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Performance Based Geotechnical Design of a Seismically Resilient Motorway: The Transmission Gully Project, New Zealand

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ABSTRACT

This paper describes the geotechnical earthquake engineering philosophy adopted for the design of the new 27 km Transmission Gully motorway route, north of Wellington, which is the first motorway procured as a Public Private Partnership (PPP) in New Zealand. The route is being constructed in a seismically active area through mountainous terrain and includes significant earthworks with rock cuttings up to 60 m high and earth embankments up to 40 m high. The challenge of providing a cost effective, seismically resilient design within the framework of a PPP project required a clear definition of the road performance requirements against which the design could be developed. This paper describes the design philosophies and development of quantitative performance based design objectives to achieve the required level of resilience across the range of limit states, whilst balancing whole-of-life costs. .

Introduction

The Transmission Gully project is located north of Wellington and is a new 27 km motorway between Kenepuru and MacKays Crossing. The route traverses challenging mountainous terrain and is located in a highly seismic area. One of the NZTA (New Zealand Transport Agency) objectives for the project is to increase the overall seismic resilience in to and out of Wellington by providing a more resilient alternative to the existing coastal road as a lifeline route.

The procurement of Transmission Gully project was undertaken via a Public Private Partnership (PPP) commercial model that through shared ownership encourages whole-of-life, value for money outcomes to be delivered for capital and operational costs. The NZTA website states:

"*PPPs allow large and complex projects to benefit from private sector innovation and funding which can increase certainty of delivery and drive better value-for-money. The 27 km Transmission Gully motorway project had the size and complexity which made it a good candidate for a PPP. The project met the government's value-for-money criteria, and offered opportunities for private sector innovations in design, construction, maintenance and operation that the NZ Transport Agency can then apply across the wider transport network. Specifically, this project has a significant number of structures and geotechnical challenges where private sector innovation can drive greater value for money than is possible by traditional public sector*".

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There is little precedent for large PPP motorway projects within areas of significant seismic and other natural hazards. This was recognised by NZTA and the PPP proponent Wellington Gateway Partnership (WGP) within the tender phase, leading to the establishment of a performance based commercial arrangement for the PPP. This included specification of a natural events regime to incentivise the operations of the motorway in response to natural hazard events. The commercial framework of the PPP contract is not discussed further, although it is noted that the commercial framework encouraged the development of the robust performance based design philosophy described herein.

This paper focusses on the process adopted by the geotechnical designers to turn NZTA's resilience objectives into quantifiable design criteria. In summary this comprised:

- Understanding NZTA's resilience objectives, and the corresponding limit state performance requirements.
- Developing project specific performance objectives to meet the limit state requirements.
- Assessing design philosophies to meet the performance objectives whilst also achieving value for money and whole-of-life outcomes for the PPP.
- Quantifying specific performance based design criteria to be used in the design and earthquake engineering of the various geotechnical works.

The seismic setting of the project and background to the selection of resilient transport routes has been discussed extensively elsewhere and detailed in NZTA reports, so is not repeated here.

Resilience

NZTA's objective of providing a nationwide network of resilient transport 'lifelines' stems from responsibilities under New Zealand's Civil Defence Emergency Management Act (2002) which, among other things, requires that 'lifeline' transport networks need to be able to function during and after an emergency event, and have plans for functioning (continuity) after such an event. The key design considerations in achieving a resilient motorway are therefore ensuring the required level of service is maintained following a given event, and the time to reinstate the motorway is acceptable.

To achieve an effective design for the Transmission Gully motorway it was critical to provide seismic resilience across the full range of seismic events and not merely focus on the largest design earthquake. This aspect of the design was informed by the NZTA Bridge Manual (2014), which is the design standard adopted for highways in New Zealand, including geotechnical design. Based on the Bridge Manual, NZTA nominated an Importance Level of 3 that defines the earthquake recurrence to be considered in design. NZTA also procured and nominated use of a site specific seismic study, which ensured the seismic loadings to be considered in design were explicitly defined for all tenderers.

