6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

The Transmission Gully Project: Method for Assessing Seismic Stability of Large Rock Cuts In Steep Terrain, Considering Topographic Amplification

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ABSTRACT

This paper presents the methodology used to analyse the 'global' seismic stability of the rock cuts along the new 27 km Transmission Gully motorway route, north of Wellington, New Zealand. The route is in a seismically active area, passing through mountainous terrain and across active faults. The rock cut height is up to 60 m, into natural slopes often over 200 m high. Due to the large number of cuts, a simple but rational methodology based on the limit equilibrium technique was adopted. The method accounts for topographic amplification, scale effects, and post-peak rock mass strength, and is able to appropriately identify the size and location of potential instability mechanisms. The method was validated using a series of fully dynamic numeric models. It is envisaged that the method could be adopted on other similar projects, especially rock cuttings for New Zealand transportation routes in steep terrain.

Introduction and project background

This paper presents the methodology used to assess large-scale seismic stability of the rock cuts along the new 27 km Transmission Gully motorway route, north of Wellington, New Zealand. The route is in a seismically active area, passing through mountainous terrain with natural slopes over 200 m high. Generally the rock cuts are to be excavated into the toes of the natural slopes.

Due to the large number of cuts, a simple but rational and contemporary method of assessing 'global' stability was required, which could identify the size, location, and stability of potential failure mechanisms. The method developed and presented in this paper brings together existing concepts with new ideas, and has been tailored to the project topography. Importantly, it recognises that although topographic amplification of earthquake shaking occurs, the effect is relatively minor for cuttings at the toe of natural slopes, and that although a weaker rock mass may be more likely to momentarily yield during an earthquake, it is also more likely to remain ductile.

It is expected that the method could be readily adapted for other similar projects, particularly to cuts and natural slopes in New Zealand topography and rock masses.

Another paper submitted to this same conference (Rouvray et al, 2015) describes the project performance based design criteria, and also discusses rock cut failure mechanisms other than

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‘global’ stability and typical countermeasures to achieve the project requirements.

Limit equilibrium analysis framework

The use of the limit equilibrium technique for assessment of seismic stability is considered particularly applicable for projects of this nature because firstly, static stability is usually assessed using the same approach, and secondly, in practice, dynamic stability analysis of all the cuttings along a 27 km route is not economically feasible. The limit equilibrium technique was therefore selected for the project, on the basis that its limitations could be adequately addressed. A primary limitation is that the analysis assumes a rigid potential slip mass moving on a defined plane. The method addresses this limitation by applying a seismic loading that explicitly accounts for the non-rigidity of the slope and the knock-on effects that result from this.

Seismic loading estimation

For the stability of a cut made into an existing natural slope, how the cut experiences the seismic loading is more important than the reaction of the overall natural slope. The loading experienced by potential failure mechanisms of the cut depends not only on the characteristics of the natural slope, but also on the size and location of the cut relative to natural slope. The procedure developed to estimate seismic loading for limit equilibrium analysis involves:

- Obtaining the peak acceleration (i.e. maximum acceleration at any time during the earthquake) at the base of the natural slope (e.g. from a seismic hazard study). For brevity we named this acceleration ‘PGA_{base}’.
- Estimating the peak acceleration at the crest of the natural slope by applying a Topographic Amplification Factor to PGA_{base}. We named this acceleration ‘PGA_{crest}’.
- Estimating the peak acceleration at the top of the slope failure mechanism being considered, by applying a Location Factor which is simply a linear interpolation between PGA_{crest} and PGA_{base} based on height. We named this acceleration ‘$PGA_{mechanism}$’.
- Estimating the average acceleration experienced by the mechanism (if it were a rigid body) by applying a Scale Reduction Factor to $PGA_{mechanism}$ which is based on the size of the mechanism in proportion to the size of the natural slope. The resulting acceleration is the ‘pseudo-static’ load to be used in the limit equilibrium analysis, commonly called k_h.

This process is shown graphically in Figure 1. Therefore in short:

$k_h = PGA_{base}$ x Topographic Amplification Factor x Location Factor x Scale Reduction Factor (1)

An importantly thing to note is that by this method, for a single cut, the seismic loading is different for each different size and location of mechanism being considered. This results in more realistic loads being estimated, for example:

- A small cut at the toe of a natural slope experiences a relatively low seismic load, regardless of the topographic amplification experienced further up the natural slope.
- Conversely a small cut or surficial mechanism near the peak of a natural slope

experiences a relatively high seismic load due to topographic amplification.

