Resilience based Design Approach for Cut Slopes along Transportation Routes

P Brabhaharan
Opus International Consultants, Wellington, NZ
brabha@opus.co.nz (Corresponding author)

D Mason
Opus International Consultants, Wellington, NZ
doug.mason@opus.co.nz

E Gkeli
Opus International Consultants, Wellington, NZ
eleni.gkeli@opus.co.nz

Keywords: cut slopes, earthquake design, resilience, transportation routes

ABSTRACT

It is recognised that earthquake design of high cut slopes in hilly to mountainous terrain is important to ensure that the next generation of transportation routes have adequate resilience to provide access to communities following an earthquake event. There is very little guidance in New Zealand or worldwide on the seismic design of cut slopes. Research and development of guidelines for the seismic design of high cut slopes was carried out by Opus for the New Zealand Transport Agency. The guidelines propose a new performance based approach where the need for resilience underpins the design. The design loadings and approach are based on the importance of the route and the resilience expectations for that link, given the national resilience context. A new Resilience Importance Category (RIC) is proposed to guide the design approach. The guidance addresses a number of critical issues in the seismic design of cut slopes, such as selection of topographic amplification factors, the use of pseudo-static ground accelerations for design, and mechanisms of slope instability. The new principle of resilience based design has a focus on achieving resilience of access for communities, through consideration of the performance of cut slopes in earthquakes, and also the likely time taken for restoration of access. The proposed approach to account for topographical amplification effects is based on the research to date as well as specific numerical analyses, and could be refined as further research information comes available.

1 INTRODUCTION

New Zealand has rugged and mountainous terrain and major transportation routes are often associated with high cut slopes. It has been always recognised that the resilience of transportation routes in New Zealand greatly depends on the performance of these high cut slopes in earthquakes. This has been distinctively demonstrated in the 14 November 2016 M7.8 Kaikoura earthquake event, by the significant cut failures and landslips that caused one of the primary road and railway transportation corridors in the South Island to close for many months (Figure 1).

Currently there is very little guidance available for the earthquake design of high cut slopes either in New Zealand or internationally. The potential for topographical amplification of earthquake shaking, and the observation of the large landslides that have affected transportation routes in earthquake events has raised the awareness of the need for research and development of guidelines for the seismic design of high cut slopes. The New Zealand Transport Agency engaged Opus International Consultants to carry out this research and the development of guidance.

The research objectives included review of the performance of high cut slopes in recent worldwide earthquakes, consideration of the influences of the distinctive aspects of New Zealand's seismicity and topography, review of relevant recent research on topographical effects from New Zealand and overseas and limited numerical analyses on characteristic topographies in New Zealand, review of current design practice in New Zealand and overseas and development of guidelines for the earthquake design of high cut slopes in New Zealand. The New Zealand topography and Seismicity as well as the existing design guidance were presented by Brabhaharan et al 2015. This paper will focus on the other aspects of the research and the development of the design guidelines.

Figure 1: Landsliding on State Highway 1 from 2016 M7.8 Kaikoura Earthquake

2 OVERVIEW OF RESEARCH FINDINGS

2.1 Lessons from past earthquakes

A review of co-seismic landsliding and performance of slopes during historical New Zealand and worldwide earthquakes was carried out as part of the research. The main findings were:

- Small or large failures in steep unsupported cuts can be triggered by earthquakes leading to MM6 or greater shaking.
- Significant or widespread landsliding occurs when earthquake shaking exceeds MM 7-8 (peak ground accelerations of 0.1g to 0.5g).
- Landslides tend to be concentrated on the hanging wall side of the fault in reverse/thrust fault earthquakes. Thrust faults appear to give rise to greater shaking for a larger distance from the fault, and hence more landslides.
- Earthquake induced landslides are predominantly small (~10^3 m^3) to large (~10^5 m^3) disrupted falls, slides, and avalanches of rock, debris, and soil. Common failure mechanisms involve translational sliding at the interface between bedrock and the overlying soil/regolith, or sliding and release along defects in bedrock.
- Steeper slopes are more prone to landsliding, but the slope angles appear to depend on the local geology, terrain and climatic conditions. Slopes steeper than 40° to 50°

underlain by young (Miocene or younger) sedimentary rocks, have been observed to be particularly prone to large types of landslides.

