Topographic amplification on steep slopes during seismic events

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ABSTRACT

The geomorphology of New Zealand has dictated that many transport corridors and residential areas have been formed on, or adjacent to, steep slopes and undulating terrain underlain by variable geology. Observations of the seismic behaviour of cliff-top properties in the Port Hills during the Canterbury earthquakes suggests the current approach recommended in NZS 1170.5 and the NZTA Bridge Manual may be unconservative at estimating the design peak ground accelerations (PGA's) for sites influenced by topographic amplification. A number of sites may pose a higher risk of seismic failure, with potential to cause damage to dwellings and infrastructure, if topographic amplification effects were to be considered under the current codes. It is fundamental to design success that accurate design PGA's are estimated for assessments of existing slopes, design of slope stabilisation works near steep slopes, and design of structures near the crests of slopes. This is particularly relevant in view of the high probability of an Alpine Fault earthquake of Mw8 and the relative vulnerability of large metropolitan areas like Wellington to seismic events. Eurocode 8 appears to be an exception to existing literature in that it is a code that provides a readily implementable criterion for estimating topographic amplification. A similar, albeit interim, simplified method for estimating topographic amplification factors in New Zealand is proposed, based on back-analysis of observed movement at the Port Hills of Christchurch during the 22 February 2011 earthquake.

Keywords: seismic performance, topographic amplification, seismic design, slope stability analysis

1 INTRODUCTION

The geomorphology of New Zealand has dictated that many transport corridors and residential areas have been formed on steep slopes and undulating terrain underlain by variable geology. The geological setting of New Zealand on the Australian and Pacific plate boundary causes tectonic deformation with frequent seismic events of varying and frequently damaging magnitudes.

For geotechnical engineering, evaluating the effects of seismic events in terms of shaking duration, magnitude, and amplitude of ground shaking, are the key inputs to most design procedures in New Zealand. Two probabilistic methods are commonly applied in practice, being the New Zealand Transport Agency (NZTA) Bridge Manual and NZS1170.5:2004. The Bridge Manual is currently favoured among geotechnical practitioners as unweighted PGA-Mw pairs can be readily estimated. At present, the Bridge Manual allows derivation of these inputs for any site in the country, although potential influences on the input values due to external factors such as topography and shallow geology are neglected. The Bridge Manual also currently specifies that slopes should be designed to a lower level of earthquake performance compared to bridges and other structures (Opus, 2014).

Topographic amplification of seismic shaking is a widely recognised phenomenon (Ashford, 1997 and Jeong, 2013), but has not been accurately quantified, presumably due to difficulties in identifying either the zone of influence or the degree of amplification. The issue affects the hazard risk of steep, vulnerable slopes, and damage from seismically induced rockslides and rockfalls. These effects need to be taken into account during design of slope stabilisation works, retaining walls, and foundations on steep slopes, particularly in view of the 30% probability of a large (likely to be Mw8) Alpine Fault earthquake in the next 50 years, based on a mean occurrence interval of 330 years (Berryman et al, 2012).

Observations following the Canterbury earthquakes has shown that steep slopes in the Port Hills area of Christchurch were subjected to high degrees of localised damage due to mass movement along with infrastructure and residential dwellings built on them (Massey et al, 2012). Damage assessments by geotechnical staff along ridgelines and around cliff tops in the Port Hills of Christchurch following the Mw6.3 earthquake on February 22 2011 recorded prominent evidence of well demarked zones of heightened damage, later attributed to the effects of seismic amplification.

It is clear that design criteria appropriate to New Zealand conditions which account for the interrelation of seismic events and topographic amplification effects need to be quantified more appropriately. The purpose of this paper is to examine current practice in New Zealand and overseas and to present an interim simplified method for determining appropriate factors based on back-analysis of measured amplification factors determined from observed damage of the 22 February 2011 Christchurch earthquake.