Seismic Limit States

The Bridge Manual specifies qualitative and quantitative requirements for achieving the desired level of resilience. It does this by defining several seismic design limit states and their associated seismic design loading (based on seismic recurrence interval) for all geotechnical

Probability of Exceedance	1/ 25	1/ 50	1/ 100	1/ 500	1/ 1000	1/ 1500	1/ 2500	>1/2500 "Extreme"
STRUCTURES (ie Bridges)								
Bridges and Geotech affecting Bridges (eg Abutments)			Minor Equiv.				Design Level	Major Equiv (MCE)
SOIL STRUCTURES (Non bridge Geotechnical elements)								
Retaining Walls >5m and 100m²	UNDAMAGED		OPERATIONAL CONTINUITY				Design Level	
Retaining Walls <5m or 100m²					Design Level			
Fill slopes <6m high				Design Level				
Cutting Slopes				Design Level				
Fill Slopes >6m high					Design Level			
DESIGN COMPLIANCE REQUIREMENTS	SLS 1		SLS 2		ULS			Collapse Avoidance

Figure 1. NZTA Bridge Manual Seismic Limit States

elements associated with highway design. These limit states define the various resilience objectives for geotechnical elements as:

- "Undamaged" – shown as Serviceability Limit State 1 (SLS1).
- "Operational Continuity" – shown as Serviceability Limit State 2 (SLS2).
- Ultimate Limit State (ULS), with accessibility and reparability objectives.

Each limit state has a specified seismic loading defined by the probability of exceedence, which varies according to the design element being considered. Figure 1 summarises the design limit states for seismic performance as defined in the NZTA Bridge Manual for Importance Level 3. It is apparent that to economically achieve the limit state requirements, a "performance based design" is required. That is, some damage is permitted in certain seismic events.

Performance Based Design Objectives

The objectives for each geotechnical seismic limit state are presented within the Bridge Manual as a combination of qualitative and quantitative objectives. Transmission Gully includes 27 km of varied geotechnical works including both cuts and embankments, and the PPP model required definitive performance based design objectives. Clear quantitative performance based design objectives were developed to correspond to each of the Bridge Manual limit states. This was critical to ensure that the operations/maintenance and commercial aspects of the Transmission

Gully PPP can consider tangible post earthquake outcomes. It also provided the framework which allowed design alternatives to be compared and design criteria to be developed.

Table 1: Performance Based Design Objectives developed from NZTA Bridge Manual

Seismic limit state	NZTA Bridge Manual Definition	Transmission Gully Performance Based Design Objectives
SLS1	Defined simply as "undamaged"	Emergency vehicle unimpeded access Motorway trafficked lanes fully operational after assessing seismic event consequence Seismic effects require only routine motorway maintenance (e.g. drain clearing, rockfall clearing) Pavement remains serviceable at design speeds Rockfall permitted within design measures/ expectations
SLS2	*"Operational Continuity", including:* *- full live load capacity is maintained* *- the road shall be useable by emergency traffic* *- full vehicle access is restorable within 24 hours* *- any necessary repairs shall be of such a nature that they can be completed within one month*	Emergency vehicle access Maintain one trafficable lane in each direction after assessing seismic event consequence Element maintains required load capacity Trafficked lane pavement serviceable, albeit at potentially reduced speed Maintenance and rehabilitation to return to motorway condition can be achieved within 1 month assuming resource availability "Non-routine" maintenance provisions permitted (e.g. crack sealing, rockfall removal, drainage measures)
ULS	*Post Earthquake function - Useable by Emergency Traffic* *Post Earthquake function (After reinstatement) - Feasible to reinstate to cater for all design-level actions, including repeat design level earthquakes* *Acceptable Damage - Damage possible, temporary repair may be required*	Emergency vehicle access at low speed Cuts can be reinstated to stable slope for remainder of asset life. Stabilisation and scaling works to cutting likely required Differential settlement does not exceed 150 mm step in trafficked lane pavement Required load capacity of embankment or cutting can be reinstated after remediation (i.e. without reconstruction).

Table 1 summarises the Bridge Manual objectives for each geotechnical seismic limit state, and the corresponding quantitative performance objectives that were proposed to the NZTA and accepted for the design of this project.

