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Analyzing the Effectiveness of Common Road Construction and Deactivation Techniques

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This study uses the finite planar slope stability model to analyze the road fill failure shown in Figure 1. The failure occurred near Pemberton B.C. within the Pacific Range of the Coastal Mountains. The model is an acceptable approximation of the local terrain, manner of road construction, and mechanics of the failure. For the failure in question, the model predicts:

- The road was stable when it was built by inexpensive sidecasting, about 20 years ago.
- It is unlikely that a mature regenerative forest growing on the road fill (i.e. natural road deactivation) would have prevented the slide.
- Inexpensive control of surface water (cross ditching) would have deferred the slide for an indefinite period. However, full pullback and sound water control would be required to assure the stability of the road fill during extreme groundwater/runoff conditions.
- Pullback, without sound water control, would have been an ineffective, potentially counterproductive, road deactivation strategy. Only full (P15) pullback would provide an immediate improvement to slope stability equivalent to sound management of surface water. P9 and P6 pullback, without adequate measures to control surface water, would have somewhat increased the slope's immediate probability of failure. See Figure 6 of this article for illustrations of P15, P9 and P6 pullback; the "P" system of prescribing pullback is defined in Advanced Road Deactivation Course Manual, 1997, drawing number 012013-00-02, TYPICAL SIDECAST PULLBACK.
- P9 pullback and sound water control measures substantially improved the stability of the road fill.
- Full (P15) pullback and sound water control provided the best, immediate, assurance of slope stability.
- The long-term effects of P6 or P9 pullback and reforestation are somewhat unclear. However, the greater the quantity of pullback (the thinner the

residual sidecast road fill) the better are the prospects for long-term slope stability. Tree roots must penetrate to at least the original forest floor or the road fill will be primed for failure.

The above predictions, made from the analysis of a single road fill failure, must be viewed with caution. Site-specific conditions will almost always take precedence over idealized analysis of an individual, historical, road fill failure. As discussed below had the failure occurred upon a side slope steeper than 32 degrees or a hillslope composed of less favorable (lower friction) soils analysis would have indicated pullback was a more beneficial road deactivation technique.

continued

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Figure 1. A southern coastal mainland road fill failure showing the workers for scale, the high cut tree stump supporting residual sidecast road fill, and the almost planar nature of the failure surface. The dashed white line highlights a layer of black, decomposed organics within the sidewall of the slide.

The Fundamentals of Slope Stability Analysis:

Slope stability analysis expresses the stability of a slope in terms of the slope's factor of safety (F) (Chatwin *et al.* 1994, p. 6).

$$F = \frac{\text{the sum of the forces within a slope resisting failure}}{\text{the sum of forces within the slope promoting failure}}$$

In theory, a slope will only fail when its factor of safety is less than 1.0 (the forces resisting failure are less than the forces driving failure). In reality, however, the input parameters for slope stability analysis are uncertain; it is prudent to say that a slope with a factor of safety between 1.0 and 1.3 “may be stable” rather than to make strong (and potentially incorrect) statements that the slope will, or will not, fail.

The five factors that determine the driving and resisting forces in a slope are:

- **The frictional resistance of the slope material(s) to sliding.** Geotechnical engineers refer to this as a material's angle of internal friction (ϕ). Forestry workers tend to use the term angle of repose when discussing a material's resistance to sliding. High friction is good for slope stability. Granitic shot rock and unweathered, well graded, till are examples of high friction forestry materials ($\sim 45^\circ$). Decomposed, “greasy”, organics are an example of a low friction forest material (~ 12 to 27°). Clay rich soils (tills containing $\sim >16\%$ clay, glaciolacustrine and most marine clays) are examples of low to moderate friction materials (~ 18 to 38° depending upon the stress history, mineralogy and moisture content of the soil).

- **The slope angle of the potential failure surface (ψ).** In general, the steeper the prospective failure surface, the less stable a slope will be.
- **The weight of material above the potential failure surface.** The weight of material above a potential failure surface can influence slope stability in several ways. If the slope angle of a potential failure surface (ψ) is:
 - less than the soil's angle of internal friction (ϕ), then more weight on the failure surface will increase slope stability;
 - the same as the soil's angle of internal friction (ϕ), then the weight of material on the failure surface makes little or no difference to slope stability;
 - greater than the soil's angle of internal friction (ϕ), then extra weight on the failure surface will reduce slope stability.