2 LITERATURE REVIEW

The results of Kaiser, et al (2014) from studies in the Port Hills showed measured amplification factors of up to 2.7 times horizontal and 3.7 times vertical for shallow soil sites, with up to 2.5 times for horizontal and 3.0 for vertical accelerations for sites on rock. Many of the events measured in their datasets were from small to medium earthquake events (i.e. high-frequency ground motions) which do not necessarily represent the effects of larger earthquake events due to nonlinear site responses. The importance of source seismic event back-azimuth in relation to the site was also noted, with amplification shown to increase or decrease depending on the slope azimuth in relation to the strike of the fault rupture (Section 4, Kaiser et al (2014). As a result, their field trials are too limited to accurately define the nature or extents of amplification in comparison to field observations but do allow useful insight into the amplification range resulting from low amplitude seismic events recorded from the after-shocks. The results can only reasonably be applied to the discrete location of the instruments used to gather the data, a limitation overcome by the proposed new method in Section 3.

Modelling amplification of seismic waves by surface topographic irregularities was addressed by Paulucci (2002) through analytical and numerical investigations, similar to the suggested approach. Firstly, a closed-form expression for estimating the fundamental vibration frequency of homogeneous triangular mountains was obtained using Rayleigh's method. Subsequently, numerical modelling based on the spectral element approximation was used to study the 3D seismic response of several steep topographic irregularities excited by vertically propagating plane S-waves. The topographic amplification factor is obtained for each case by a suitable average of the ratio of acceleration response spectra of output motion to input motion. The 3D amplification factors are then compared with those derived by 2D slope stability analyses as well as with the topographic factors recommended in Eurocode 8 for seismic design. A factor of >=1.7 was derived for slopes of similar height to width ratio and of slope angles between 30° and 60°, although the simplified method proposed in this article seeks to provide an interim factor for a wider range of parameters.

Laboratory testing by Jeong (2013) demonstrated the results of testing physical models such as compacted sand layers in a laminar box and derived numerical finite element models. This showed complex wavefields that characterise the response of topographic features with non-homogeneous soil cannot be predicted by the superposition of topography effects and site response - a common assumption in engineering and seismological models. Nonlinear soil response was observed to increase amplification effects due to low velocity layers intensifying the impedance contrast and accentuate energy trapping and reverberation in higher velocity layers. Topographic amplification was shown to vary with changes in soil type, indicating that both phenomena need to be accounted for in seismic code provisions and ground motion predictive models. 'Parasitic' waves (interactions between vertically propagating S-waves and non-flat ground surfaces) were also outlined as a site-specific factor. No method for calculating site-specific factors was given, although the complexities of doing so were outlined.

Studies by Cauzzi et al, 2012 sought to include topographic amplification factors in ground motion prediction equations (GMPEs) by assessing the results of numerical models against measured slope displacements in selected field areas in Italy and Switzerland. The Italian Building Code was referenced in this paper which provides topographic amplification factors based on slope angle (0-15, 15-30, 30+) and geometry, (flat, slope, ridge). Results showed large errors can affect predictions when site effects are not directly related to the reduction in seismic impedance in near-surface layers. Topographic amplification factors from a numerical model calibrated to a site in Italy shows topographic amplification factors of 0.5-3.0, with a mean value of approximately 1.4 and a standard deviation of 0.5. Practical flaws in the dataset include non-representative slope geometries, inaccuracies in the geological model, and complex 2D and 3D topography not being characterised.

Case studies such as that presented by Sepulveda, 2005 document seismometer readings at a hydro-dam site during a Mw=6.7 quake in Pacioma Canyon, California in 1994. A clear correlation between increased measured ground motions and differing topography is made – peak accelerations at the base of the canyon of 0.5g and nearly 1.6g on the dam abutment (Sepulveda et al, 2005). As with GNS (2014) however, the analysis and conclusions are limited to that of the immediate study area and do not present a method immediately applicable to other sites without having the pre-requisites of well-defined geology, accurately measured seismic data at the slope location and back-analysed slope movements with inputs from precedent performance.

An assessment of worldwide standards and literature on the subject of topographic amplification of cut slopes is presented by Opus (2014). Key findings of their literature review indicate that topographic crests are where seismic ground motion amplification is generally greatest, with several topographic and geological factors making numerical methods inaccurate. Key aspects of New Zealand geology and seismicity are characterised as landform categories, approximations of geological properties and earthquake probabilities. It outlines key research areas for NZ practice and makes suggestions for the formation of future seismic guidelines, but does not present a means to derive topographic amplification factors for New Zealand geotechnical conditions.

