Business as Usual…or an Engineered Solution?

Modelling forest road construction alternatives

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ABSTRACT

Selecting forest road construction options that protect the environment and are cost effective over time are vital to the performance of the forest industry. Balanced cut and fill constructions were compared with full bench construction using a model, developed in Excel, evaluating earthworks per lineal metre. A stabilised fill construction was formulated as part of this investigation to address areas of steep terrain. The influence of terrain slope and cut slope angles were investigated. It was found that conventional cut and fill construction provides up to 50% less exposed cut batter and total earthworks than a full bench and up to 75% less cut volume. The stabilised alternative requires more total earthworks than a full bench but reduces cut batter slope and cut volume by up to 48% and 46% respectively. The stabilised alternative offers further benefit in a situation where end-hauling is necessary, requiring only the organic topsoil, rather than the entire earthworks as with full bench to be end-hauled.

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INTRODUCTION

Forest road construction carries some of the highest costs and environmental risks of any forestry activity. There is an increasing need for new road infrastructure in New Zealand as a significant portion of the total forest estate is in its first rotation (Fairbrother, Visser, & McGregor, 2009; Neilson, 2012; NZFOA, 2012). This study evaluates the merits of balanced fill construction methods compared with full bench road construction, and makes a case for when the engineered alternative might be most appropriate.

CONSTRUCTION ON STEEP SLOPES

A challenging issue for road construction is areas of steep terrain where slope stability is a concern. This situation is particularly prevalent in the East Cape region of New Zealand, where forestry has been established on especially steep erodible sites. Forest roading manuals suggest full bench construction on very steep and unstable slopes (B. C. Ministry of Forests, 2002; Larcombe, 1999; LeDoux, 2004; NZFOA, 2012; Ryan, Phillips, Ramsay, & Dempsey, 2004). Methods for constructing roads on stabilised fill are also presented by Keller & Sherar (2003). It is suggested that these methods are a suitable construction approach in relatively steep slopes of 40-60%.

The general practice in steep terrain involves full bench construction, where enough material is removed to allow the entire running surface to be located on the competent underlying material (Figure 1). This requires a substantial volume of material to be either end-hauled (at considerable expense), or side-cast (with significant environmental impact).

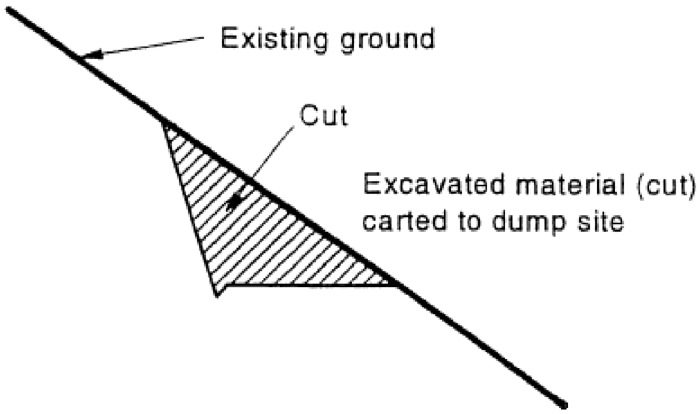

Figure 1: Full Bench Cut & End-hauling

(After Larcombe, 1999, p. 110)

An alternative approach involves cutting an additional key – a smaller bench below the formation height – and constructing part of the road surface on a fill prism. In this case, the fill prism is constructed by re-laying the cut material with some stabilisation measures. Effectively this is a further engineered application of the conventional balanced cut and fill method. A similar construction with multiple benches is shown in Figure 2. This approach still requires substantial earthworks (especially stabilising works) but the volume of end-haul (or side-cast) is reduced and the bench-cut is much smaller. One significant disadvantage of this method is the cost and complexity of implementing an engineered solution. This raises an industry wide question; when does an engineered solution become more worthwhile, or even necessary.

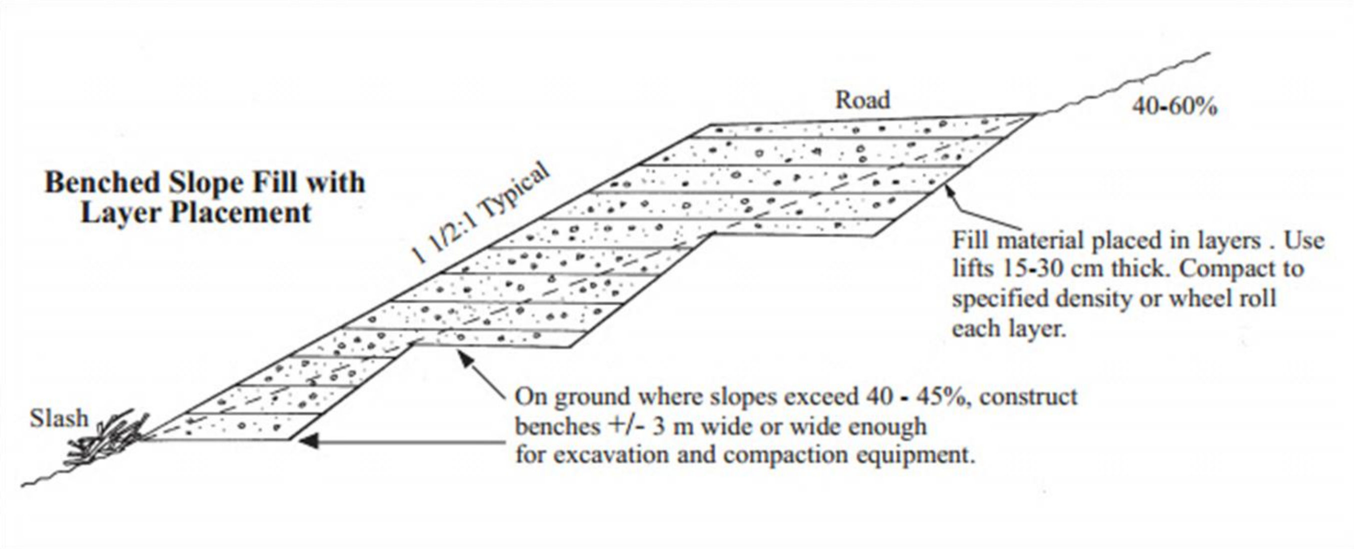

Figure 2: Stabilised Fill

(After Keller & Sherar, 2003, p. 107)

Construction on Gentle Slopes

Even on gentler slopes, full bench construction is often used for forest roads (LeDoux, 2004). On slopes below 40% a balanced cut and fill method can be applied (Keller & Sherar, 2003). Over-subscription in the use of full bench construction stems from concerns that the fill surface in a cut and fill construction may not provide sufficient strength to bear road traffic loads.

Full bench construction on a gentler slope simply entails excavating material and placing it down the slope under the pretence that the resultant side-cast will be sufficiently stable to avoid mass movements.

For the balanced cut and fill approach, fill material excavated from the road cut is compacted to provide part of the running surface (Figure 3). Balanced cut and fill is a recommended means of minimising earthworks in most commonly encountered terrain (Keller & Sherar, 2003).