To illustrate the above principles, place a coffee cup on the face of a hard cover book. Incline the book slightly; to initiate “failure” of the empty coffee cup (causing the coffee cup to slide down the face of the book) requires a significant push of your hand. Place a significant weight in the coffee cup (an office stapler works well) and repeat the experiment. The loaded coffee cup's greater weight requires even more of a push to initiate failure than the lighter, empty cup. In the language of geotechnical engineering, when (ψ) (the angle of the prospective failure surface- the book's cover) is less than (ϕ) (the angle of internal friction for the coffee cup on the book cover), then adding weight to the coffee cup (our surrogate road fill) will improve slope stability.

Now gradually increase the tilt (angle of inclination) of the book; at a critical slope angle the coffee cup, whether empty or full, will slide down the book cover at your slightest touch. In engineering terms, when (ψ) (the face angle of the book cover) is equal to (ϕ) (the angle of internal friction for the coffee cup on the book cover) the stability of the road fill (the coffee cup) does not depend on the weight of the prospective failure mass (the loading, or weight, of the coffee cup).

Next, increase the tilt of the book cover a little bit more; whenever the face angle of the book is steeper than the critical slope angle determined in the previous experiment, you must use your fingers to hold the coffee cup in place. Holding a coffee cup, loaded with a stapler, requires more stabilizing force from your

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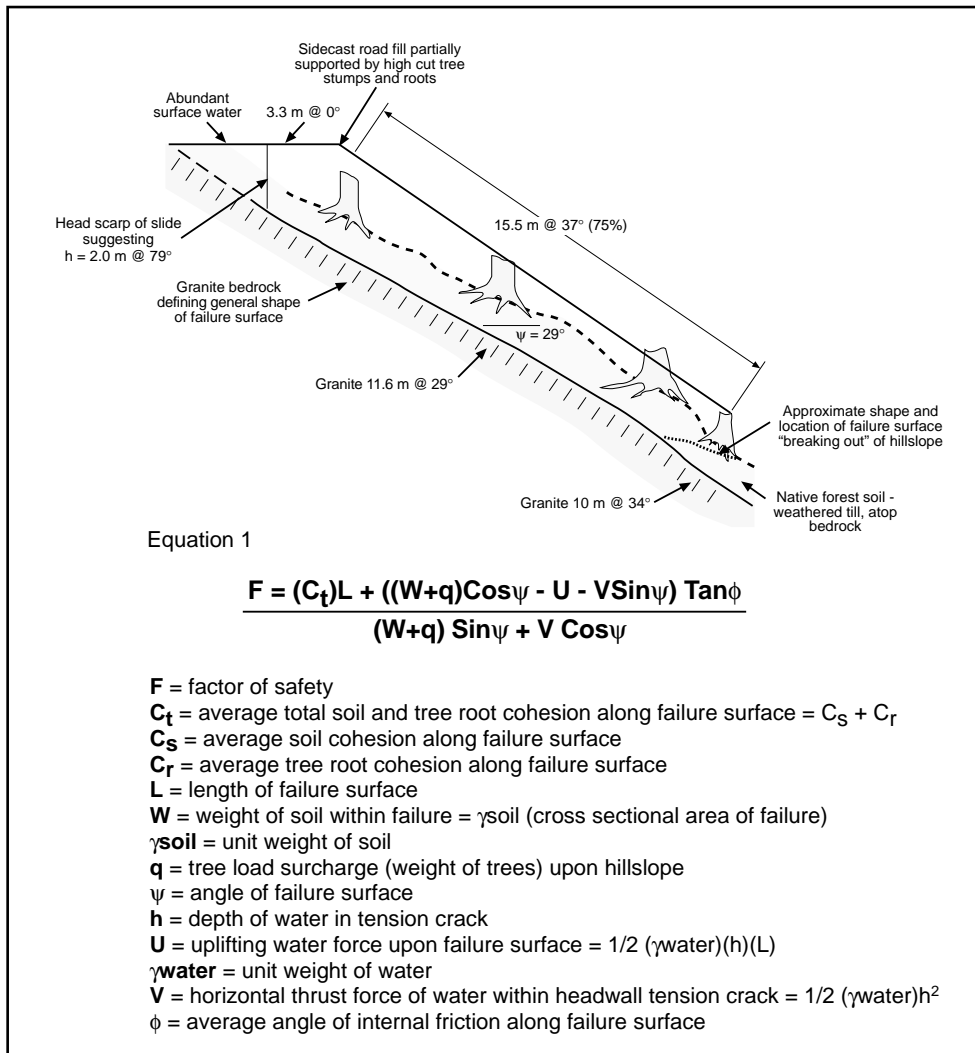