- Landslides in much gentler slopes in volcanic soils have been observed in the April 2016 Kumamoto earthquakes in Japan (Brabhaharan, 2017).
- Steep slopes in competent bedrock with few joints exhibit low to moderate risk of widespread failure and are prone to more localised shallow rock slides and rock falls. Steep slopes (>45° - 50°) in well jointed strong rocks are prone to larger and more damaging primarily defect-controlled failures as also recently observed in Kaikoura.
- Earthquake induced slope failures appear to predominate in the upper parts of slopes, and this may be related to the topographic effects as well as weaker ground conditions.
- Antecedent rainfall and climate appears to have a strong influence on the extent of landsliding in earthquakes, for example in the 2016 Kumamoto earthquakes.
- Slopes can be weakened but not fail during strong earthquake shaking. Post-event rainfall or aftershocks have been observed to trigger widespread failures (e.g. 1999 Chi-Chi earthquake, 2016 Kaikoura earthquake followed by the April 2017 cyclones).
- Similar post- event behaviour was observed in the 2016 Kaikoura Earthquake where both areas near the epicentre and in Wellington were affected by the earthquake. A severe rainfall in Wellington event two days after the earthquake triggered numerous slips around the city that caused closure of roads for a day to a week and damage to many residential properties on slopes.
- Slope stabilisation measures such as rock bolts, anchors and shotcrete appear to have been effective against earthquake induced landsliding, but design records appear to have not been available or researched to confirm and understand their effectiveness.

Historical seismicity in New Zealand shows that shallow M 5 and 6 or greater earthquakes that trigger damaging landslides are more likely in northwest Nelson, the central Southern Alps, Fiordland, Marlborough, Kaikoura, Wellington, Wairarapa, Hawke's Bay, and East Cape areas. Central North Island, Auckland, Central Otago and Southland areas have a lower hazard.

A critical point to be considered in developing the earthquake design methodology of large cuttings from the study of past earthquake induced landslides, are the cumulative effects of a sequence of earthquakes and storms following the main event. Although ground shaking during the main event may not always trigger immediate brittle failure in all the cases, it produces systematic preferential tensile fracturing in the rock and zones of deformed material. These incipient failure zones have degraded properties relative to the pre-earthquake conditions, and that in turn can generate geological and topographical amplification effects in subsequent earthquakes, leading to large scale slope failure in aftershocks and storms.

2.2 Topography effects and numerical analysis

Research into topographic effects has been carried out over the last 15-25 years, and has indicated the complexity of the subject with a wide variety of topographies, geology and seismicity having important effects. The main conclusions of past research is that topography has a clear effect on ground shaking in steep terrain. Ground accelerations appear to be amplified at the crest of the slope, and possibly attenuated at the mid height and at the toe of the slope and also deeper into the hill. Topographic effects are frequency dependent, but amplification also depends on a number of other factors, e.g. the incident angle of the seismic waves, the geometry of the slope, the surrounding morphology (e.g. multiple ridges), the geology etc. Numerical modelling indicates topographic amplification factors which are on the order of 1 to 1.5 or perhaps up to 3, whereas experimental observations indicate much greater topographical amplifications, say up to 10.

Limited numerical analyses were carried out as part of this research to provide a better insight into the variation of ground acceleration along the height of the slope. Understanding the performance of the common New Zealand, and particularly lower North Island topographies, i.e.

ridge and terrace like slopes was the focus of this recent research. The slopes were assumed to consist of rock, to avoid high complexity and multi-factored influences in the model. Strain softening of material or appropriate properties of rock under dynamic loading were not part of this study. Limited analyses were also carried out to examine the effects of a weaker layer overlying bedrock on the slopes, either a soil overburden layer or highly weathered rock.

The conclusions from the analyses for New Zealand conditions are in general agreement with the observations drawn from the literature review, which are summarised below:

- For the terrace topography the amplification effect is found to be mostly influenced by the frequency of the excitation and the slope height, when the slope consists of rock. The amplification effect at the upper part of the slope is negligible for the small frequencies when the slope consists of rock but amplification factors of the order of 1.2 and 1.4 are indicated for higher frequencies. Amplification factors become significant for normalised slope height $H/\lambda > 0.1$ and maximum for $H/\lambda \approx 0.2$, which is in general agreement with the conclusions of the literature review (where H is the height of the slope and λ the wavelength).
- For the ridge topography, the amplification of the top of the ridge topography is about 30% higher than that of the corresponding terrace-like slope, i.e. with the same height and inclination. The amplification factors at the crest do not seem to have a consistent trend (e.g. increase or decrease) with frequency but appear to be predominantly influenced by the relationship of the geometry of the ridge (height and width of top and base) to the wavelength.
- De-amplification of the seismic ground motions is observed at the toe of the slope, at mid-slope height and inside the slope for the terrace topography. Complex, alternating patterns of amplification and de-amplification on different parts of the ridge slope varying with the wavelength of the seismic excitation were observed in our analyses, and also indicated from our research from literature.
- Amplification is significantly pronounced by the presence of weaker overburden soil material or highly weathered rock overlying unweathered or slightly weathered bedrock, with amplification factors exceeding 10 for both topographies.
- Amplification factors comparable to those at the crest, are observed on the ground surface at a distance of 20 m behind the crest for the high frequency excitations in the terrace topography. Literature review indicates that free field conditions behind the crest are usually observed at a distance of the order of (2 to 8) H, where H is the height of the slope, but this was not tested in our analyses.
- Vertical accelerations were examined for the ridge topography only as part of this research. The vertical accelerations observed for the bedrock case and the case with HW rock overlying bedrock were of the order of 0.6 g – 0.8 g, while for the case with soil overburden were much higher. The variation of vertical acceleration does not seem to vary consistently with frequency, but appears to be increasing at the higher frequencies.
- Amplification of seismic acceleration was observed at the crest of the cut slope in the case of a ridge with a cut excavated at its toe. The amplification factors show a tendency to increase as the irregularity becomes more pronounced, i.e. for steeper cut slope angles in relation to the natural slope angle.

3 DEVELOPMENT OF DESIGN GUIDELINES IN NEW ZEALAND

3.1 Resilience Concept

Resilience is the ability of an entity to recover readily and return to its original form from adversity. Brabhaharan et al (2006) adapt this concept of resilience for application to transportation networks as conceptually illustrated in Figure 2.

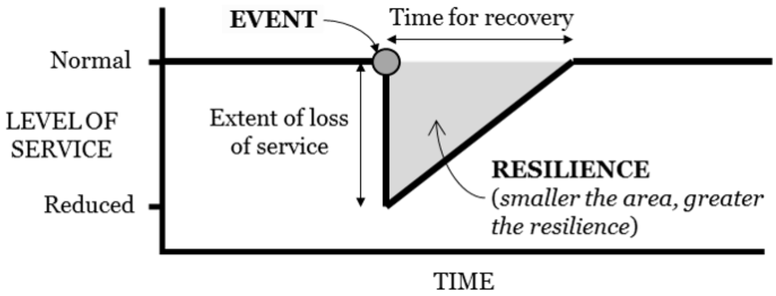

Figure 2: Characterisation scheme for New Zealand topography

Road networks provide a vital lifelines function to society, and their availability is critical for emergency response and recovery after major natural events. In this context, the concept of resilience of road transportation lifelines is dependent on their vulnerability to a loss of quality or serviceability, and the time taken to bring them back into original usage state after the reduction or loss of access, as illustrated in Figure 2. The smaller the shaded area, the more resilient is the lifeline. The greater the area, the poorer is the performance.

To achieve a more resilient society, we need to go beyond our focus on life safety from earthquakes, and consider the resilience of the built environment. This requires focus on how a loss of functionality can be minimised, as well as achieving a form that is conducive to quick return to functionality (Brabhaharan, 2013).

3.2 Design Guidelines framework

The design guidelines framework was developed on the basis of the key findings of the research in conjunction with the resilience concept explained in the previous section. The objective is to design cut slopes for resilience with low vulnerability to failures and subsequent closure of the route. This will be achieved by minimising the size and nature of failures, thus enabling the functionality of the transportation route to be restored quickly.

3.2.1 Importance Level Category (ILC)

The first step in the design guidelines is the classification of cut slopes to enable selection of appropriate levels of earthquake shaking and adopt an appropriate design approach for cut slopes. This enables cut slopes to be designed in accordance with the resilience expectations for the transportation facility it affects; and use a level of design which is consistent with the importance of the transportation route, as well as the criticality of the cut slope for the performance of the route. Four Importance Levels (IL) are defined, IL1 to IL4, as defined in AS/NZS 1170.0 and supplemented by the Bridge Manual for highways and arterial roads. The aim of this selection has been to use the existing importance level framework in the New Zealand standards and Bridge Manual. Further, the anomaly as to how cut slopes are currently considered in the Bridge Manual is attempted to be addressed.