- A large cut, even one extending a fair distance up a natural slope, can still experience relatively low seismic loading in accordance with the size of the mechanisms involved.

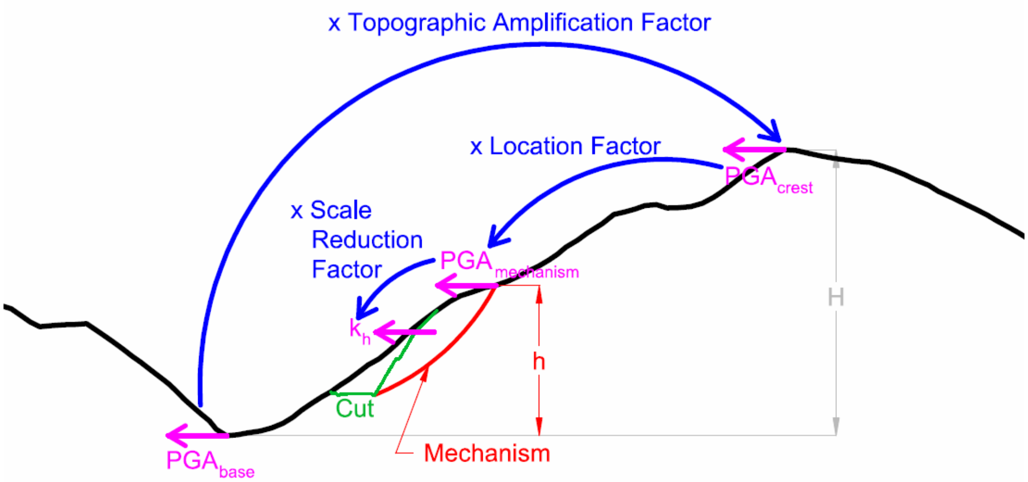

Figure 1. Seismic loading estimation procedure

To help quantify the various factors listed above dynamic numerical modelling was undertaken on six typical two-dimensional cross-sections along the project alignment. The dynamic modelling was undertaken by elastic time-domain analysis using the Abaqus software (Simulia, 2012). A uniform Young's modulus of 12 GPa was adopted, corresponding to a shear wave velocity of about 1400 m/s. The models were subjected to three different earthquake records that matched well to the 'design' response spectrum at the base of the natural slope. The modelling was targeted at key sections and was designed to prove the method rather than as an investigation of academic rigor as seismic subtleties not affecting the outcome were not investigated.

Topographic Amplification Factor

Given that a natural slope is not rigid, it has the potential to amplify (or dampen) the seismic shaking that passes up through it. Most of the literature on this topic is in the domain of seismology. There are engineering approaches for certain scenarios these being mostly for soil slopes e.g. earth dams and coastal bluffs. This project had different considerations because the natural rock slopes are larger and stiffer than what has been considered in soil slope approaches.

From the numerical analyses, the peak accelerations experienced along the natural slope surface at any time during the modelled earthquake were extracted. In Figure 2 these accelerations have been normalised against the peak acceleration at the natural slope base and so they represent the Topographic Amplification Factor. Based on these results and with guidance from the literature (e.g. Beuch et al, 2010, and Davis & West, 1973), the Topographic Amplification Factors shown in Table 1 were adopted. Note that this approach assumes that the cutting does not significantly modify the overall natural slope geometry (which was true for this project).

For other applications in particular smaller scale mechanisms it may be appropriate to increase the Topographic Amplification to account for features such as a soil mantle and local prominences.