Figure 2. The Finite Planar Slope Stability Model.

fingers than holding the same, empty, coffee cup on the slope. In engineering terms, whenever (ψ) (the angle of the prospective failure surface- the book cover) is greater than (φ) adding weight to the coffee cup decreases slope stability. That is, you must apply more force from your fingers to hold the loaded versus the unloaded coffee cup on the book cover.

- The cohesion or “stickiness” of the material(s) in a slope. In forestry, there are two common sources of “stickiness” in a hillslope: soil and tree root cohesion.
 - Hardpan (unweathered till) is an excellent example of a forest material with high soil cohesion; hardpan is difficult to dig until the “stickiness” (cohesion) between adjacent chunks of soil is broken; once broken, hardpan is easy to dig.
 - The effects of tree roots upon shallow slope stability are complex; for simplicity, trees roots

are usually modeled as a thin (roughly one metre deep) veneer of “extra-sticky” soil.

- Total cohesion is the available soil cohesion plus the available tree root cohesion. High cohesion is good for slope stability. On steep hillslopes (slopes steeper than (φ) for the local soil) cohesion stabilizes the hillslope in much the same manner as peanut butter could be used to “glue” a coffee cup to the cover of a steeply inclined book.
- The magnitude and direction of water pressures in a slope. The role of water in slope stability merits special attention.

Water pressures less than atmospheric pressure are good for slope stability; a modest amount of water in soil causes “apparent” cohesion between soil particles, due to the capillary effects of water. Many soils are more resistant to sliding when slightly moist, rather than when completely dry. For example, moist sand makes better sand castles than dry

ple,

sand; a few drops of water around the base of a cup can “glue” it to a book cover.

Water pressures greater than atmospheric pressure push soil particles apart, decreasing slope stability. For example, turning on a garden hose buried in a sand castle will induce failure of previously stable sand castle walls; a garden hose can easily blow a coffee cup from a book cover. The higher the water pressures, the less stable the slope.

The direction and rate of water movement (the water pressure seepage vector) in a hillslope can have a profound effect on slope stability; the jet of water from a garden hose is far more effective at inducing failure of a sand castle’s walls than the same quantity (and driving pressure) of water dripping from a soaker hose. Because water has such negative effects on slope stability:

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- Failures are almost always triggered by intense rainfall, snowmelt, or concentrated ditch water.
- Failures frequently occur in areas of concentrated water flow such as gully headwalls, sidewalls, stream escarpments, zones of seepage-prone (fractured) bedrock, cross ditch, and culvert outlets.
- Failure surfaces are often located along the top of a “water trap” (an impermeable soil layer) such as hardpan (unweathered till), or bedrock.

All of the above generalities have to be analyzed and molded into a host of slope stability equations and models. There are dozens, possibly hundreds, of slope stability models. Each model is designed to approximate a specific style of slope failure. In general, the most complex, site specific models, supported by extensive field assessments and costly laboratory testing, are the best approximations of specific slope failures. Until and unless researchers focus such advanced analytical techniques on forestry road fills, simpler models, such as the one used in this paper, will have to suffice.

Rationale and Limitations of the Two Dimensional Finite Planar Slope Stability Model

This model, adapted for use upon a typical sidecast road fill, is illustrated in Figure 2, equation 1; at the base of Figure 2 is the equation for calculating the factor of safety for a typical sidecast road fill. The model requires the prospective failure surface to be a straight line, but readily accommodates convoluted ground (fill slope) surfaces and tension cracking. The model is a useful approximation of road fill failures because:

- It is widely observed that road fill failures approximate planar failures (Gray and Leiser, 1982. pp 33-34).
- The core equations for numerical modeling of finite planar slope failures are well established (Hoek and Bray, 1981. pp 7.1-7.3) and can be readily modified to incorporate tree load surcharging, tree root cohesion and water pressures, which the US Forest Service (Hammond et al, 1992. pp 53-74 and 82-86) suggests are appropriate for coastal BC (Figure 2).
- Forested hillslopes are frequently primed to produce planar failures. Most tree roots penetrate about a metre into a hillslope before spreading out laterally along some manner of hardpan; and, eventually all trees die. Over hundreds, in some cases thousands, of years, thin layers of decomposed tree roots accumulate on specific layers of hardpan; it is reasonably common to find slickensided (sheared) plates of “greasy” (low friction) decomposed organics in the initiation zone of recent landslides (Baumann, 1997. p. 3).