Design Philosophy

In addition to NZTA's resilience requirements, commercial aspects such as the costs to build, operate, maintain, and repair, were obviously important considerations for the project.

A fundamental tenant of the design philosophy was to consider seismic performance across the full spectrum of design earthquakes required to be considered. This means that rather than focusing on resilient outcomes for the largest earthquake event being considered, the smaller and more frequent earthquake events may govern the design solution, albeit accepting that a more adverse outcome may occur for the larger earthquake. This required an assessment of value for money by considering initial capital expenditure in combination with maintenance and reinstatement costs in the future.

Under the performance based design framework of the project, it was possible to holistically compare design options. The following provides two semi-quantitative examples of geotechnical design solutions including postulated post earthquake outcomes. The dollars should be considered relative only and are deliberately without scale to emphasise the relative as opposed to absolute comparison. It is emphasised that this comparison was specific to Transmission Gully and does not intend to universally propose one design solution over another for seismically resilient design.

Embankments: unreinforced versus reinforced slopes

Figure 2 compares the design outcome for an unreinforced versus a reinforced slope within an area of the project route that was significantly constrained and located within steep topography. Figure 3 presents a comparison of the initial construction cost and relative cost for maintenance and/or reinstatement for various scales of earthquakes. The design limit states are also indicated.

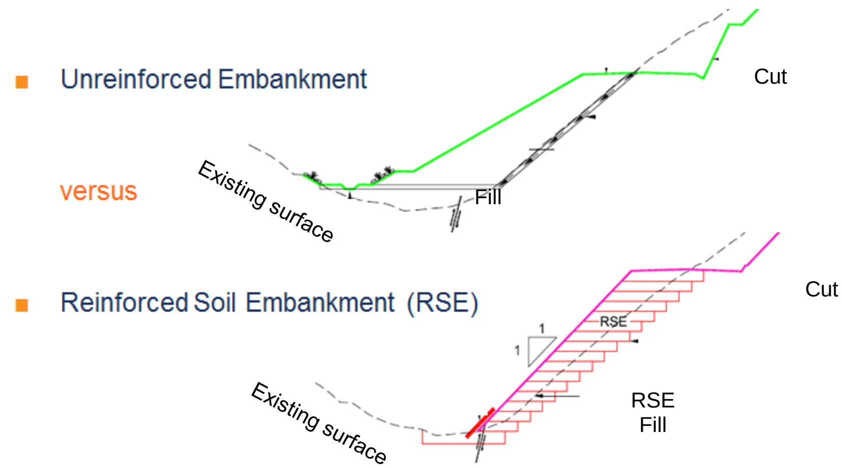

Figure 2. Unreinforced fill versus Reinforced Soil Embankment (RSE) designs

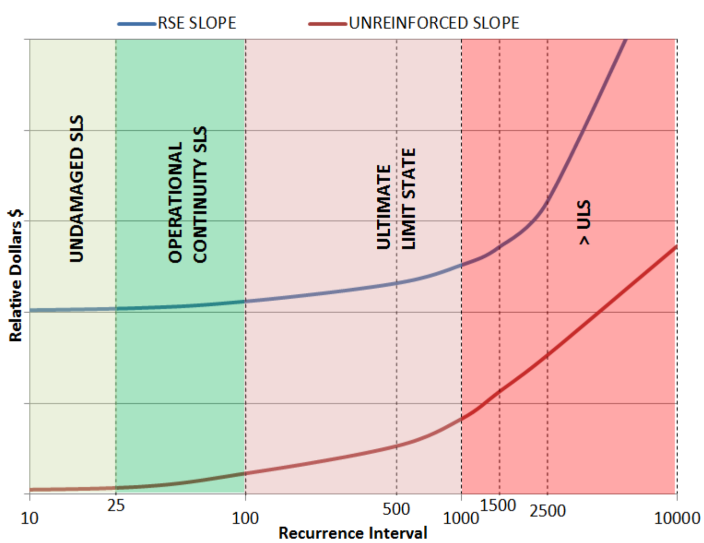

Figure 3. Whole of life costs for unreinforced and reinforced slopes

The significant initial construction cost saving of an unreinforced slope is a major benefit in spite of the higher post earthquake maintenance costs (represented by the steeper gradient of the line) that would be incurred up to the ULS event. This is consistent with standard RSE design approaches which generally result in reinforcement being sized for the ULS event, thereby, by default limiting deflection for the smaller scale serviceability events. Provided that the unreinforced embankment is able to meet the performance based design requirements, it is the preferable design solution.