3.2.2 Resilience Importance Category (RIC)

Resilience Importance Categories have been developed to provide for incorporating the local context and resilience expectations into the design process. The resilience importance category (RIC) of cut slopes take into consideration the Importance Level of the transportation route as well as the resilience expectations of the section of route from a regional network context. This recognises that sections of the transportation network may have a higher resilience importance because of the nature of the regional network, its resilience and the availability or lack of alternative routes in the event of incidents. Five categories, RIC I – RIC V are developed in the proposed framework. It is envisaged that the transportation authority would consider the regional context and select the Resilience Importance Category to be used in the design of cut slopes for a particular transportation corridor.

3.2.3 Design Approach

A four-level design approach is proposed, to suit the design importance level and Resilience Importance Category (RIC) of cut slopes, as follows:

- Design Approach 1 – is a simplified design approach suitable for use by practitioners for simple relatively low height cut slopes of relatively low importance.
- Design Approach 2 – is a standard design approach for use where performance is important for continued functionality on relatively moderate height cut slopes in simple geotechnical conditions.
- Design Approach 3 – use where performance is important for continued functionality, with relatively high cut slopes and moderately complex geotechnical conditions.
- Design Approach 4 – use where performance is critically important for continued functionality, very high cut slopes, or in complex geotechnical conditions.

A fundamental difference of the design approach given compared to that stipulated in AS/NZS 1170 is that the design is for resilience rather than life safety alone. Cut slopes most commonly affect the functionality of transportation routes, although they can also be critical to life safety in some circumstances. The selection of the Design Approach is based on the Resilience Importance Categories, the height of the slope and the geotechnical conditions.

3.2.4 Peak ground accelerations and topography effects

The peak ground accelerations for design are selected based on the Bridge Manual (NZTA, 2014), which provides peak ground accelerations that are not weighted by their relevant magnitudes. The peak ground accelerations selected based on the Bridge Manual represent free-field accelerations before any topographical effects are taken into consideration. Spectral accelerations may be considered if there is a dominant period for the site.

The numerical analyses and evidence from observations in earthquakes clearly indicate that topographical amplification is present and highest at the crest of slopes. The amplification further down the slope at mid height or below is much lower, or even de-amplification may be encountered. The evidence of slope failures from earthquakes also suggest that slope failures are predominant at the top of slopes, both ridges and terraces. It is also clear that the ground accelerations whether amplified by topography or not, are likely to be different along the height of slopes and the peak acceleration is not expected to be encountered at the same point in time during an earthquake along the height of the slope.

Therefore, a lower average acceleration is appropriate for pseudo-static design when large failure mechanisms are considered. Topographical amplification factors to use in design are given in the proposed design framework, based on up to date research and current knowledge. Understanding and quantifying topographical amplification is an area of recent research and development, and there is more research required to develop a good understanding of the issues.

There is an anomaly in the current Bridge Manual in that it provides for different hazard levels for different types of structures – bridge, retaining wall, embankments and cut slopes – on transportation routes with a selected importance level. For example for an important transportation route, a bridge or retaining wall is designed for a 2500 year return period earthquake, while the cut slopes on the same route (regardless of height) are designed for earthquakes with return period of 500 years, i.e. $1/5^{th}$ of the return period used for bridges. High embankments are designed for a 1,000 year return period. The hazard levels for cut slopes proposed in this design framework are higher than currently provided for in the Bridge Manual.

This is proposed to ensure appropriate design of cut slopes, consistent with the hazard levels for bridges, to avoid the formation of new transportation routes that have poor resilience.

3.3 Performance Criteria

In the earthquake design of cut slopes, it would be important to set appropriate performance criteria, to:

- Achieve a level of performance that is consistent with the resilience objectives set for the transportation route / project
- Achieve an economical solution.

Unlike made structures such as bridges and earth structures (e.g. embankments), cut slopes are mostly formed in natural materials with their inherent variability and in situ ground characteristics. Smaller failures, such as small wedge failures in rock, are difficult to prevent, unless a significant expenditure is incurred to protect / stabilise the slope against such small failures. A resilience based design would be suitable, i.e. consideration of the effect of any failures on the level of service or performance of the transportation route, but also of the time it would take to restore the level of service or access. It would be more economical to accept such small failures in large events, but design the cut slope to avoid or minimise the risk of large scale failures that would affect the performance of the route. For example, small failures that affect only the shoulder and can be quickly reinstated, can be accepted as it would have only a small effect on resilience. However, large failures that could close the road, and for long period of time, should be designed against.

Safety of the users of transportation routes and other people is an important consideration in addition to resilience of access. The cut slopes should be designed to ensure safety, i.e. small failures that do not impact on safety may be accepted, and larger failures or mechanisms that impact on safety, should be carefully considered and designed for. One of the mechanisms, rock fall, can affect safety and should be considered in the design under normal conditions, in storm events as well as earthquake events. This may require rock fall protection measures to be implemented, particularly to allow use of the route to be restored.