Figure 3. Photograph of the slide's initiation zone. Note the planar nature of failure surface, high cut tree stumps supporting road fill and abundance of water flowing over the headwall of the slide.

- When buried in sidecast road fill, tree stumps approximate soil piles. Piles buttress the soil above them; soil will arch between closely spaced soil piles and tree stumps (Gray and Leiser, 1982. pp 55 and 59). The soil buttressing and arch effects are visible behind the tree stumps in Figures 1 and 3. Tree stumps transmit any sliding forces in the fill slope to the base of their root wad, where pockets of low friction, decomposed, tree roots are mostly likely to exist.
- Sidecast road fills held together by “sill” logs and tree stumps approximate low face angle retaining walls. There are four “classic” stability tests for retaining walls. All retaining walls should be analyzed for: rotational stability where the wall topples over due to the weight of soil and water it is attempting to support, bearing capacity failure (crushing the soils at the toe of the retaining wall), global stability (deep-seated slope failure potential) and rankine sliding (a style of planar failure). Because sidecast road fills are generally built with modest face angles, the likelihood of rotational and bearing capacity failure is very low. Hardpan or bedrock generally prevents deep-seated global failure of road fill. In effect, the nature of forest soils (low friction organics ~ one metre below the original forest floor), together with hardpan or bedrock concentrating groundwater near the zone of maximum root penetration and the buttressing effects of tree stumps, force road fills to fail in a form of rankine sliding. The planar slope stability model is a good approximation of rankine sliding.
- The finite planar model is simple yet robust; the factor of safety generated by the model is a respectable approximation of the more complex “method of slices”, rankine or translational slip models which a slope stability purist might apply to a road fill failure.

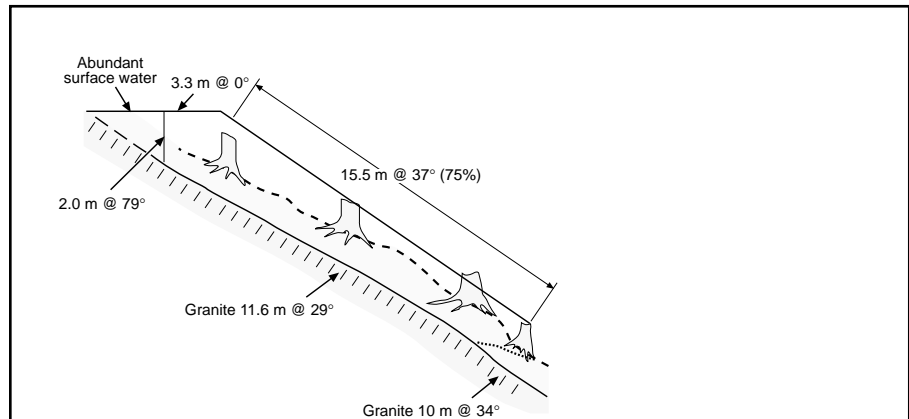
The model is especially well suited to the slope failure illustrated in Figure 1. The geometry of the site, woody debris in the fill slope, well defined headwall of the slide and shallow soil depth to the smooth, massive, underlying bedrock, make this slide an almost ideal example of a planar slope failure.

The analysis of very old (or poorly built) sidecast road fills is more complex. The decomposition of logs and stumps in very old road fills invalidates several of the model's assumptions; without the support of woody debris, steeper failure surfaces could develop in the unreinforced road fill. In addition the long-term effects of soil erosion upon the shape and weight of sidecast road fill are difficult to predict; a hundred years of soil erosion could easily reduce the weight and depth of a modern fill slope. In general, it is ill advised to project the long-term slope stability of a road fill, from the back analysis of a recent slope failure.

An Illustrative Example

The site illustrated in Figures 1 and 3 was surveyed within 72 hours of failure. Figure 4 is a best estimate, cross-sectional reconstruction of the road fill moments before it slid from the hillslope. The failure was triggered by an abundance of surface water entering open tension cracks along the shoulder of the approximately 20-year-old, abandoned roadway. The road was built by sidecasting on an open, steep, uniform slope composed of a thin veneer of weathered, silty sand, non plastic (~<10% silt and clay) till upon massive, smooth, granitic bedrock. The weathered till and top of the bedrock were laced with thin, discontinuous, seams of decomposed organics.