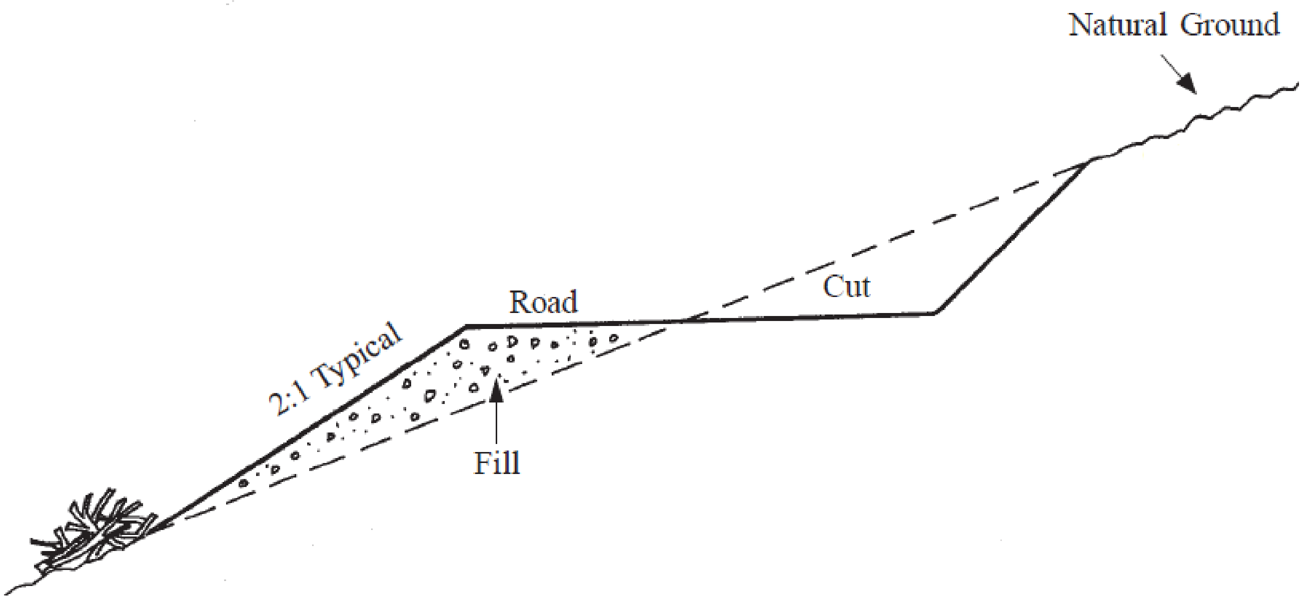

Figure 3: Balanced Cut and Fill
(After Keller & Sherar, 2003, p. 106)

Literary Review

Established Practice

In the earthworks Best Environmental Practices (BEP) guidelines, the New Zealand Forest Owners Association (2007) advocates employing engineering expertise when it is prudent to do so. However, the reader is not directed in how to decide when it is prudent. Due to time pressures and lack of engineering expertise in the forest industry, forest road design efforts are often very minimal (Mills, Pyles, & Thoreson, 2007; Neilson, 2012). Usually the roading contractor has considerable design responsibility, which means much of the design process is empirical. An established construction strategy is followed with local adjustments for areas perceived, from past experiences, to be inherently less structural capable. This mostly ensures a simple and very constructible solution but as with any experiential design there is the tendency to produce a rather conservative solution. This tendency is often exacerbated by the conflicting interests of the contractor, who does not want their design to fail and, most likely, is on an hourly rate (Mills et al., 2007; Neilson, 2012).

Harvesting requirements and climatic conditions often conspire to only provide short planning and construction timeframes. This means a holistic life-cycle analysis is not considered when comparing road construction options and a solution that is known to work is used. Other barriers to implementing more robust engineering practice include the lack of understanding or appreciation of engineering principles among practitioners in general (Neilson, 2012).

Bench Construction

On steep terrain, earthworks represent over 80 percent of the road construction cost (Stückelberger, Heinimann, & Burlet, 2006). During full bench construction, a cut is made into the slope and material is excavated, and either side-cast or endhauled, until the width of the running surface and drainage structures can be located on the mineral soil (Larcombe, 1999; NZFOA, 2012). Evidently, this technique requires a substantial volume of earthworks.

As well as these cost considerations, road construction has significant environmental implications. The New Zealand Forest Owners Association (2012) identify the major potential adverse effects of earthworks to the environment as; accelerated erosion from increased soil exposure and instability, and excessive sediment discharge to waterways. Forest roads contribute 50-90% of the sediment load in plantation forestry (Fransen, Phillips, & Fahey, 2001). Mass movements resulting from slope failure are a major source of sediment. In fact, they have the greatest potential to harm stream ecosystems (Fransen et al., 2001). Removal of soil has significant impacts on slope stability. Therefore, limiting the cut area is of upmost priority during road construction. In the interests of limiting effects on waterways it would seem reasonable to expect endhauling material from a full bench in steep terrain rather than side-casting, which coincides with the recommendation in roading manuals (B. C. Ministry of Forests, 2002; Larcombe, 1999; NZFOA, 2012). However, endhauling is expected to induce a tenfold increase in earthwork costs comparative to cut-and-fill techniques (Larcombe, 1999). Either way, any solution that helps reduce the volume of soil removed is preferred.

Stabilisation

Sub-grade improvement through compaction has been identified as an opportune development for road construction. It is both an effective and low-cost technology. Yet, for the bulk of the industry, dedicated compaction of the sub-grade is either not done or is poorly implemented (Mills et al., 2007; Neilson, 2012). Effective compaction efforts increase soil strength, and decrease permeability. This is best achieved by compacting in several lifts and ensuring that the moisture content is optimal. Compaction appears to be a key mechanism in achieving the necessary fill stability for the challenge presented in this project. Even so, for fills of most soils a fill slope angle of 1½:1 or flatter is required to maintain stability (Keller & Sherar, 2003). For steeper fill slope angles additional stabilisation measures will be necessary. Other established stabilisation measures for steep low-volume roads include retaining structures, mechanical stabilisation, and geo-synthetics (Fannin, 2000; Iordache, Niță, & Clinciu, 2012; Keller & Sherar, 2003; Larcombe, 1999; Swift, 1984). Keller & Sherar (2003) present a reinforced fill design with a 1:1 fill slope angle (Figure 4). This design involves layered placement of compacted fill material with geosynthetic reinforcement between lifts.