Overall, it can be seen that work to date has mainly been directed towards modelling and identifying the underlying mechanics and spatial variations of the effects of topographic amplification (Caruzzi, 2012 and Jeong 2013). Several authors have highlighted that spatial variation of the degree of amplification is common in virtually all sites which indicates that using a fixed value to represent amplification across an entire slope may be problematic. It has also been identified by (Opus, 2014) that applying overseas research may also be inappropriate for use in New Zealand given the disparities of terrain and geology when compared to their countries of origin.

The only published reference for deriving amplification factors for seismic design actions was given in Annex A of Eurocode 8: Design of structures for earthquake resistance, Part 5 Foundations, Retaining Structures, Geotechnical Aspects, despite over-simplification of amplification and de-amplification mechanisms and slope geometry. It is clear that at least a simplified method should be available to practitioners in New Zealand in the interim until more rigorous analysis are developed. This will ensure that topographic amplification effects do not continue to be ignored in practice.

3 BACKGROUND AND RATIONALE FOR PROPOSED METHOD

The site seismic performance observations from Glendevere Terrace, Redcliffs provided a geotechnically fascinating case history of the style of damage that extreme accelerations can cause on cliff-top properties. Figure 1 shows a very low angle landslip that developed within loess overburden a short distance from the cliff crest. The static safety factor for the shown slip was calculated at over 3. The observed displacement was attributed to:

a) either very large horizontal accelerations or, more likely,
b) moderately high horizontal accelerations in phase with large downward vertical accelerations due to the overburden that has a moderately high frictional component of strength.

Of interest here was that the direction of movement of the slip was strongly oblique to the slope direction. Much more displacement would have resulted had the earthquake acceleration vectors been more directly aligned in the direction of steepest slope (normal to the cliff face) as mentioned in Kaiser et al, (2014).

The approach used by this new topographic amplification factor derivation method is seen as one step towards limiting future recurrences of seismic damage in the study area, or other residential areas with steep terrain - particularly Wellington, Queenstown or coastal land where relatively recent shoreline erosion has formed steep cliffs.

Figure 1. Low angle slip in loess affecting 3 houses in a clifftop seismic amplification zone. Slip has displaced 500 mm horizontally with only minor vertical displacement despite having a back-calculated sliding FOS = 3. Most distant house has collapsed; central house has rafted en masse with shear passing underneath. Seismic amplification factor for this slide (from back-calculation) comes to over 1.6.

4 OVERVIEW OF PROPOSED METHOD

The proposed method was developed primarily on the wealth of empirical evidence (observed land deformation, structural damage, measured accelerations and detailed profiles from several hundred cross sections developed from accurate LiDAR data) accompanied by limit equilibrium back-analysis of damage at known sites within the Port Hills as a result of the Canterbury Earthquake sequence.
Much of the dataset was from the worst affected clifftop areas such as Mt Pleasant, Redcliffs, Richmond Hill, and Whitewash Head. The observed behaviour and information collected (including ground accelerations almost an order of magnitude higher than the customary ultimate design accelerations) provided a rare opportunity to appreciate topographic effects and the need to address a significant technical omission in the current standard (NZS 1170.5).