Earth structures can be designed for allowing a limited amount of displacement in earthquakes, because the limited displacement occurs when the resistance against instability is exceeded during an earthquake of a short duration. This approach is suited to ductile earth structures such as embankments and reinforced soil walls, and to a lesser extent to natural soils, where there is confidence that the displacement will not be associated with a reduction or loss of the resistance to instability. The displacement behaviour of natural soils need to be understood to ensure that they can accommodate limited displacements without an associated loss of strength. Large strain strength properties should be used in assessing displacements of slopes in earthquakes.

Rocks are generally brittle, and displacement leads to breakage through intact rock through en echelon type failures, and this leads to a permanent loss in the strength of the rock mass.
Cracks associated with displacements in rock and soil materials can also allow infiltration of surface water, leading to a reduction in stability, and failure of slopes in storm or rainfall events after the earthquake. Such failures have been observed in a number of earthquakes including in the recent 2016 Kaikoura earthquake. Therefore, this needs to be considered in limiting any displacements and associated cracking of ground particularly above cut slopes. Therefore in considering rock slopes, design based on acceptance of displacements should be avoided, or acceptable displacements are limited to very small values.

4 CONCLUSIONS

Past earthquakes have caused extensive slope failures in both natural and cut slopes. These have been observed in steep slopes of greater than 40 to 50 degrees in both rocks and soils, but have also been observed in much gentler slopes in volcanic soils. Topographical amplification and the weaker or weathered materials at the upper part of slopes appear to play a significant role in earthquake induced slope failures observed in high slopes. Numerical analyses to represent New Zealand conditions were carried out, and indicate the potential for significant topographical amplifications of 1.5 to 3 or more, and the potential for amplification at the upper part of cut slopes formed in the toe of natural hill slopes.

The proposed design approach in this guidance, uses a novel resilience based approach to cut slope design, and addresses significant gaps in current design guidance for cut slopes. This takes into consideration the resilience context of new cut slopes in the regional context of the transportation route, and a design approach based on the criticality of the cutting. A resilience based acceptance of small failures that do not impact on safety or route availability for significant periods, and design to minimise the risk of larger failures than can compromise resilience of the route and can lead to closure for long periods is proposed. A displacement based design approach is also proposed to allow displacements in soils with a more ductile behaviour, but avoiding or limiting displacements to very small values in rocks with brittle behaviour.

5 ACKNOWLEDGEMENTS

We acknowledge the commissioning of this research by the NZ Transport Agency and their encouragement to publicise the findings through technical papers such as this one.

REFERENCES

Australian / New Zealand Standards (2002). Structural design actions - Part 0: General principles. June 2002.

Brabhaharan, P (2006). Recent Advances in Improving the Resilience of Road Networks. *Annual Conference of the New Zealand Society for Earthquake Engineering.* Napier, 10-12 March 2006.

Brabhaharan, P. (pers com) (2016). Comments following the Learning from Earthquakes mission to Japan to observe damage from the Kumamoto Earthquakes in April 2016.

Brabhaharan P., Mason D., Gkeli E. (2015). Research into Seismic Design and Performance of High Cut Slopes in New Zealand, *6th International Conference on Earthquake Geotechnical Engineering*, 1-4 November 2015, Christchurch, New Zealand.

Brabhaharan, P, Mason, D and Gkeli, E (2017). *Seismic design and performance of high cut slopes*. NZ Transport Agency research report 613. Opus International Consultants. February 2017.

Hancox, G. (2015). *Performance of slopes in past New Zealand earthquakes: Literature review and lessons learned from historical earthquakes.* GNS Science Report CR2015/04. Prepared by Hancox, G.T. as part of the Opus led research into the seismic performance and design of high cut slopes, March 2015, 66 p.

New Zealand Transport Agency (2014). *Bridge Manual*. Third edition. Wellington, New Zealand.

New Zealand Standards (2004). *Structural Design Actions.* Part 5: Earthquake Actions, New Zealand. December 2004.

Opus International Consultants (2012). *Wellington Region Road Network Earthquake Resilience Study*. Risk Study Report. Prepared by Brabhaharan, P and Mason, D for the NZ Transport Agency, Wellington City Council, Hutt City Council, Upper Hutt City Council, Porirua City Council and Kapiti Coast District Council. Report No 2012-21. August 2012.