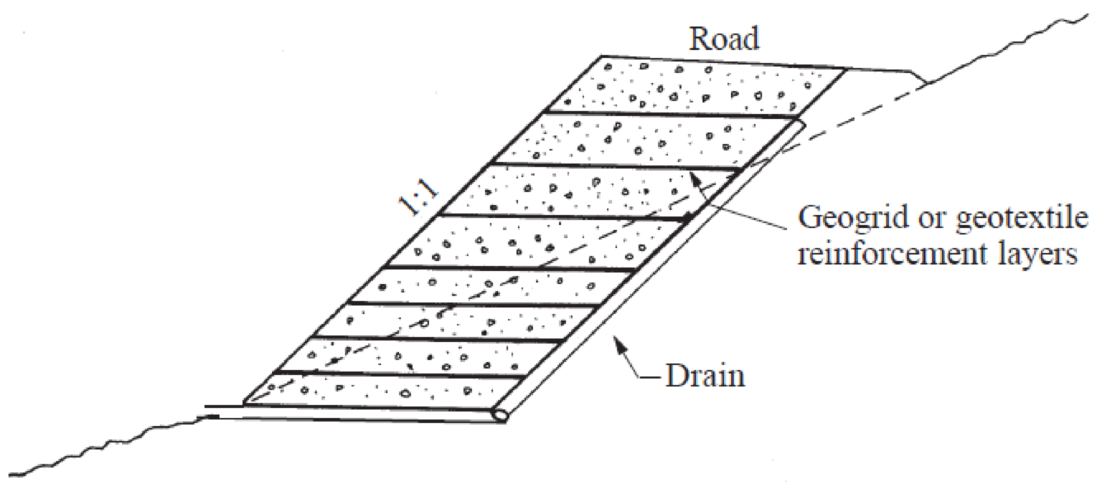

Figure 4: Reinforced Fill

(After Keller & Sherar, 2003, p. 107)

Fannin (2000) presents a case study of a fill slope stabilisation project where a uniaxial geogrid was used. This project was similar in nature to the challenge at hand with the road partially located on a bench in steep terrain (80%), however it was a repair project rather than construction. The unstable fill side of the road was excavated, and re-laid in six layers with geo-synthetics laid in-between and compacted. Although it is difficult to establish whether a similar approach would be cost-effective over a wider scale the general approach seems transferable.

Construction Constraints

The benched fill placement method of construction (Figure 2) is presented as being suitable for slopes of 40-60% (Keller & Sherar, 2003). Below 40% the fill can usually be placed directly on the slope after removal of the organic material. Slope failures typically occur where a slope is over-steep. To retain stability, ¼:1 to ½:1 cut angles are used for very well cemented soils, meanwhile for most soils ¾:1 to 1:1 cut angles are needed. Also as previously mentioned fill slopes are usually stable as built at 1½:1 or flatter, but over-steep constructions – such as 1:1 – can be achieved with stabilisation (B. C. Ministry of Forests, 2002; Garga & O'Shaughnessy, 2000; Keller & Sherar, 2003; Larcombe, 1999; Swift, 1984).

Hypothesis

It was expected that at some stage as the slope increases it will become more prudent to employ a construction method which places the running surface on fill. Specifically, it was anticipated that the fill construction methods will provide lower cut areas and that the relative earthworks volumes and cut areas compared to full bench construction will decrease with increasing slope. Also it is expected that as the cut slope angle is relaxed the relative reduction in cut area – or even total earthworks – will become more pronounced.

METHOD

This study set out to quantify the implications of using a full bench construction compared to a balanced cut and fill construction. Depending on terrain slope this comparison was either a conventional cut and fill or an engineered alternative versus a full bench construction. This was achieved using a spreadsheet based numerical model. The model directly compares the batter slope lengths, excavated material (cut volume), and total earth movement (earthworks) produced by either approach for user defined terrain slopes and cut slope angles.

For the purposes of this model, the full bench approach was conceptualised as a triangular prism cut into the slope (Figure 1). The balanced cut and fill method envisages a somewhat smaller triangular cut prism with the soil from this cut being re-laid downslope and compacted to form another triangular prism of fill with equal soil mass (Figure 3). For the stabilised alternative the cut areas are conceptualised as a main triangular cut prism with a second key cut triangular prism below it (Figure 5). The fill area is a parallelogram built up in lifts with compaction and stabilisation measures applied.

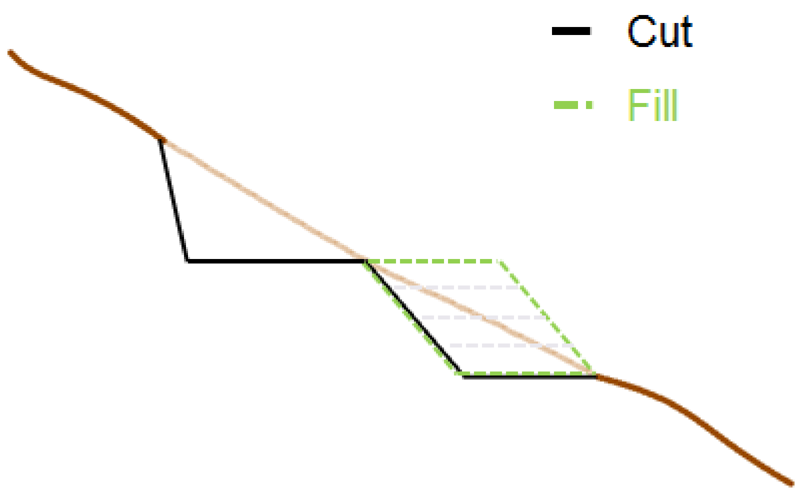

Figure 5: Stabilised Alternative Cut and Fill Construction

A key measure reported for all of these approaches is the batter slope length (denoted X in Figure 6). This represents the area of mineral soil exposed by the cut process. Steep cut slopes used for road construction are difficult to re-vegetate (Claassen & Zasoski, 1998; Keller & Sherar, 2003; Larcombe, 1999). Therefore this area is very vulnerable against erosional processes. This measure is defined as the distance from the top of the mineral soil at the top of the cut to the edge of the water table drain. Other key variables are cut volume and total earthworks. For the full bench approach these variables are not unique and represent the triangular prism of soil excavated from the slope. For the cut and fill methods the cut volume is the soil excavated in the cut prisms, whereas the total earthworks is the sum of the cut volume and the fill volume. Hence, earthworks represent the total movement of earth. As previously mentioned, the removal of large soil masses impacts long-term slope stability which has both environmental and maintenance implications. Meanwhile, earthworks are intended as a proxy measure to help estimate the short-term costs during construction.

<u>ASSUMPTIONS</u>

For ground slopes below 40% the model compares against the conventional cut and fill approach. However, for ground slopes between 40% and 60% the comparison was made against the alternative stabilised approach. The model calculates output values for the mineral soil. In other words, it is assumed that the organic soil has been stripped prior to construction works so the distances and volumes reported do not include this horizon. Stripping is a recommended forest road construction practice (NZFOA, 2012; Swift, 1984).

In reality the formation geometry is not as regular as triangles. There is a small volume associated with the road camber reducing the cut prism (increasing the fill prism). Also there is further excavation required to produce a water table drain. Some preliminary sensitivity analysis using recommended road crossfall slopes of 3-6% and water table drain dimensions of found these two volumes to be both; approximately equal, and inconsequential compared to the calculated outputs (Keller & Sherar, 2003; Larcombe, 1999; Ryan et al., 2004). As a result, these contributions were ignored in the model.

The road formation was assumed to consist of a 0.6m wide water table drain, 1m wide shoulders, and a 4.5m wide running surface, giving a total formation width of 7.1m. The road component dimensions reflect values reported across many roading manuals (B. C. Ministry of Forests, 2002; Keller & Sherar, 2003; Larcombe, 1999; NZFOA, 2012; Ryan et al., 2004). This formation width is relatively wide, Larcombe (1999) for instance presents a 6.6m wide road formation.

A significant concern for the construction of the stabilised alternative approach is the safe operation of compaction equipment. Keller & Sherar (2003) suggest that a 3m wide working platform is required. Therefore, it was assumed that the key cut and stabilised fill prism were a minimum of 3m wide. This is why the stabilised fill prism is constrained to a parallelogram rather than a more general trapezium.

