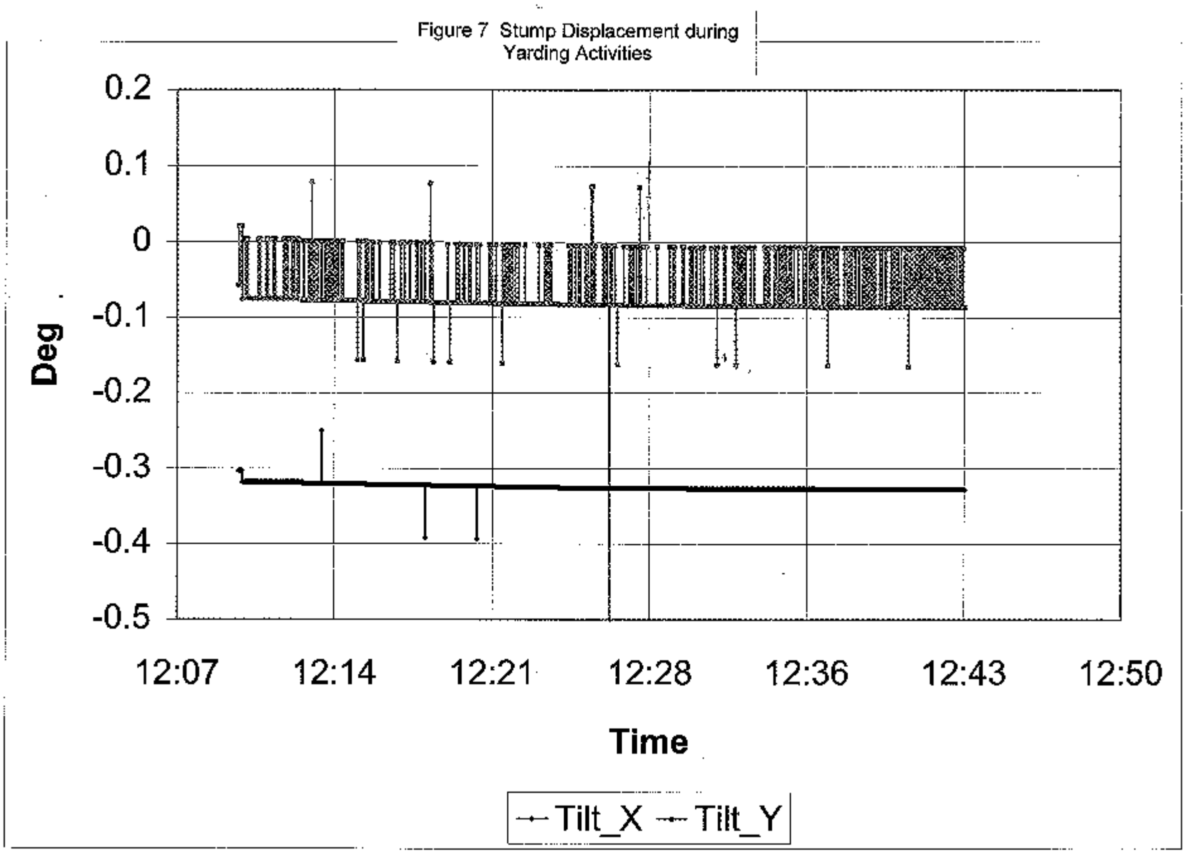


Figure 7 Stump Displacement during Yarding Activities

DISCUSSION

The results of the stump pull testing agree reasonably well with the results published by M.R. Pyles, J.W. Anderson and S.G. Stafford. As can be seen in Figure 3, which is a plot of both sets of results, there is a definite trend to more ultimate resistance for larger diameter stumps.

The actual resistance will be dependent on the health of the stump, the soil and groundwater conditions, the slope, the load application (direction, duration, rate) and the root structure. It must be considered prudent to do site and species specific testing prior to selecting a stump resistance to be used in analysis.

When selecting the value of stump resistance to be used in the analysis, consideration must be given to the duration and frequency of loading. For short term, infrequent loading the ultimate resistance may be appropriate, if some downslope deformation can be accepted. For longer term or more frequent loading, the ‘elastic’ resistance may be appropriate.

The loads measured by the total earth pressure cells will be influenced by the load distribution below the track, the seating of the cell and inherent inaccuracies in the measurements. However, the loads measured provide a good indication of the relationship between the static weight of the yarder and the loading imparted during yarding operations.

The measurements in the fill slope with the in-place inclinometer were unsuccessful. It would likely be more effective to use inclinometer casing buried horizontally across the slope at various levels. This would provide a better indication of the existence and location of downslope deformation than the system used.

The measurements of the tilt of the stump and the soil movement were small and difficult to correlate with the timing of the load application. Therefore, it is not possible to accurately define the failure surface or loading on the stump based on the field measurements.

The results of the stability analysis indicate that for the loads imparted during yarding, the stump loading approached the ultimate resistance. This should have caused deformation of the stump crib structure; however, very little was observed. There are likely two reasons for this. The load applied to the fill, in our analysis, was that recorded at the middle earth pressure cell. The outside ones measured far less load. Therefore, our assumption of the middle loading being representative of the whole track length is conservative. Soils can often resist short duration loads at less deformation than similar loads applied statically. Therefore, some of the soil strength parameters are also likely to be conservative.

CONCLUSIONS

The objectives of this study were to determine:

- Measure the load imparted by a grapple yarder during operations.
- Measure the pullout resistance of stumps.
- Determine the most critical failure mechanism.
- Determine if the loads are transferred to the stump.
- Establish a method of monitoring the stump crib structure.

The loads impacted by a grapple yarder during typical operations were almost three times the static load on the outside track. The loading also peaked to nearly four times the static load.

The pullout resistance of stumps is variable; however, it appears to increase with increased stump diameter for Douglas-fir stumps in silty sand colluvium. The ‘elastic’ resistance can be estimated as 40% to 50% of the ultimate.

Based on computer modeling, the most critical failure mechanism appears to be a surface, which extends through the rockfill and overburden to the overburden/rock interface, that re-emerges near the log. This could not be confirmed by field measurements.

The tilt measured at the stump could not be correlated to the loading from the yarder. However, there was downslope movement measured, which may indicate load transfer.

More information on the load transfer between fill slope and stump crib structure will be required before a monitoring system can be developed. The load deformation curve for the stump pull will provide some basis for this work.

RECOMMENDATIONS

The stump pull testing was successful and provided useful data for the analysis both regarding load deformation and ultimate loading. This technique can be applied to other sites to obtain this data.

More information is required regarding the load transfer from the yarder to the stump crib structure. Additional testing with horizontal in-place inclinometers may be informative.

Stump crib construction appears to be a viable construction method for temporary or short-term roads (<3 years) on steep terrain, and could be considered as a cost-effective alternative to full bench endhaul construction. Due to the uncertainties in the analysis; however, it is recommended that some conservation be built into such analyses. This can be in the selection of a required FoS, the stump resistance or the loading.

Additional study is required to refine a stability model, which better represents the stump crib construction.

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