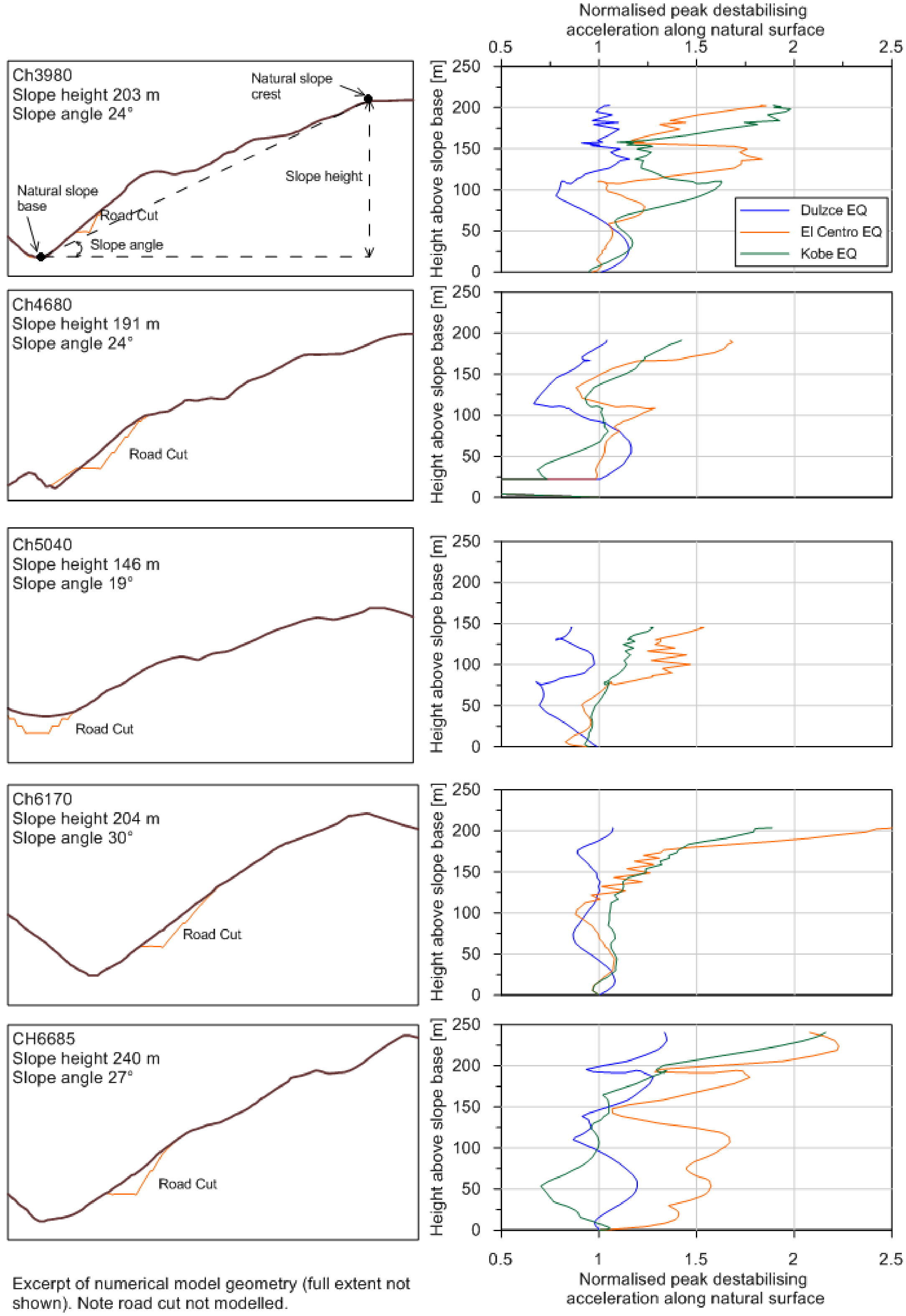

Figure 2. Topographic amplification

Table 1. Topographic Amplification Factors

		Slope angle		
		0° to 15°	15° to 30°	> 30°
Slope height	0 m to 50 m	1.0	1.2	2.0
	50 m to 200 m	1.0	1.5	3.0
	> 200 m	1.0	2.0	4.0

Discussion on slope dynamics

It is recognised that the most common view is that topographic amplification is largely dictated by the resonant behaviour (natural period) of the slope, which is dependent on stiffness (dynamic rock mass modulus) as well as geometry, rather than just geometry as shown in Table 1. Amplification is thought to be greatest when the predominant period of the earthquake corresponds with one of the slope's resonant periods.

The authors agree in principle with this view. However in this study, sensitivity analyses (not presented herein) found no strong correlation between rock mass modulus and topographic amplification. This may have been due to the inherent variability of the real earthquake records used. A detailed modal assessment may shed more light on this as it provides the slope dynamic response, independent of the earthquake characteristics. The authors have successfully used this approach for similar purposes on previous projects (e.g. Toh et al, 2013).

The authors are also aware of methods for calculating resonant periods of soil slopes, most of which are based on slope height and shear wave velocity (e.g. Ambraseys, 1960). They do not consider these methods universally applicable, especially since natural slopes have so much inherent variability in their properties and geometry. Consequently if topographic amplification effects are important for a project, the authors currently recommend that some site specific numerical analysis is undertaken.

An important observation regarding investigations into slope dynamics is that traditional geotechnical "conservatism" (cautiously under-estimating parameters) does not apply when selecting rock mass modulus; instead a best guess (and probably sensitivity analysis) is required. This is because a low modulus gives a flexible slope that doesn't attract much load; conversely a high modulus gives a more rigid system may attract higher loads.