The engineering characteristics of such heterogeneous (mixed) soils profiles, especially the organic lenses, is a complex function of soil moisture content, the void ratio of the soil, stress history, total magnitude and rate of pre-failure slope deformation and layering of the materials in the



Road Fill Failed @ 20 yrs post harvest

- $\phi = 32^\circ$ on failure surface by back analysis
- $C_t = 4.4$ kPa on failure surface by back analysis
- $L = 17.7$ m length of failure surface by geometry
- γ soil dry = 16.0 kN/m³ by Lisa figure 5.11
- γ soil wet = 20.0 kN/m³ by Lisa figure 5.11
- $\psi = 29^\circ$ angle of failure surface by geometry
- $h = 2.0$ m by field measurement
- $V = 1/2 \gamma_{water} h^2 = 1/2(9.8 \text{ kN/m}^3)(2.0 \text{ m})^2 = 19.6 \text{ kN/m}$
- $U = 1/2 \gamma_{water} hL = 1/2(9.8 \text{ kN/m}^3)(2.0 \text{ m})(17.7 \text{ m}) = 173 \text{ kN/m}$
- $A =$ cross sectional area of failure = 44 m²
- $W_{wet} = A(\gamma \text{ soil wet}) = 44 \text{ m}^2(20.0 \text{ kN/m}^3) = 880 \text{ kN/m}$
- $W_{dry} = A(\gamma \text{ soil dry}) = 44 \text{ m}^2(16.0 \text{ kN/m}^3) = 704 \text{ kN/m}$
- $q = 0$ kPa

Sample calculation- Therefore, equation 1 at the moment of failure becomes:

$$F = \frac{(C_t)L + ((W+q)\cos\psi - U - V\sin\psi) \tan\phi}{(W+q) \sin\psi + V \cos\psi}$$

$$= \frac{(4.4 \text{ kPa})(17.7 \text{ m}) + [(880 \text{ kN/m} + 0) \cos 29^\circ - 173 \text{ kN/m} - (19.6 \text{ kN/m}) \sin 29^\circ] \tan 32^\circ}{(880 \text{ kN/m} + 0) \sin 29^\circ + 19.6 \text{ kN/m} \cos 29^\circ}$$

$$= \frac{77.9 \text{ kN/m} + [880 \text{ kN/m} \cos 29^\circ - 173 \text{ kN/m} - (19.6 \text{ kN/m}) \sin 29^\circ] \tan 32^\circ}{880 \text{ kN/m} \sin 29^\circ + 19.6 \text{ kN/m} \cos 29^\circ}$$

$$= \frac{77.9 \text{ kN/m} + [770 \text{ kN/m} - 173 \text{ kN/m} - 9.5 \text{ kN/m}] 0.625}{426.8 \text{ kN/m} + 17.2 \text{ kN/m}}$$

$$= \frac{77.9 \text{ kN/m} + [587.5 \text{ kN/m}] 0.625}{444 \text{ kN/m}}$$

$$= \frac{77.9 \text{ kN/m} + 367.1 \text{ kN/m}}{444 \text{ kN/m}} = \frac{445 \text{ kN/m}}{444 \text{ kN/m}} = 1.002$$

Figure 4. Back analysis of the failure illustrated in the two photographs.

hillslope. It is well established that other soil types, such as a weathered high fines (plastic) till, may exhibit inferior engineering characteristics. Conversely an unweathered, slightly cemented, low fines, till may exhibit substantially superior engineering characteristics.

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A comprehensive discussion of the soil mechanics and groundwater hydrology for all conceivable soil types is beyond the scope of this paper. For further information, interested readers are directed to reference books such as: *An Introduction to Geotechnical Engineering* by R.D. Holtz and W.D. Kovacs 1981 and *Hammond et al.* 1992.

From the abundance of water at the site (see Figures 1 and 3) it is possible to infer that the tension cracks at the headwall of the slide were completely full of water at the moment of failure. Using iterative calculations, the average angle of internal friction and average total cohesion along the failure surface at the moment of failure can be estimated. The text portion of Figure 4 summarizes the slope stability input parameters derived from iterative back analysis of the failure, engineering judgement, and experience.