A 1½:1 fill slope was adopted for balanced cut and fill construction, in line with the recommendations in literature. However, preliminary modelling found that for the stabilised alternative, applying both a 1½:1 fill slope and the 3m wide fill prism produced a solution which was not operationally viable. In all cases the road formation would have to be widened to increase the cut volume to, in turn, balance the fill requirements. To achieve a more feasible design a 1:1 fill slope was adopted for this approach, which necessitates extra stabilisation measures in conjunction with compaction.

In the results presented it was assumed that the excavated soil occupied the same volume as the compacted fill when balancing cut and fill. In practice, soil may swell or shrink depending on the original consolidation state. A cut to fill factor is provided in the model spreadsheet to enable customisation to a particular situation.

<u>MODEL</u>

Given the above constraints and inputs of terrain and cut slope angles the model mathematically evaluates the output variables. The mathematical functions are derived from trigonometric relations applicable to non-right triangles. Cut and fill prism equations were derived from two expressions; the Sine Rule and the generalised expression for the area of a triangle (Appendix 1). Figure 6 sets out the template for the stabilised alternative and summarises the known parameters. Area 1 is the main cut prism, Area 2 is the keyed bench prism, and the fill prism is Area 3. The user defines the terrain slope, *s*, which gives one angle in each of these areas (Figure 6). The exterior angle of the formation and the cut batter for Area 1 is the cut slope angle, *c*, by simple geometry the angle between formation and cut batter is then *180°-c*. Since the angles of a triangle sum to 180°, the final angle between the cut batter and original ground slope must be *c-s*. Applying the same logic to Area 2, the other two angles must be *180°-f* and *f-s* where f is the fill slope angle. Area 3 is simply twice Area 2. A new variable is also introduced, the length of road surface placed on fill (*z*).

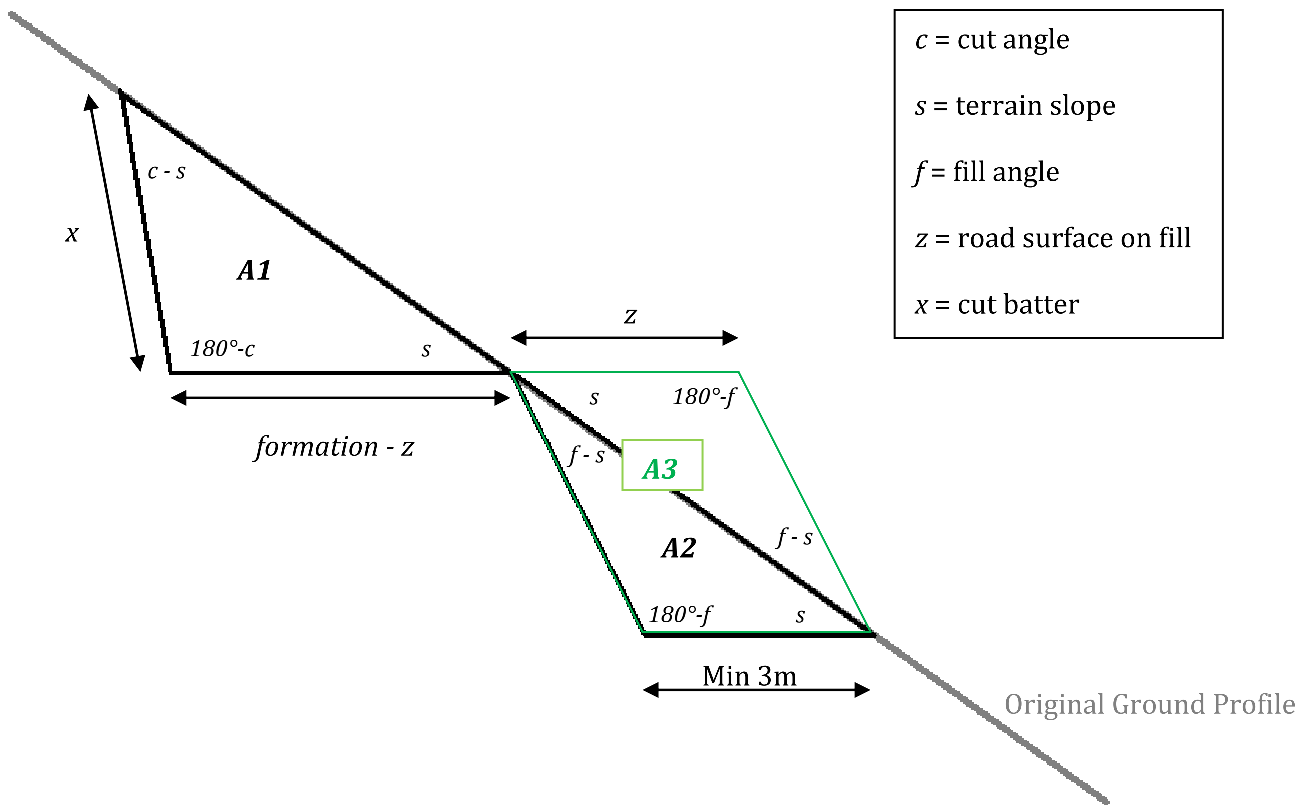

Figure 6: Template for the Stabilised Alternative Cut and Fill used in the Model

To simplify the mathematical expressions the variables *i* through *j* were defined as follows;

[1]

[2]

[3]

[4]

[5]

The bottom edge of the Area 1 triangle is already defined (formation – *z*), so the length of one other side is needed to calculate the area (Appendix 1). This can be found using the Sine Rule.

[6]

[7]

Rearranging yields;

[8]

Equation 8 can be substituted into the general area of a triangle expression (Appendix 1) to find Area 1;

[9]

[10]

[11]

Similarly, Area 2 can be found using;

[12]

Due to symmetry Area 3 is;

[13]

Using a goal seek function in excel enables setting the total cut area (Area 1 + Area 2) equal to the fill area (Area 3) by varying the length of the road surface placed on fill (z). This provides a balanced cut and fill system.

For the conventional cut and fill the same goal seeking procedure is undertaken but cut area is represented by Area 1, and the fill area is Area 2. Batter slope length for both the fill constructions is calculated using Equation 8. Meanwhile, for the full bench approach the cut area is calculated using a simplified version of Equation 11, excluding the z term;

[14]

Likewise, the cut batter slope length is derived from equation 8 and is expressed as;

[15]

For this report, terrain slope angles of 5% to 60% were investigated in 5% increments, in each case the cut slope angle was varied between ¾:1, ½:1, and ¼:1 (133%, 200%, and 400% respectively).

RESULTS

It was found that the ratios of cut volume and earthworks for the fill methods, relative to the full bench approach, increased as the terrain slope increased. These ratios also increased with increasing cut slope angle. These same trends, of a relative increase with terrain and cut slope increases, were apparent in the batter slope length also.

For the conventional cut and fill methods batter slope length, cut volume, and earthworks were all significantly less than the full bench method in all investigated cases (Table 1, 2 & 3). Conventional balanced cut and fill construction provides a 41.9-49.5% reduction in cut batter slope length, a 66.3-74.5% reduction in cut volume, and a 32.5-49% reduction in total earthworks compared to a full bench construction.