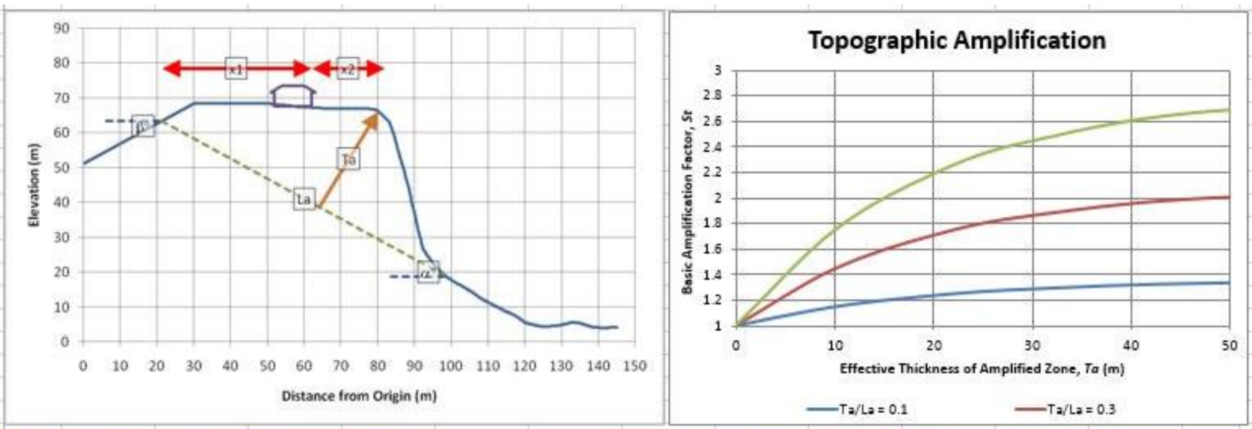
An informative example of the observed behaviour is provided in Figure 1, which illustrates the movement of a very low angle landslide in the loess overburden encompassing three houses on the top of Redcliffs. Having determined the applicable strength parameters for these materials and the slide profile, back-analysis using widely recognised limit equilibrium analyses confirmed peak accelerations must have been significantly higher than those reported by instrumentation in the valley floor. After collating the field evidence, a spreadsheet was developed to enable more robust design for (i) consideration of zoning for building on cliff-top sites based on potential seismic performance, and (ii) what amplification factor should be applied in design for any given location where a building site on or above a steep slope is proposed.

4.1 DESCRIPTION OF METHOD

The proposed methodology acknowledges the practicalities of determining appropriate design parameters for seismic code accelerations bearing in mind the uncertainties which are associated with quantifying topographic amplification.

It uses the factual information from extensive observed performance to establish the extent of the amplification zone and the relevant amplification factor. This approach is considered more robust at quantifying area-wide vulnerabilities when compared to discrete instrumentation methods.

At present the method has been set out with a practical spreadsheet interface as shown in Figure 2. It consists of an eight-step procedure using a representative cross section through any site of interest. Outputs for the model include a site amplification factor for inclusion in all earthquake related requirements (geotechnical and structural design), as well as the distance from the cliff edge to the end of the amplification zone. Additional inputs are required compared to the Eurocode but are all readily estimated by a representative cross section.



Calculator for defining the zone of clifftop seismic amplification, and factor to apply to NZS 1170.5 ate: only the yellow cells should be edi

Slope of tangent line extending from toe of cliff	α	30 °	Plan Factor (step 5 above)	Fp	1
Slope of ridge	β	20 °	Material Factor (step 6 above)	Fm	1
Length of slope tangent line	La	90.0 m	Ridge Factor (step 8 above)	Fr	1
Amplifiable Thickness	Ta	30.0 m			
Distance from inland limit to edge of structure	x1	40.0 m	**Basic Amplification Factor (step**	St	#NAME?
Distance from closest edge of structure to cliff edg	x2	20.0 m	**Site Amplification Factor (step**	Adjusted	#NAME?
			Distance from cliff edge to end of amp zo		60

Note: the above are based largely on visual observations and back-analysis as an interim measure to acknowledge the gap in NZSS 1170.5, pending a rigorous model s
There are good data for defining the extents of the amplification zone, but the magnitude is more tentative and warrants further study.

Figure 2: Screenshot of spreadsheet used for calculation of topographic amplification factors using proposed new method.

Typical amplification factors of 1.2 to 2.8 are output from the model, which are then directly multiplied by the PGA determined in accordance with NZS1170.5 or NZTA Bridge Manual to give an estimate of the amplified PGAs likely to be experienced at the site. These factors are generally in accordance with those measured by Kaiser, et al, (2014, p13). Adopting amplification factors for design are not necessarily onerous, for example, some sites developed near the crest of cliffs in areas of low reported seismic risk will only be designed to the same PGAs as similar structures in areas of higher seismic risk.