When considering resilience beyond the ultimate limit state, provided the higher maintenance cost for smaller scale events is tolerable, the unreinforced embankment may ultimately be more resilient. This is owing to the potential for the RSE slope to be more susceptible to major reconstruction costs in a side fill situation. The susceptibility relates to the risk of large displacements of the RSE acting as a block at the interface with the natural slope, with the RSE block "jacking" away from the side slope on which it is constructed. This would likely be less of an issue for an unreinforced embankment which would tend to be more compliant at this interface.

Cuttings in steep natural terrain - steeper versus flatter slopes

Figure 4 compares steeper and flatter cut slopes within steep natural terrain. Clearly the flatter cut would achieve a higher factor of safety for global stability mechanisms and therefore would be expected to experience smaller movements than the steeper cut under the ULS event. However, the performance under smaller scale earthquakes was assessed to be perhaps improved for the steeper cut because it provides far less disruption to the natural slope environment. This reduces the area of the cutting face required to withstand the earthquake event, thereby potentially minimising the total amount of potential rockfall (even though rockfall may be more likely). The steeper cut also has benefits for other limit states and design criteria e.g. those related to erosion and maintenance.

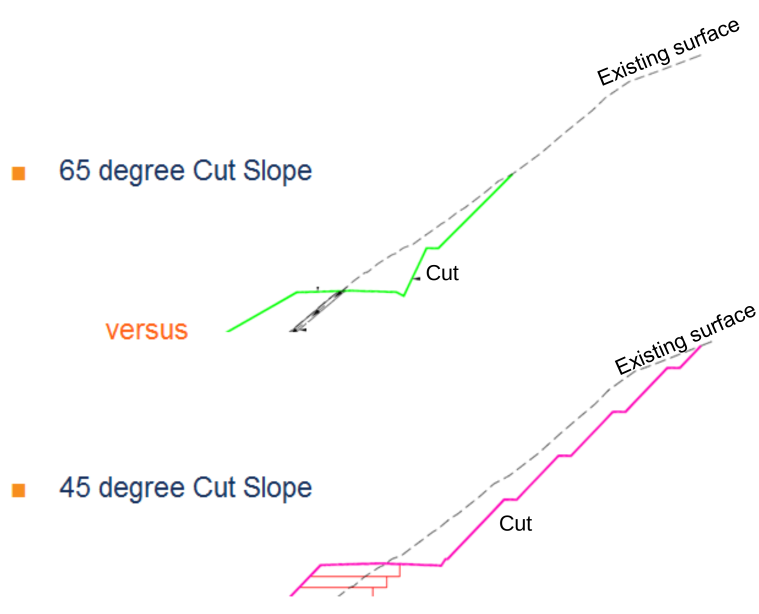

Figure 4. Steep versus flatter cut slopes in steep natural terrain

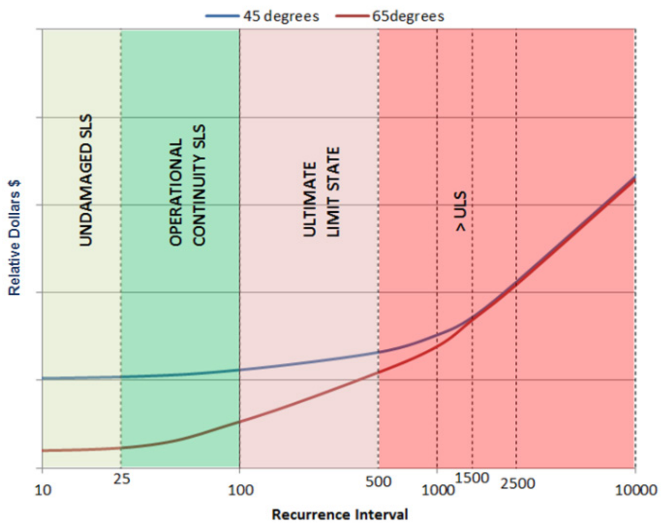

Figure 5. Whole of life costs for steep versus flatter slopes

Therefore as shown in Figure 5, the initial cost saving of reducing difficult earthworks in steep terrain by constructing steeper and lower total height cut slopes is of benefit up to the ULS seismic event. This is in spite of a higher maintenance cost for the smaller earthquakes (i.e. potentially more localised rockfall albeit still meeting performance objectives). For earthquakes beyond the ULS event the slope becomes affected at a larger scale (i.e. global instability). Once the earthquake is large enough the damage expected is somewhat independent of slope angle, that is due to the steep natural terrain above the cutting, the overall slope will perform similarly irrespective of the cutting angle. It should be noted that this relates to cuttings in steep terrain where the cutting for the motorway does not significantly modify the overall natural slope angle. For cut slope design in flatter terrain, a different relative comparison would likely result.

Design Criteria

The performance based design objectives in Table 1 need to be accompanied by a robust set of design criteria and application for each geotechnical element. The most challenging application of the objectives was in the cut slope design. This was due to the challenging natural environment (i.e. steep topography and complex structural geology) and the lack of significant precedent design or standards for seismic design of large cut slopes for infrastructure projects. The design criteria developed for the cut slopes is presented herein to show the lineage from the performance based design objectives into a geotechnical engineering design method.

