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Application of Decision Trees to Landslide Risk Management

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ABSTRACT

Quantitative Risk Analysis (QRA) is one of the tools used in Landslide Risk management. This paper extends this QRA tool to event trees for modelling decision options. The decision trees show decisions, consequences, outcomes and payoffs associated with the probability of occurrence. Risk profiles can then be determined for each decision via a cumulative payoff tree. Two case studies are used to examine the application of decision trees. Case 1 examines the remedial options for a pipeline within a recent landslide and with a road up-slope of the pipeline. The consequences associated with the road, is different from that associated with this high water pressure pipe. The consequences and payoffs from the decision tree were used to rationalise the acceptable factor of safety for this site. Case 2 discusses a site with a road down-slope of an existing pipeline, and cutting on both sides of the road. The possible event of a leak and the unlikely event of a pipe burst both have a catastrophic consequence, which would include a slope failure in addition to flooding of the site. These high consequences using this QRA can result in a high risk site classification despite a low probability of occurrence. The decision tree associated with the various options and consequences results in a more considered decision for LRM evaluation.

Keywords: landslide risk management, decision trees, probability of failure, factor of safety

1 INTRODUCTION

1.1 Landslide risk management

AGS (2007) uses Quantitative Risk Analysis (QRA) in Landslide Risk management (LRM). The QRA is a decision tool with risk analysis at its core after the combination of likelihood and consequence is assessed. This is a simple tool to apply when there is only 1 consequence. However, sometimes varying degrees of consequences occur. Choosing the maximum credible consequence rather than a likely consequence can provide a completely different risk profile. Additionally where different infrastructure owners are involved, the consequences and hence risk profile can be different. Pipeline infrastructure represents a static asset, while road and rail have both a static (physical) asset and a temporal (moving traffic) value. The latter is often of greater value when the cost of delay time associated with high traffic volumes, and life value are included.

Decision trees are applied to two case studies to rationalise the LRM risk profile, which in both cases would involve significant expenditures. This provides a balanced overview of both the risks and rewards associated with each possible decision, and the associated consequence.

1.2 Decision Trees

Decision trees are used to rationalise financial management options. The basic components of decision trees with respect to geotechnical engineering are covered in Gilbert et. al. (2008) and Baecher and Christian (2003). This paper extends the QRA tool to event trees for modelling all possible decision options. The decision trees show these options, outcomes and payoffs, along with the values and probabilities associated with them. Bayes' theorem is used to assess the probability of each event. Risk profiles can then be determined for each decision via a cumulative payoff tree. The value of each path in the tree is calculated by summing the value for each branch in the path with its probability. Each branch represents a choice between alternatives. The consequences are uncertain and are associated with various probability of occurrence.

The AGS LRM procedure is given in tabular form for a single event. A decision tree presents such information in a pictorial form, and allows multiple events to be assessed. The decision cost is calculated by applying a weighted average of the consequential costs of each outcome factored with its probability of occurrence and solved in 2 stages: 1) Forward pass where the alternatives are represented as the limbs joined by decision nodes; 2) Backward pass - this evaluation stage allows the consequences of such decisions to be compared with alternative decisions.

Precision Tree (2009), an add-in to excel was used to create the decision trees shown.

2 CASE STUDY 1: PIPELINE BELOW ROADWAY

A landslide occurred following the high summer 2010/2011 rainfall events in Queensland and affected a roadway, a high water pressure pipeline down-slope of a roadway, and adjacent farmland (Figure 1). The cost of remediation over 150m was significant, yet the consequences in terms of the owners of the roadway or the pipeline are quite different. However, the traffic volume for this roadway is relatively low, and the high cost of repair was disproportionate to the risk profile. The pipeline owner would require factors of safety as compared to the road owner for this site. The consequences and payoffs from the decision tree were used to rationalise the acceptable factor of safety for this site. The adjacent farmland would be a different risk profile for this landslide.