The slope stability “life cycle” of the road fill failure

Using the data in Figure 4, the factor of safety for the road fill can be calculated using the infinite (not presented in this paper) and finite slope stability models (Figure 2). Specifically, this is accomplished by adding: q_0 (tree load surcharge) prior to harvesting, or

upon full reforestation, for the slope as estimated from the LISA manual (Hammond et al, 1992) table 5.1 as 2.0 kPa. C_r (average tree root cohesion across the failure surface) was estimated from the LISA manual figures 5.6 and 5.7. Average root cohesion, anchored into the underlying granite, was estimated to be 2.5 kPa immediately before and after road construction. Root cohesion across the “breakout” portion of the fully reforested road fill was estimated to be 10 kPa (assuming a maximum rooting depth of roughly one metre). The slope’s factor of safety was calculated for fully saturated and dry conditions. Given the abundance of surface water runoff and climate of the site, such extreme groundwater conditions were deemed a reasonable approximation of field conditions.

Figure 5 is a plot of the slope’s factor of safety versus various slope treatments which loosely correspond to the age of the sidecast road fill. Along the y axis of the graph is the factor of safety (F); plotted on the x axis is slope treatment. The horizontal lines at $F = 1.0$ and $F = 1.3$ illustrate the range of uncertain slope stability due to foreseeable errors in the back analysis of slope stability input parameters and site geometry. Open

squares on the plot are the calculated dry (completely unsaturated) factor of safety for the slope treatment described along the bottom of the graph. Black squares are the calculated wet (fully saturated) factor of safety (F) for each slope treatment. The dashed lines between open and black squares illustrate the relative change in F between the various slope treatments. The analysis of the fully regenerated road fill is speculative due to the potential for long term erosion of sidecast road fill and decomposition of woody debris in the fill slope. The key conclusions from Figure 5 are:

- The road fill was quite stable when built; however, stability of the road fill decreased with decay of the supporting tree roots. The abundance of water flowing into open tension cracks eventually floated the road fill from the hillslope.
- The failure would not have occurred had there been sound water control measures at the site.
- If the road fill had not failed it would have remained potentially unstable, in severe groundwater/runoff conditions, into the indefinite future. Even fully reforested, it is possible that some future storm or snowmelt event could have induced failure of the road fill. Because $(\phi) > (\psi)$, the weight of the regenerative forest on the road fill would have modestly improved the stability of the road fill. However, reforestation would not have significantly

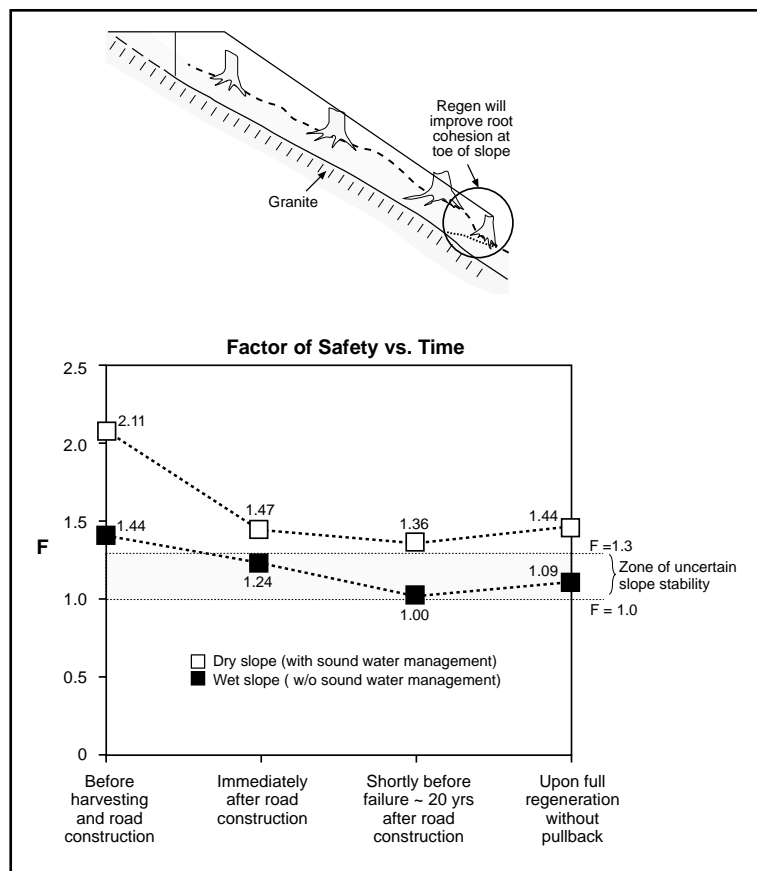


Figure 5. The slope stability “life cycle” of the road fill.