Table 2 presents the design criteria developed for two of the most common mechanisms governing the cut slope design; block instability and rock mass failure. It is noted that the transformation of performance based design objectives becomes relatively more complex when there are several mechanisms of different nature and scale that potentially affect a geotechnical element. This paper is not intended to provide technical justification for each of these design criteria, rather they are presented to demonstrate the evolution from performance based objectives to engineering design criteria for the consideration of the reader. For example, the reader can infer that a Factor of Safety (FoS) >1.0 demonstrates that no displacement occurs. Similarly a FoS < 1.0 may be acceptable where the scale of failure or displacement is acceptable.

Table 2: Design criteria for rock cuttings

Mechanism	Block Instability	Rock Mass Failure
Description	May include rockfall, wedges, toppling, planar rock block failure	Failure through a fractured rock mass, circular or non-circular
Static Stability	FoS > 1.5 Limit equilibrium	FoS > 1.5 Limit equilibrium
Seismic Behaviour	Assumed brittle failure mechanism. That is FoS < 1.0 causes failure	Assumed ductile for < 5% strain along failure path
SLS1 Undamaged	FoS > 1.0, or FoS <1.0 acceptable if complying performance.	FoS > 1.0 (ie no displacement)
SLS2 Operational Continuity	1. Small mechanisms (to $10m^3/m$) FoS < 1.0 is acceptable. 2. Medium mechanisms (to $100m^3/m$ for box cuttings and $300m^3/m$ for side cuttings) FoS > 1.0, or FoS < 1.0 acceptable if complying performance. 3. Large mechanisms ($>300m^3/m$) FoS>1.1 or complying performance.	FoS > 1.0 or FoS < 1.0 but estimated displacements <50mm (ie no strength loss expected)
ULS Ultimate Limit State	As above but For Medium: FoS < 1.0 acceptable, and For Large: FoS <1.0 acceptable, if performance is complying	FoS > 1.0 or FoS < 1.0 and strains < 5% of failure path and performance is complying

Note: complying performance means that the Performance Based Design Objectives are achieved.

Conclusions

Aspects of the performance based geotechnical design approach to seismic engineering for the Transmission Gully project have been presented. This approach was developed within the framework of the NZTA Bridge Manual to achieve NZTA's project specific seismic resilience objectives. Importantly, it is observed that project specific seismic resilience objectives, when related to quantifiable criteria, allow the geotechnical designer to develop value for money whole-of-life outcomes for infrastructure.

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References

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