4.2 METHOD REFINEMENT AND FORMAL REVIEW

The fundamental reason for proposing a rapid analysis method using a calibrated spreadsheet calculation of amplification based on slope geometry and other parameters, (rather than a full dynamic analysis), is the uncertainty associated with the base motion (prior to amplification). The Port Hills study made it very clear that in practice, the magnitude of deformation or displacement that will occur in an earthquake as a result of topographic amplification is not a simple parameter that can be calculated deterministically, because as well as magnitude of the seismic event itself, some of the evident variables were:

1. Profile, i.e. steepness of the cross section through the slope
2. Height relative to crest of profile
3. Distance back from the crest
4. Lithology
5. Overburden depth or weathering profile and strength parameters
6. Focal depth
7. Distance from epicentre
8. Scale effect (out of phase effects minimise deformation on long, gradual slopes)
9. Phase of vertical versus horizontal accelerations
10. Direction of the predominant acceleration vector relative to the direction of steepest slope

Because all of the above factors will interact to allow only a probabilistic assessment of seismic deformation, it may be argued that in practice, comprehensive dynamic analyses are unlikely to provide a more reliable or more cost effective evaluation than a simplified approach such as the proposed spreadsheet collated from the Port Hills observations.

Accordingly, the Redcliffs research is proposed for interim application as a pragmatic step towards a more conservative amplification factor. This can be applied in addition to current code requirements to meet what appears to be a significant shortcoming. It needs to be considered only where unusually steep slopes or cliffs are involved and the situation presents safety or serviceability issues, but where more sophisticated methods are not warranted. It is not intended to be a substitute for a critical situation where more formal dynamic modelling of seismic amplification with sensitivity analyses would be appropriate.

The model could be readily upgraded to 3D, by further adaptation using GIS software. This could be undertaken by collating any series of adjacent cross sections, to presenting the data as a 3D contour model. The output from a series of spreadsheets can then be automatically presented as colour coded topographic amplification factors superimposed on a standard topographic contour drawing. This would allow the practitioner a convenient overview of the critical areas that can be readily transferred to common GIS packages.

The variation of seismic shaking over the height of the slope can be explored in further detail and become supplementary as a standard model output. The focus is primarily on providing a simple procedure, not dependent on a rigorous model, in view of the uncertainties in the seismic accelerations prior to amplification as referenced as limitations by Jeong (2013) and Cauzzi (2012).

5 FUTURE WORK

Further work is required to define quantitative analytical models of the mechanics of amplification in two-dimensional and three-dimensional space. Refinement could also include taking on board the slope performance and earthquake parameter information from studies of NZ events such as that by Kaiser et al, (2014). Model validation for dynamic analysis is expected to use primarily the well-recognised GeoStudio Suite, as that is most likely to be used by other practitioners, although an assessment of whether there is any more suitable software for this specific purpose would consequently be required.

These further studies will also identify areas for calibrating the model for variations in slope characteristics (lithology, weathering, water table level etc). Robust guidelines appropriate to derive equivalent pseudo-static loads for topographic amplification zones could then be provided for other sites throughout New Zealand.

Where necessary, this method is intended to be adapted in line with international best practice. The intention is that once appropriate validation has been completed, the existing spreadsheet would be used for sites by engineering practitioners and infrastructure asset managers where the consequences of failure are low to moderate. For more critical sites, the spreadsheet would still be useful as a screening tool to decide whether a full dynamic analysis model is warranted based on derived amplification values and potential site complexities.

6 CONCLUSIONS

This paper presents a review of literature on the derivation of site-specific topographic amplification during earthquakes on steep slopes. Slope stability problems remain prevalent in geotechnical and earthquake engineering due to the desirable real estate or strategic infrastructure attributes of sites on or at the crest of steep slopes. Key limitations of current practice are a narrow scope of field studies, the requirement for detailed site knowledge (in excess of that normally available outside of well-studied areas) and a lack of availability of readily-usable methods with an acceptable degree of approximation. This paper presents the background for a geometrically-based spreadsheet method of deriving a topographic amplification factor for slopes in New Zealand. This is intended, with refinement, to enable more efficient seismic design practices in the future and act as a pragmatic interim measure until more rigorous methods become developed.

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