Table 1: Comparative Earthwork Parameters for a Balanced Cut & Fill with a ¾:1 Cut Slope

Full Bench Earthworks Prism				Balanced Cut/Fill Prism			
Terrain Slope (%)	*Cut Slope Angle*	Total Volume *[m^3/m]*	Cut Batter *[m]*	Fill Road Surface [m]	Cut Batter *[m]*	Total cut volume *[m^3/m]*	Total earthworks *[m^3/m]*
5	*133%*	1.31	0.46	3.51	0.23	0.33	0.67
					50.5%	25.5%	51.0%
10	*133%*	2.72	0.96	3.48	0.49	0.71	1.42
					51.1%	26.1%	52.1%
15	*133%*	4.26	1.50	3.43	0.78	1.14	2.28
					51.7%	26.7%	53.4%
20	*133%*	5.93	2.09	3.38	1.09	1.63	3.26
					52.4%	27.5%	55.0%
25	*133%*	7.76	2.73	3.32	1.45	2.20	4.40
					53.3%	28.4%	56.8%
30	*133%*	9.76	3.44	3.25	1.86	2.87	5.75
					54.3%	29.5%	58.9%
35	*133%*	11.96	4.21	3.16	2.34	3.68	7.36
					55.5%	30.8%	61.6%
					(% Bench Batter)	*(% Bench Vol)*	*(% Bench Vol)*

Table 2: Comparative Earthwork Parameters for a Balanced Cut & Fill with a ½:1 Cut Slope

Full Bench Earthworks Prism				Balanced Cut/Fill Prism			
Terrain Slope (%)	*Cut Slope Angle*	Total Volume *[m^3/m]*	Cut Batter *[m]*	Fill Road Surface [m]	Cut Batter *[m]*	Total cut volume *[m^3/m]*	Total earthworks *[m^3/m]*
5	*200%*	1.29	0.41	3.50	0.21	0.33	0.66
					50.7%	25.7%	51.3%
10	*200%*	2.65	0.84	3.45	0.43	0.70	1.40
					51.4%	26.4%	52.8%
15	*200%*	4.09	1.29	3.39	0.67	1.11	2.23
					52.2%	27.3%	54.5%
20	*200%*	5.60	1.76	3.33	0.94	1.58	3.16
					53.1%	28.2%	56.5%
25	*200%*	7.20	2.27	3.25	1.23	2.12	4.23
					54.2%	29.4%	58.7%
30	*200%*	8.90	2.80	3.17	1.55	2.73	5.46
					55.4%	30.7%	61.4%
35	*200%*	10.69	3.37	3.06	1.91	3.46	6.91
					56.9%	32.3%	64.7%
					(% Bench Batter)	*(% Bench Vol)*	*(% Bench Vol)*

Table 3: Comparative Earthwork Parameters for a Balanced Cut & Fill with a ¼:1 Cut Slope

Full Bench Earthworks Prism				Balanced Cut/Fill Prism			
Terrain Slope (%)	*Cut Slope Angle*	Total Volume *[m³/m]*	Cut Batter *[m]*	Fill Road Surface [m]	Cut Batter *[m]*	Total cut volume *[m³/m]*	Total earthworks *[m³/m]*
5	*400%*	1.28	0.37	3.49	0.19	0.33	0.66
					50.8%	25.8%	51.6%
10	*400%*	2.59	0.75	3.43	0.39	0.69	1.38
					51.7%	26.7%	53.5%
15	*400%*	3.93	1.14	3.36	0.60	1.09	2.18
					52.7%	27.8%	55.6%
20	*400%*	5.31	1.54	3.28	0.83	1.54	3.07
					53.8%	29.0%	57.9%
25	*400%*	6.72	1.95	3.19	1.07	2.04	4.07
					55.1%	30.3%	60.6%
30	*400%*	8.17	2.37	3.09	1.34	2.61	5.21
					56.5%	31.9%	63.8%
35	*400%*	9.67	2.81	2.98	1.63	3.26	6.52
					58.1%	33.7%	67.5%
					(% Bench Batter)	(% Bench Vol)	(% Bench Vol)

For the stabilised alternative the cut batter slope and cut volume were reduced compared to the full bench construction. However, total earthworks were increased (Table 4, 5, & 6). In this case 38.4-48.1% and 24.1-46.1% reductions were predicted in cut batter and cut volume respectively. While total earthworks increased by 7.9-51.8% compared to the full bench.

Table 4: Comparative Earthwork Parameters for an Alternative Stabilised Fill with a ¾:1 Cut Slope

Full Bench Earthworks Prism				Alternative Stabilised Fill Prism				
Terrain Slope (%)	*Cut Slope Angle*	Total Volume *[m^3/m]*	Cut Batter *[m]*	Fill Road Surface [m]	Cut Batter *[m]*	Total cut volume *[m^3/m]*	Total earthworks *[m^3/m]*	Extra formation width [m]
40	*133%*	14.40	5.07	3.41	2.63	7.77	15.53	0.00
					51.9%	53.9%	107.9%	
45	*133%*	17.12	6.03	3.39	3.15	9.37	18.75	0.00
					52.3%	54.8%	109.5%	
50	*133%*	20.16	7.10	3.35	3.75	11.24	22.47	0.00
					52.8%	55.7%	111.5%	
55	*133%*	23.60	8.31	3.31	4.43	13.42	26.84	0.00
					53.3%	56.9%	113.8%	
60	*133%*	27.50	9.68	3.27	5.23	16.02	32.04	0.00
					54.0%	58.3%	116.5%	
					(% Bench Batter)	*(% Bench Vol)*	*(% Bench Vol)*	

Table 5: Comparative Earthwork Parameters for an Alternative Stabilised Fill with a ½:1 Cut Slope

Full Bench Earthworks Prism				Alternative Stabilised Fill Prism				
Terrain Slope (%)	*Cut Slope Angle*	Total Volume *[m^3/m]*	Cut Batter *[m]*	Fill Road Surface [m]	Cut Batter *[m]*	Total cut volume *[m^3/m]*	Total earthworks *[m^3/m]*	Extra formation width [m]
40	*200%*	12.60	3.97	3.30	2.13	7.24	14.48	0.00
					53.6%	57.4%	114.9%	
45	*200%*	14.64	4.61	3.25	2.50	8.62	17.25	0.00
					54.3%	58.9%	117.8%	
50	*200%*	16.80	5.29	3.19	2.91	10.18	20.37	0.00
					55.1%	60.6%	121.2%	
55	*200%*	19.12	6.02	3.13	3.37	11.96	23.93	0.00
					55.9%	62.6%	125.1%	
60	*200%*	21.60	6.80	3.06	3.87	14.01	28.03	0.00
					56.9%	64.9%	129.7%	
					(% Bench Batter)	*(% Bench Vol)*	*(% Bench Vol)*	

Table 6: Comparative Earthwork Parameters for an Alternative Stabilised Fill with a ¼:1 Cut Slope

Full Bench Earthworks Prism				Alternative Stabilised Fill Prism				
Terrain Slope (%)	*Cut Slope Angle*	Total Volume *[m³/m]*	Cut Batter *[m]*	Fill Road Surface [m]	Cut Batter *[m]*	Total cut volume *[m³/m]*	Total earthworks *[m³/m]*	Extra formation width [m]
40	*400%*	11.20	3.25	3.19	1.79	6.79	13.58	0.00
					55.1%	60.6%	121.2%	
45	*400%*	12.78	3.71	3.13	2.08	8.00	16.00	0.00
					56.0%	62.6%	125.2%	
50	*400%*	14.40	4.18	3.06	2.38	9.34	18.69	0.00
					56.9%	64.9%	129.7%	
55	*400%*	16.07	4.67	3.00	2.73	11.00	22.00	0.05
					58.5%	68.4%	136.9%	
60	*400%*	17.79	5.17	3.00	3.18	13.50	27.00	0.27
					61.6%	75.9%	151.8%	
					(% Bench Batter)	*(% Bench Vol)*	*(% Bench Vol)*	

So, for a relaxed cut slope angle and a relatively gentle terrain slope the stabilised alternative requires approximately half the cut volume of the full bench with minimal extra total earthworks (Table 4). Whereas, for near vertical cut slopes, the benefits of cut reduction begin to diminish yet substantial extra earthworks are necessary.