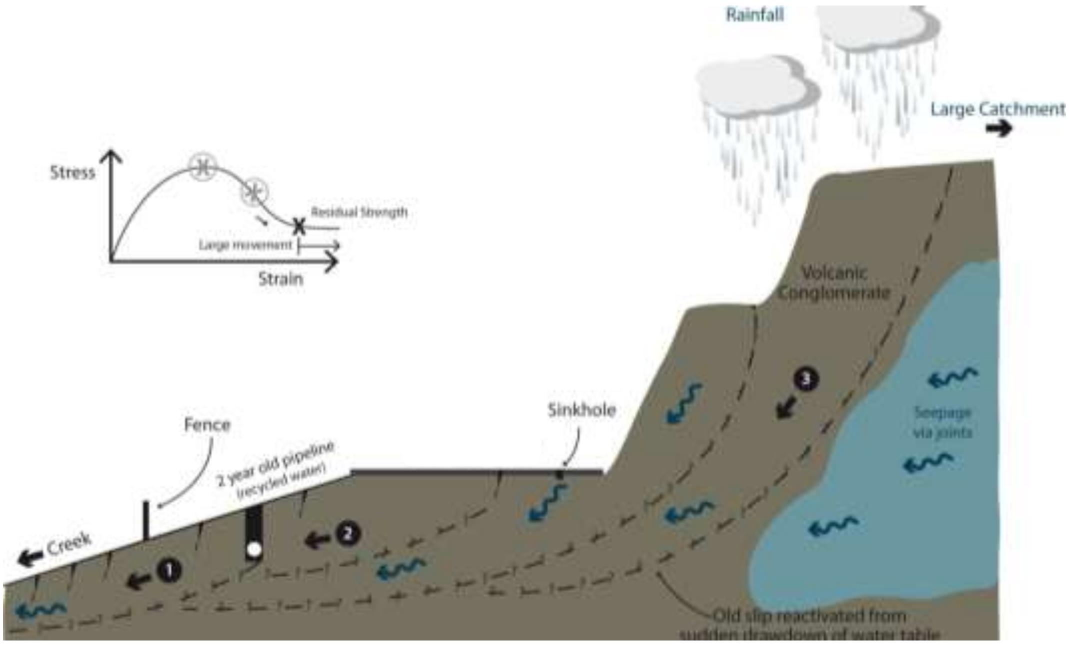

Figure 1 Pipeline located down-slope of road with active landslide

2.1 Stability Analysis

This high pressure water main is located in a landslide area. This movement occurred following a high summer rainfall. Analysis showed 3 distinct elements to the stabilisation of this landslide:

1) Installing trench drains which would limit the of water to a depth of 2m below the ground surface;

2) Unloading the slope above the road - but this was limited to the land within the road corridor;

3) To arrest further creep movement with potential damage to the pipe, a structural support (anchors)

Elements 1) and 2) were carried out as “temporary works” to control the landslide movement which may occur for the next summer rainfall. This provided a factor of safety (FS) which varied from 1.2 to 1.3 over the 150m landslide extent. The long term remediation involved anchors to control the movements above and below the pipeline at the critical section. A construction cost was estimated to be greater than 5 million dollars for a preliminary design using a FS greater than 1.5 to control the movements. Such costs were not comparable to the risk costs of the pipeline not functioning or being relocated. A risk assessment was therefore undertaken in parallel with design optimisation.

2.2 Risk Assessment

The decision tree (Figure 2) shows the design alternatives, and the associated risk. The decision nodes shown are for the current situation i.e. follows the TRUE branch only. If an "accept risk" approach had been adopted, then there are 2 possible outcomes. The analysis for the 2 outcomes shows a net $3.5 million dollar risk (70% probability of occurrence times the $5 million dollars worth of this pipeline asset). This does not account for societal and political "costs".