Location Factor

The Location Factor is a linear interpolation between PGA_{crest} and PGA_{base}, to obtain the peak acceleration at the top of the mechanism ($PGA_{mechanism}$). A linear interpolation is considered reasonable if not slightly conservative, based on the results in Figure 2. Mathematically:

$$\text{Location Factor} = \frac{\text{Height from natural slope base to top of mechanism ('h' in Figure 1)}}{\text{Height from natural slope base to natural slope crest ('H' in Figure 1)}}$$

Scale Reduction Factor

The non-rigidity of natural slopes also means that the average acceleration acting within a mechanism is less than the peak acceleration. This is especially the case for large mechanisms. When the peak acceleration is experienced at one location within a mechanism, other locations may experience far lower accelerations, or even accelerations in the opposite direction.

A Scale Reduction Factor is therefore required to calculate k_h from $PGA_{mechanism}$. The factor is based on the height of the mechanism compared to the height of the natural slope. To calculate the factor, four different size mechanisms were investigated for each cross section analysed. This is a similar to common approaches in the literature. Refer to Figure 3 for an example of the calculation method. Figure 4 shows the results of the calculation. The adopted Scale Reduction Factor ranges from 100% to 70%, and it is noted that the 70% errs on the conservative side.

For this scale effect, again traditional geotechnical "conservatism" does not apply. A lower modulus giving a more flexible slope would mean greater scale reduction.