The earthwork and cut volume results in the above tables are also presented graphically (Figure 7, 8, 9, 10, 11 & 12).

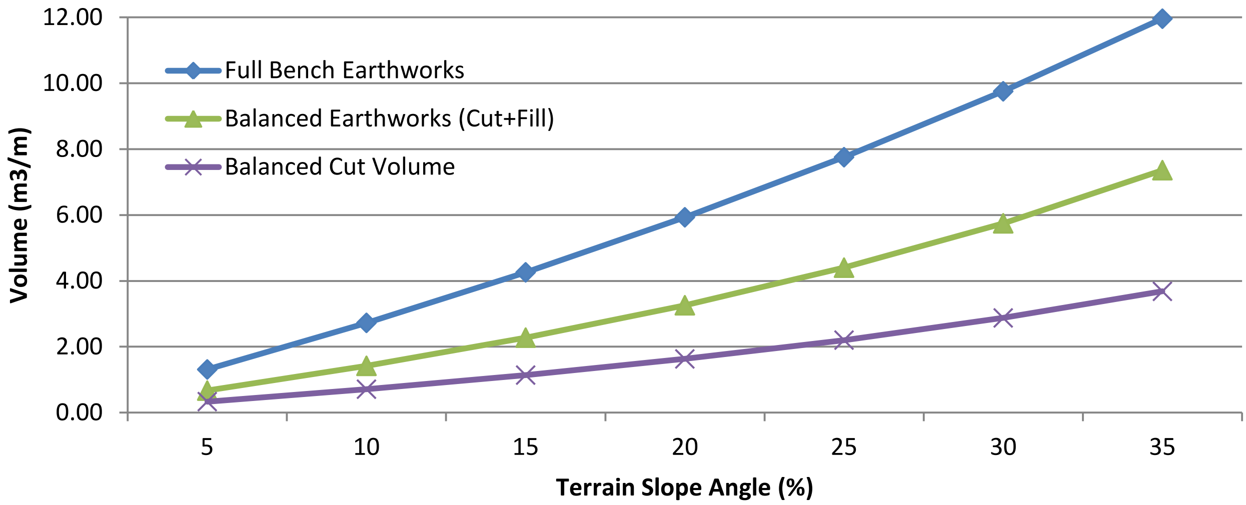

Figure 7: Earthwork Volumes for a 3/4:1 Cut Angle (Conventional Cut & Fill)

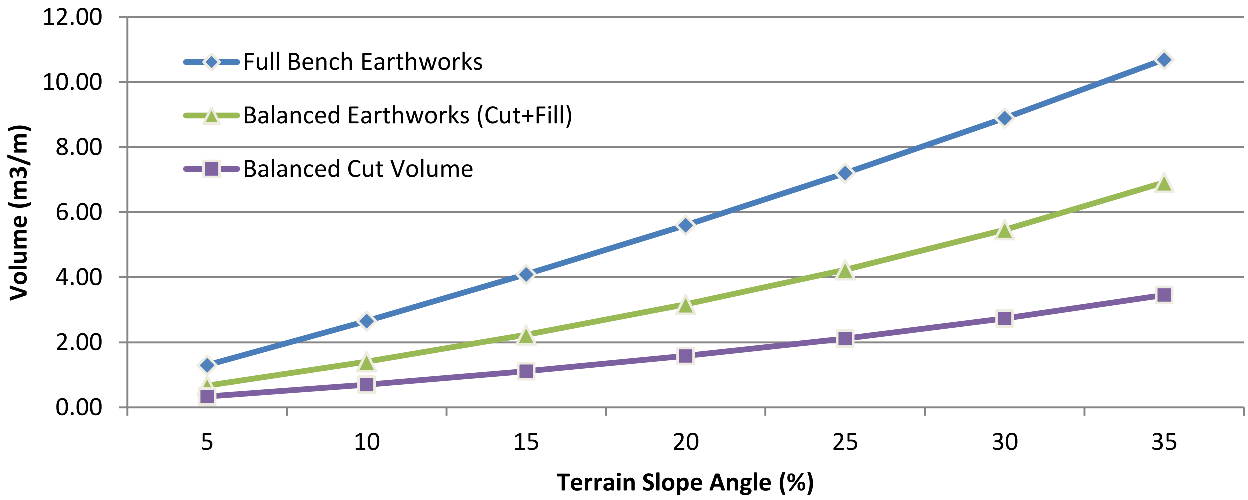

Figure 8: Earthwork Volumes for a 1/2:1 Cut Angle (Conventional Cut & Fill)

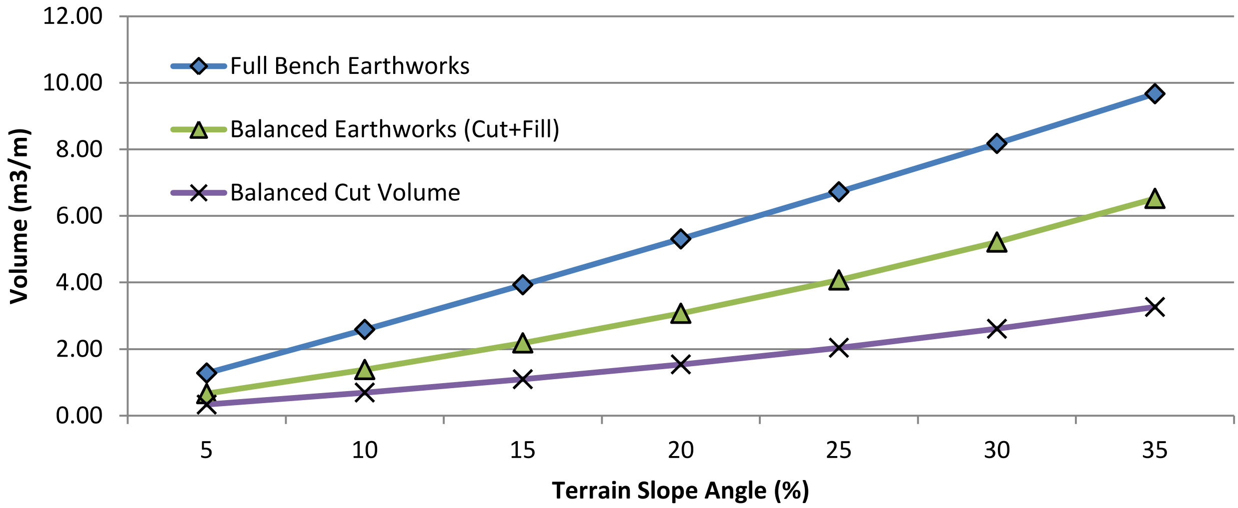

Figure 9: Earthwork Volumes for a 1/4:1 Cut Angle (Conventional Cut & Fill)