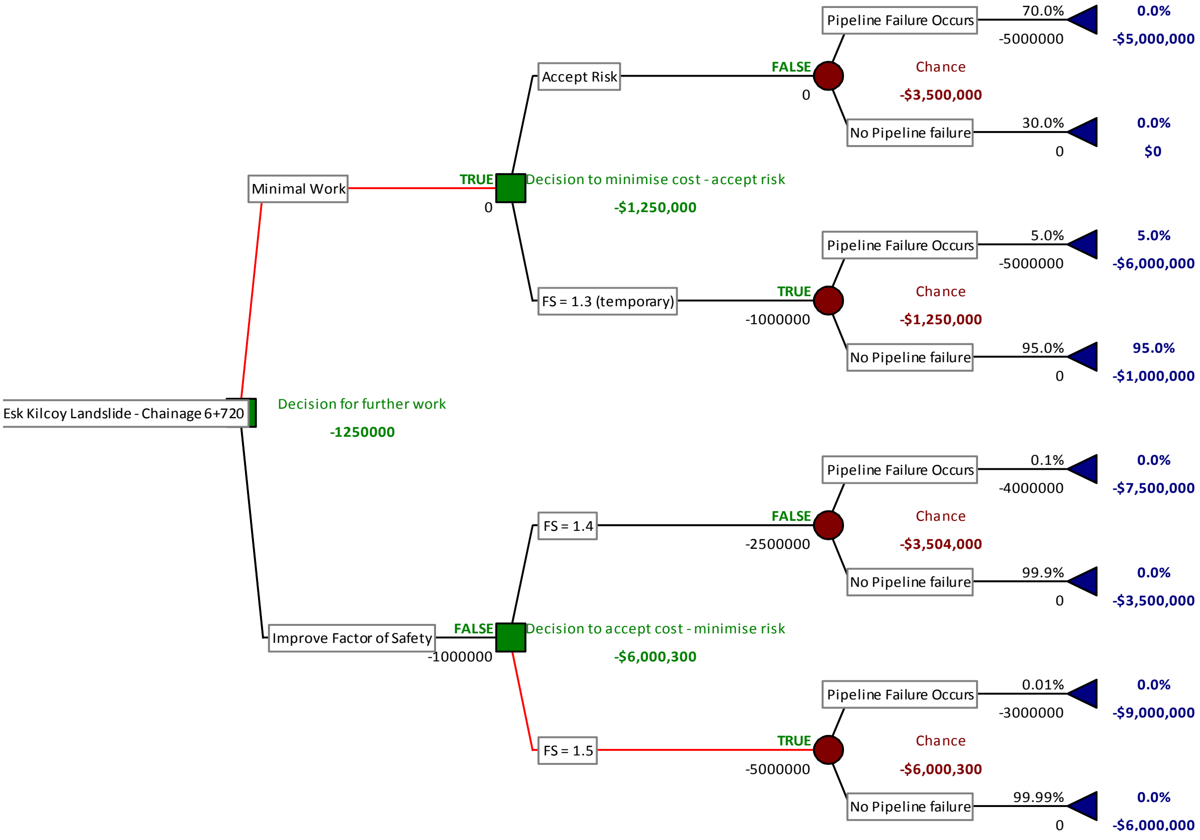

Figure 2 Decision tree showing costs of various risk management options

For this case study, the top branch is the do nothing option which would provide an almost certain likelihood according to the AGS 2007 descriptors. The temporary fix (FS ~ 1.3) is a likely condition of failure in the long term. The branch which has an improved factor of safety (FS) of 1.4 and 1.5 represents a possible and an unlikely likelihood, respectively.

Typically a "temporary" factor of safety has a 1% to 10% chance of failure, and 5% was used in the above analysis with $1 million dollar expenditure to place trench drains and unload the slope above the road. There would now be a 5% probability of occurrence times the $5 million dollars worth of this pipeline asset in addition to the $1 million dollar expenditure which would result in $1.25 million dollar total loss if failure still occurred.

The "usual" factor of safety (FS) of 1.5 would result in a design where the expenditure ($5 million of anchors) would be excessive as compared with the risk. The "do nothing" option had a $3.5 million net risk cost while this tree branch now has a net $6,000,300 net risk cost. As a geotechnical engineer, the traditional preference is for the least risk option i.e. the FS > 1.5 which equates to an unlikely event. However, this is a low volume road (< 1,000 vehicles per day), with other landslides further along this road competing for a limited funding. The preferred least risk option at this site must be considered with the larger road length risk that if full expenditure occurred on this one landslide, then this may preclude fixing of other landslides.

Reducing the factor of safety to 1.4 and with the associated $2.5 million expenditure provides a break even cost – risk decision i.e. $3,504,000 which is approximately equivalent to the "accept risk" branch of the decision tree. The decision tree suggests that the current expenditure level (Stage 1 only) may well be the optimal cost - risk level. However this is at a 5% risk of failure which is high for any significant infrastructure as continued creep movement may still occur. But this "significance" was different for the road, pipe or farmland owners.

The decision tree calculates a breakeven construction cost for a factor of safety of 1.4 instead of the usually applied factor of safety of 1.5. This decision would balance the risk vs. expenditure, but with a 0.1% probability of failure, which would be generally acceptable to the road owner but not to the pipeline owner. Given the significant expenditure (and low traffic volumes) the road owner may also consider a 1% (10^{-2}) probability of failure (Table 1). The farmland owner risk profile is also shown.