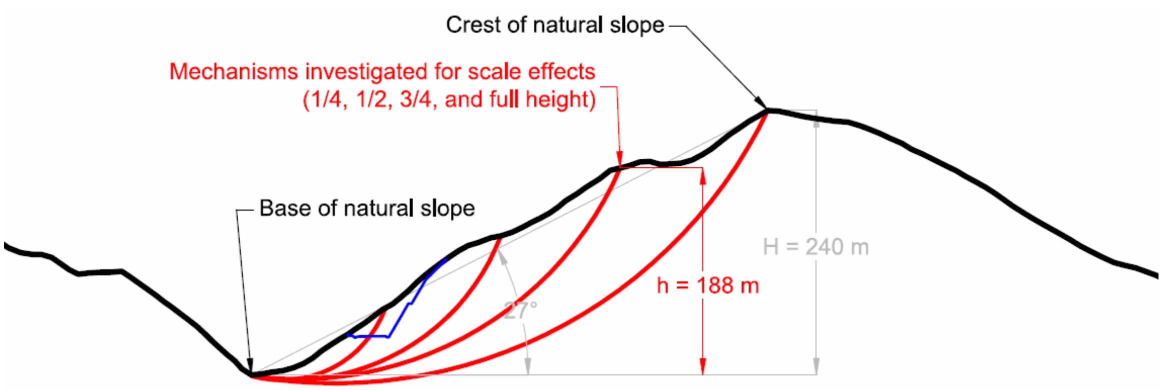

Figure 3. Scale Reduction Factor calculation method

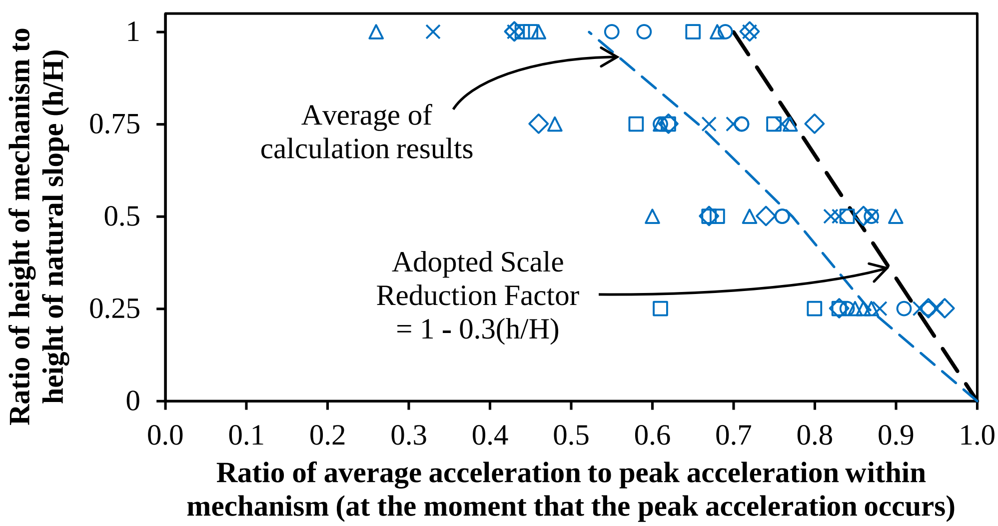

Figure 4. Scale Reduction Factor

Rock mass strength

If the limit equilibrium factor of safety is less than one, Newmark sliding block models can be adopted to estimate coseismic displacements provided there is no strength loss. There is little in the literature for post yield rock mass strengths under static conditions and even less for dynamic conditions. A GSI based approach (Hoek & Brown, 1997) predicts that high strength good quality rock masses are brittle and experience significant post yield strength loss, while low strength fractured rock masses are ductile and do not experience strength loss post yield. Refer to Figure 4 for an interpretation of this assessment.

Interestingly this probably means that in most practical scenarios for 'global' stability a Newmark sliding block model can be adopted, because it is the low strength rock masses that are more likely to yield whereas high strength rock masses are less likely to experience factor of safety drop to below one (unstable).

The following scenarios may also not satisfy the 'no strength loss' criterion:

- Slip surfaces entirely through rock substance (would probably be of a small scale).
- Where there are high tensile stresses (e.g. toppling mechanisms, steep failure surfaces).
- Where there is low or no confinement to prevent high dilation or break up of the rock mass (e.g. for shallow rock slides and debris flows).
- Defect controlled mechanisms where the defect is not already at residual strength.

This re-emphasises the need to examine individual mechanisms, as not only is the loading different for each mechanism, the strength response can also be different.

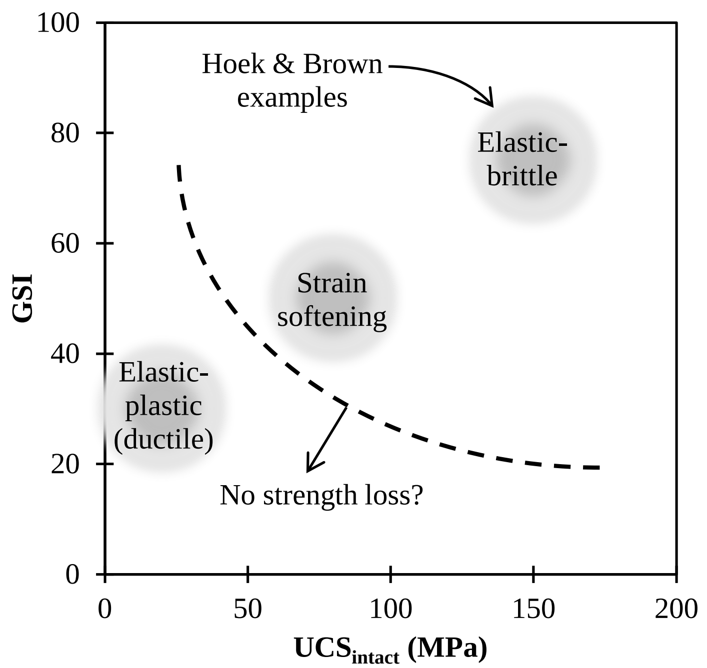

Figure 5. Post peak rock mass behaviour

Conclusions

A method has been developed to assess large scale seismic stability of cuts made into natural topography by limit equilibrium techniques. It requires, for each potential failure mechanism:

1. Estimation of the seismic load coefficient for limit equilibrium analysis, accounting for topographic amplification, the location of the mechanism within the natural slope, and the size of the mechanism.
2. Undertaking limit equilibrium stability analysis for each mechanism.
3. If the factor of safety is less than one for any mechanism, assessment and adoption of post yield rock mass strength and estimation of coseismic displacements.

The method provides a rational approach to estimating seismic loading which results in sensible outcomes, for example seismic loading is relatively lower for small cuts near the toe of natural slopes and for very large mechanisms, and relatively higher for small or shallow mechanisms near the crests of natural slopes. Importantly, by considering each of these mechanisms separately, they can be assessed on their individual merits.

It is expected that the method could be readily adapted for other similar projects, particularly to cuts and natural slopes along transportation routes in New Zealand topography and rock masses. It would be worth further investigating slope dynamics particularly by modal analysis of slope resonant periods, to see how strongly topographic amplification is linked to slope resonance, and to further distill the key factors affecting the response.

Acknowledgements

The authors acknowledge the NZTA and the Wellington Gateway Partnership including the Leighton HEB JV and the AECOM URS JV, for their support. Also the assistance of PSM colleagues on the project, Ben Rouvray, Ralph Cammack, Beatriz Estrada, and Garry Mostyn.

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