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improved stability of the road fill because few of the regenerative tree roots would have grown across the most probable failure surface in the fill slope (the zone of historical maximum rooting depth).

Stabilization options:

Figure 6 illustrates the four most practical stabilization options for the site. The slope's factor of safety (**F**) response to each of the stabilization options was calculated by making appropriate modifications to the weight (cross-sectional area) of the prospective road fill failure and water pressures in the fill slope.

The immediate slope stability effects of road deactivation:

Figure 7 is a factor of safety plot (**F**) for each of the stabilization options illustrated in Figure 6. The key conclusions from Figure 7 are:

- Water control accounts for most of the slope stability improvement in all of the analyzed stabilization options.
- P6 and P9 pullback decrease the stability of the road fill in fully saturated (wet) conditions. P6 and P9 decrease the stability of the road fill by reducing the weight of the potential failure mass; since $(\phi) > (\psi)$ removing weight on the potential failure surface decreases slope stability. Therefore, directing surface water on a partially pulled back, previously dry sidecast road fill is a calculated risk. As cross ditches are the leading cause of "road deactivation related landslides (Advanced Road Deactivation Course Manual, 1997. p 11)," there is an excellent correlation between the conclusions derived from slope stability analysis and field observations of actual road deactivation works.
- None of the analyzed stabilization options immediately assured the stability of the road fill. Poor control of surface water could easily defeat P6 and P9 pullback and might even defeat full (P15) pullback. (Please note that water-induced failure of the P15 pulled back road fill would require there to be significant errors in the back calculated slope stability parameters of the road fill.) Only sound water control and P15 gave substantial, immediate, assurance of stabilizing the residual road fill.
- P15 contributes more to slope stability by water control (see the equations for water-induced forces V and U in Figures 2 and 4) than by removal of excessive weight of sidecast road fill. Pullback reduces the water pressures in the fill slope by reducing the maximum possible depth of a tension crack (and therefore the water column and pressures) in the fill slope.