Table 1: Risk perceptive of the asset owners

Owner of	Consequences (Ref AGS 2007)	Acceptable annual probability for moderate risk	Comment	"Static" probability
Road	Major – Medium	10^{-3} to 10^{-4}	Alternative route available	< 10^{-4}
Pipeline	Catastrophic - Major	10^{-4}	No alternative route	10^{-4}
Farmland	Insignificant	10^{-1}	Undulating cow paddock is only effect	10^{-1}

3 CASE STUDY 2: PIPELINE ABOVE ROAD CORRIDOR

This "what if" case study is for a stability and risk assessment similar to Figure 1, but for a stable cut soil slope but with the cutting on both sides and a high traffic major transport corridor down-slope of an existing pipeline. Most cuttings above 7m would have benches of typically 4 to 5m width. If large enough, this space then becomes attractive to other providers such as a water corridor or bike path, where there is a trend to have multi use service corridors.

This case study examines the changes in risk profile if a high pressure water pipeline is now located under the middle bench of the cutting. The possible event of a leak and the unlikely event of a pipe burst both have a catastrophic consequence, which includes a slope failure and/or flooding of the site. These high consequences results in a high risk site classification for an unlikely probability of occurrence. This change of use for the same slope now has a different risk profile. The change in risk profile if the bench also includes a bike path is also examined.

3.1 Stability Analysis

A slope stability analysis may show an adequate factor of safety for both the short and long term condition. The probabilistic approach would typically produce a probability of failure less than 1 % to 0.1% when calculated. However, based on the LRM approach, a value less than 0.01% would be more appropriate with a high consequence and higher potential risk to life. This scenario of both an extreme event of a pipe leak as well as the water table raised is required to be evaluated for both a typical rainfall and extreme water event.

The effect of the pipe bursting on the slope stability depends on the permeability of the in-situ material, susceptibility to erosion, loss of strength due to increase in moisture content and soaking. These water table changes and material change parameters can be modelled in the slope stability analysis with a corresponding probability of failure if the soil strength mean and standard deviation value is input.

3.2 Risk Assessment

The hazards identified that can lead to risks on their own or contribute to other risks when a change of use occurs include:-

1) Cut slope failing due to high water level at trench, and strength reduction;

2) With a buried pipe line, the pipeline leaking or bursting completely;

3) A paved bike path increases service vehicles/machinery operating on the slope middle bench

The less likely event of a leak (assuming a well constructed pipe line) and the rare event of a pipe burst are both valid failure mechanisms but with a low and high consequence, respectively. With a high pressure water main, the flooding can occur quickly and have a high consequence for a high speed roadway located below even for a light traffic volume.

If the LRM approach is used directly the catastrophic consequences at this site governs the assessment resulting in an overall very high to high risk level. But judgement is now required to differentiate between the most likely events of a pipe leak versus a maximum credible event of a pipe burst. The consequence of the pipe bursting could be major if the water travels directly towards the road corridor. This may result in flooding the roadway, delays to road users and may cause injuries. The latter is a catastrophic event, but the more likely event of pipe leaking only has lower consequences. Thus this one hazard needs to be refined further for a spectrum of consequences.

3.3 Decision Tree assessment

Table 2 shows the likely probability if failure associated with the case with and without a pipe trench and with the addition of an additional heavy (service vehicles) surcharge load resulting from a paved access corridor (the bike path). The factor of safety is still acceptable but the probability of failure (likelihood) has changed. More importantly the consequences have change significantly.

Table 2: Risk perceptive of the asset owners

Bench use	Slope stability	Probability of failure	Risk
None	FS > 1.5	10^{-3} to 10^{-4}	Low to moderate
With Pipeline	reduced strength : FS > 1.5	10^{-2} to 10^{-3}	High to very high
With Pipeline + bike path / vehicle access	Increased surcharge FS > 1.5	10^{-2} to 10^{-3}	High to very high

With the increased probability of failure and risk, the geotechnical decision would be to not use the bench for a service corridor. However, with environmental and public acceptance constraints, corridor sharing is often preferred. Incorporating geotechnical risk into the financial equation now occurs.

Figure 3 shows the decision tree for various options with and without the pipe trench, and the relative cost benefit. The costs associated with major and minor consequence ($10 million vs. $1 million) are shown as negative values, and has to be factored for its probability of occurrence. The investment cost of this infrastructure ($3 million and $5 million) for the pipe only and pipe with bike path combined, respectively, is a positive contribution i.e. value adding, despite the above offset risk. The “costs” of reputation and injury could be higher than the more quantifiable asset value and delay time shown. A sensitivity analysis shows the probability of the pipe burst and its consequential cost would need to be an order of magnitude higher for the decision to use the bench as a service corridor to be unattractive.