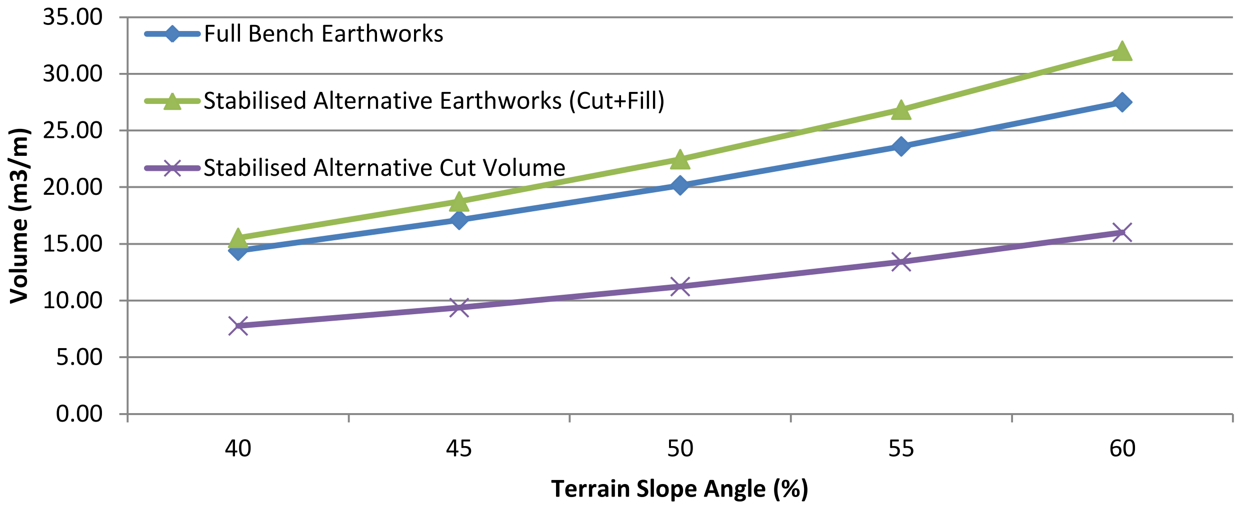

Figure 10: Earthwork Volumes for a 3/4:1 Cut Angle (Stabilised Alternative)

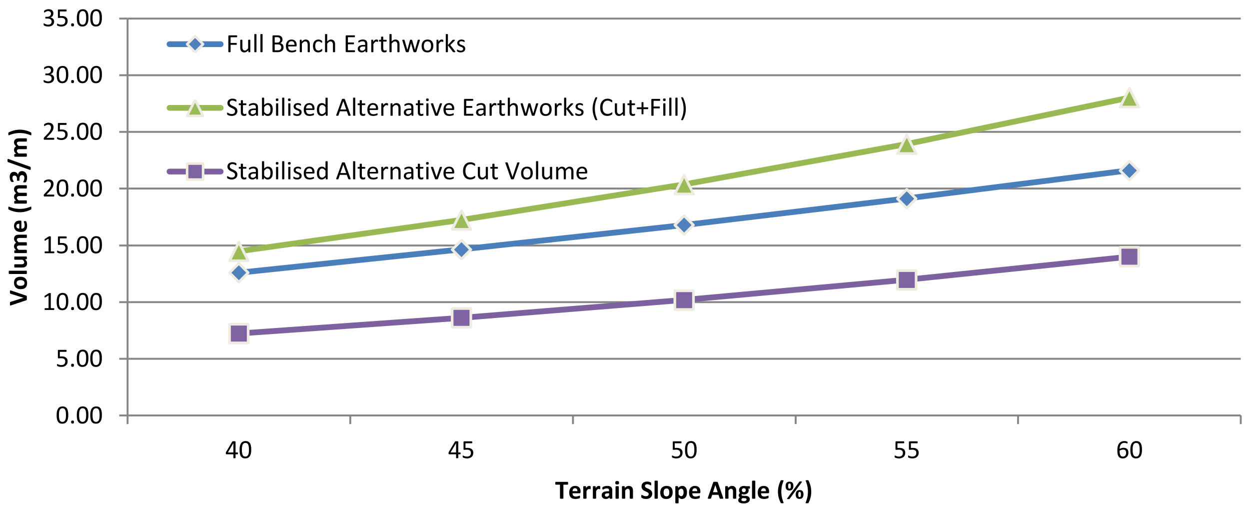

Figure 11: Earthwork Volumes for a 1/2:1 Cut Angle (Stabilised Alternative)

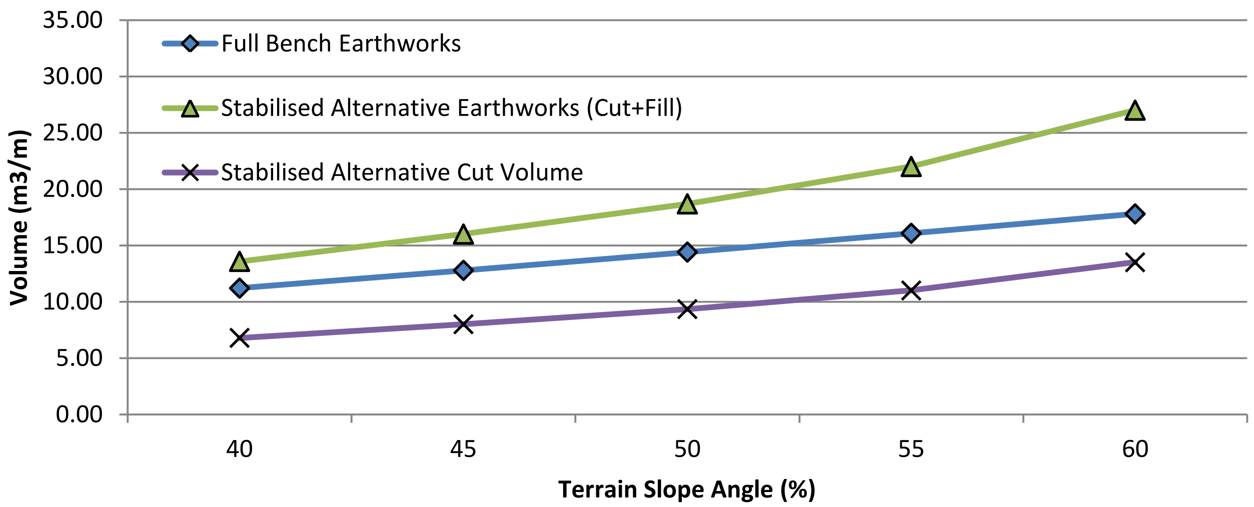

Figure 12: Earthwork Volumes for a 1/4:1 Cut Angle (Stabilised Alternative)

Discussion

The results clearly show the original hypothesis - that the relative cut volume and earthworks decrease with increased terrain slope - is not true. In fact, they show the opposite to be true. In the graphs it is evident that the full bench earthworks are increasing approximately linearly. On the other hand, the balanced cut and fill metrics are increasing at an increasing rate. These phenomena are particularly evident in Figure 11. By logically considering the situation it becomes apparent why this is the case. In a full bench construction the earthworks are determined only by the cut area which increases steadily with terrain slope. Meanwhile, for a fill construction the earthworks are a function of both cut and fill volume. As the terrain slope begins to approach the fill slope angle the fill area needed will rapidly increase.