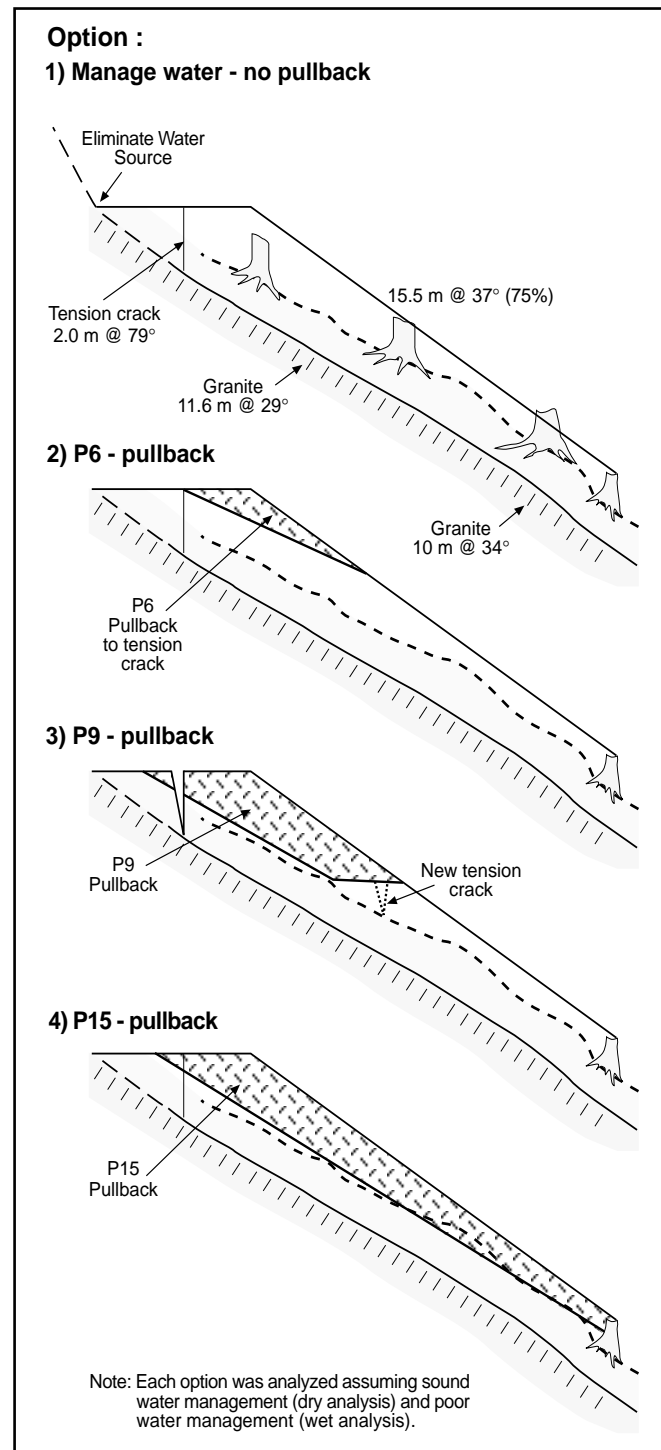


Figure 6. Stabilization Options - the most probable deactivation treatments.

The long term effects of road deactivation:

The long term effects of road deactivation work and reforestation are difficult to assess from the back analysis of a modern road fill failure. However, a few specific

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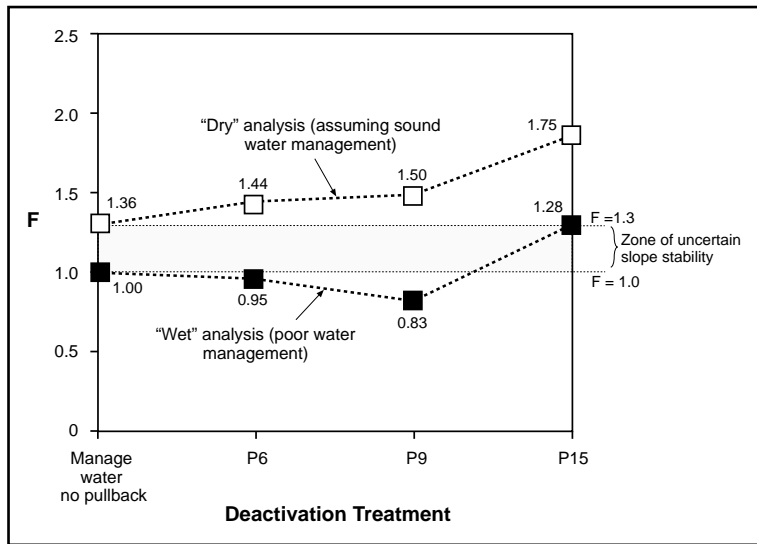


Figure 7. The Road Fill's Immediate Factor of Safety Response to Deactivation.

observations on the long-term effects of road deactivation and reforestation are possible:

- The stability of sidecast road fills generally decreases with time due to the decomposition of woody debris within the fill slope. The resulting loss of shear strength within the fill slope may be seriously compounded, or generously offset, by natural deactivation/deterioration of a site's water control measures.
- It is hard to go wrong with sound control of surface water. Control of surface water is an inexpensive and effective investment to improve the stability of sidecast road fill.
- The less residual fill on a hillslope, the better. Tree roots will not significantly improve the stability of the residual road fill unless they can reach beneath the prospective failure surface(s) in the fill slope.
- Reforestation will add tree load surcharge to the residual road fill. Whenever $(\phi) > (\psi)$ the weight of the regenerative forest on the residual (or undisturbed) road fill will very modestly improve slope stability. Conversely, wherever $(\phi) < (\psi)$, reforestation will very modestly reduce the stability of a road fill.

Conclusion

The general principles of slope stability analysis are always more robust than the details of a specific slope stability analysis. The key principals from the above analysis are: sidecast road fills can be remarkably stable when built, but quickly become potentially unstable with decay of the supporting tree roots and woody debris; and water control is the most effective

(and least costly) short-term road deactivation technique. However, long-term stability of a deep sidecast fill slope can only be assured by extensive pullback, sound water management, together with reforestation.

Slope stability analysis is a tool to explore the landslide hazard reduction potential of road deactivation work. Selecting the "right" road deactivation prescription requires broader based knowledge of landslide consequences and, ultimately, acceptable risk.

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