Only the “true” branch is shown in Figure 3 and referenced to its probability tree. The other referenced trees are not shown for paper brevity. The decision tree (true branch) shows a “positive” financial risk when the probability and consequence costs with the pipe trench is placed on the bench. The net negative cost of $20,000 is a weighted cost, which includes various consequence costs factored with likelihood and the 98.9% probability that no consequences costs occur. Therefore while there is an increased risk and probability of failure, the weighted consequential costs are low enough (from a probability perspective) to consider as a “positive” risk when combined with the asset value benefit. This should not detract from the responsibility to reduce these major consequences to an acceptable level. Subsequent branches assessed the risk minimisation of the catastrophic consequence by quantifying the risk profile.

4 CONCLUSION

The decision trees allow complex situations to be presented in pictorial form. This provides a quantitative assessment of both probability and consequential cost to various decision options. Two case studies were used to illustrate the application of decision trees in landslide risk management

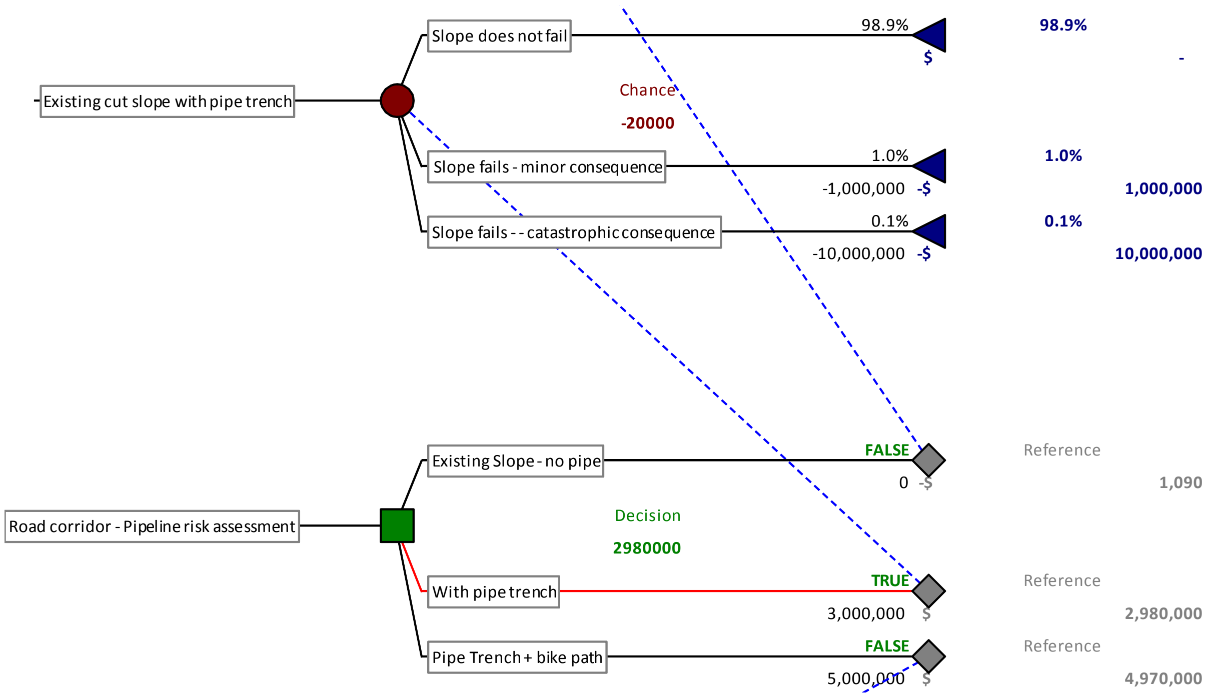

Figure 3 Decision tree showing risk – benefit - cost of various options

For a failed slope the decision tree shows that remedial options using a factor of safety of 1.5 can have a disproportionate cost with the associated risk. Yet that factor of safety is the traditional approach which equates to an unlikely event. Using a risk management approach provides a consideration of consequences. The decision tree becomes another tool to assess different consequential costs by balancing cost–benefit with probability of occurrence. The "cost – benefit" factor of safety was lower than the traditional factor of safety for this case study. The perceived consequences can vary based on an asset owner consideration and different risk profiles may result.

For a stable slope a factor of safety approach (FS > 1.5) would lead to a do nothing option. Yet using the LRM guidelines result in a high risk due to consequences to the road below. The catastrophic consequence determines the high risk although there is a low probability of occurrence. The range of consequences needs to be factored into the decision. The additional risk associated with installing a pipe trench is shown as both the probability and its consequences increased.

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