It is left to the forest manager to decide what relative values to place on soil exposure, excavation, and construction earth movements but some general conclusions may be draw from the results presented. For slopes where a conventional balanced cut and fill can be applied it appears most prudent to take this approach as it offers less exposed cut batter, smaller cut volumes, and less overall earth movement. In contrast, the alternative stabilised fill approach seems appropriate to situations where reducing disturbance is a key consideration. It shows promise as a preferred option in areas with less cohesive soils and moderate terrain. In steeper areas where it is determined that end-hauling is a necessary procedure it also may well be a prudent choice as only the organic material needs to be end-hauled away. Whereas, for the full bench, the entire earthworks volume, along with the organic soil, must be end-hauled.

The assumption that a 3m working platform is necessary for safe operation of machinery on steeper terrain carries reasonable significance as it directly affected some results. For certain configurations this constraint required extra formation width to be added (Table 6). This substantially influenced the cut and earthworks volumes as can be seen in the last two points in Figure 12.

CONCLUSION

The forest industry faces increasing demand for forest road infrastructure. Also, forest road construction has significant environmental impacts. This means selecting appropriate construction methods and reducing excavation where possible are both very important. This study focussed on comparing full bench construction with two different fill construction methods. This was accomplished using a spreadsheet based mathematical model comparing the batter slope length, cut volume, and total earthworks. For gentler terrain a conventional cut and fill was contrasted with a full bench approach. Meanwhile, for steeper terrain a further engineered stabilised fill construction template was developed and also compared with a full bench approach. It was found that as the terrain slope angle or cut slope angle increases the relative cut volume and earthworks of the fill methods increases compared to the corresponding full bench option. A conventional cut and fill construction produces up to a 50% reduction in cut batter length and total earthworks, along with up to a 75% reduction in cut volume compared to a full bench. For relatively gentle ground slopes and relaxed cut angles the stabilised alternative requires minimal extra earthworks compared to the full bench while achieving up to a 48% reduction in batter slope length and a 46% reduction in cut volume. However in the extreme case only a 25% reduction in cut volume was attained while requiring one and a half times the earthworks of the full bench approach.

This project has developed both a model which can be specified to a particular situation and a tabulated set of results for a generalised set of configurations. These can be used as a decision support tool for evaluating environmental impacts and as input into costing models when considering road construction options.

The model produced could be further refined by further research into the width requirements of operating heavy equipment on steep terrain. Furthermore, it could be expanded with additional research into appropriate construction solutions for even steeper terrain. Including questions such as, whether the engineered solution developed could operationally be applied to these situations. Case studies examining the constructability and practical performance of the stabilised fill construction would also, no doubt, be well received by industry.

REFERENCES

B. C. Ministry of Forests. (2002). *Forest road engineering guidebook*. Forest practices code of British Columbia (2nd ed.). Victoria, B.C: British Columbia, Ministry of Forests.

Claassen, V. P., & Zasoski, R. J. (1998). A comparison of plant available nutrients on decomposed granite cut slopes and adjacent natural soils. *Land Degradation & Development*, *9*(1), 35–46. doi:10.1002/(SICI)1099-145X(199801/02)9:1<35::AID-LDR273>3.0.CO;2-V

Fairbrother, S., Visser, R., & McGregor, R. (2009). Forest Road Pavement Design in New Zealand (p. 8). Presented at the 32nd Annual Meeting of the Council on Forest Engineering (COFE 09), Kins Beach, CA, USA. Retrieved from http://ir.canterbury.ac.nz/handle/10092/2621

Fannin, R. J. (2000). *Basic geosynthetics: a guide to best practices*. Richmond, B.C: BiTech Publishers.

Fransen, P. J. B., Phillips, C. J., & Fahey, B. D. (2001). Forest road erosion in New Zealand: overview. *Earth Surface Processes and Landforms*, *26*(2), 165–174. doi:10.1002/1096-9837(200102)26:2<165::AID-ESP170>3.0.CO;2-#

Garga, V. K., & O'Shaughnessy, V. (2000). Tire-reinforced earthfill. Part 1: Construction of a test fill, performance, and retaining wall design. *Canadian Geotechnical Journal*, *37*(1), 75–96. doi:10.1139/t99-084

Iordache, E., Niță, M.-D., & Clinciu, I. (2012). Planning Forest Accessibility with a Low Ecological Impact. *Croatian Journal of Forest Engineering*, *33*(1), 143–148.

Keller, G., & Sherar, J. (2003). *LOW-VOLUME ROADS ENGINEERING: Best Management Practices Field Guide*. US Agency for International Development (USAID).

Larcombe, G. (1999). *Forest roading manual*. Rotorua, N.Z: Liro Forestry Solutions.

LeDoux, C. B. (2004). Determining safe clearing limits for skid road/trail construction. *Proceedings of the 14th Central Hardwood Forest Conference* (pp. 148–153). Retrieved from http://www.fs.fed.us/ne/newtown_square/publications/technical_reports/pdfs/2004/316papers/LeDouxGTR316.pdf

Mills, K., Pyles, M., & Thoreson, R. (2007). Aggregate surfacing design and management for low-volume roads in temperate, mountainous areas. *Transportation Research Record*, *2*, 154–160.

Neilson, D. (2012). Building better roads using better technology. *Engineering Value Growing & Harvesting Forests for Novel Wood Structures*. Presented at the New Zealand Institute of Forestry, Christchurch, N.Z.

NZFOA. (2007). *New Zealand Forest Owners' Association Environmental Code of Practice* (Version 1.). New Zealand Forest Owners' Association.

NZFOA. (2012). *New Zealand Forest Road Engineering Manual*. Wellington, N.Z: New Zealand Forest Owners' Association.

Ryan, T., Phillips, H., Ramsay, J., & Dempsey, J. (2004). *Forest Road Manual: Guidelines for the design, construction and management of forest roads*. Dublin: COFORD, National Council for Forest Research and Development.

Stückelberger, J. A., Heinimann, H. R., & Burlet, E. C. (2006). Modeling spatial variability in the life-cycle costs of low-volume forest roads. *European Journal of Forest Research*, *125*(4), 377–390. doi:10.1007/s10342-006-0123-9

Swift, L. W. (1984). Soil Losses from Roadbeds and Cut and Fill Slopes in the Southern Appalachian Mountains. *Southern Journal of Applied Forestry*, *8*(4), 209–216.

APPENDIX 1:

The Sine Rule states that;

[Sine Rule]

Where *a*, *b*, and *c* are lengths of the sides of a triangle and *A*, *B*, and *C* are the opposite angles (See Figure). The general expression for the area of a triangle is;

[General Triangle Area]

Where, as before, *a* and *b* are two sides of the triangle and *C* is the angle between these two sides (See Figure).