Proposed amendments to geotechnical requirements of NZTA Bridge Manual

A K Murashev, D K Kirkcaldie, C Keepa
Opus International Consultants Limited, Wellington, NZ
Alexei.Murashev@opus.co.nz

J N Lloyd
New Zealand Transport Agency, Wellington, NZ
Nigel.Lloyd@nzta.govt.nz

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ABSTRACT

Work is currently underway to update the NZTA Bridge Manual (BM) based on recent advancements in bridge design practice in New Zealand and worldwide, and also the NZTA's experience on the performance of bridges during the Canterbury earthquakes. In the current 2nd edition of the BM various geotechnical design requirements are included in a number of different sections of the Manual. In the new 3rd edition, a new section, Section 6 "Site Stability, Foundations, Earthworks and Retaining Walls" now combines most of the geotechnical design requirements and deals with geotechnical design of bridges and other highway structures; natural cut and fill slopes as well as mechanically stabilised earth structures and retaining walls. The proposed amendments include the use of unweighted peak ground accelerations (PGAs) for the assessment of soils' potential for liquefaction and lateral spreading; recommendations on the assessment of liquefaction potential of soils and soil – structure interaction under seismic conditions; design strategy for bridge foundations on liquefiable sites; soil testing techniques; categorisation of retaining structures and slopes in terms of their importance level; more detailed minimum post-earthquake performance standards; no collapse requirement under a greater than design event seismic loads; maximum allowable seismic displacements for walls and slopes and additional design requirements for geosynthetic-reinforced soil structures. Early next year this work will be further complemented by results from a NZTA Research Project to develop design guidelines for bridges and other highway structures located on sites prone to liquefaction and lateral spreading, which is currently underway.

1 INTRODUCTION

NZTA manages and develops New Zealand's state highway system. The BM provides design standards and performance expectations for the design of bridges and highway structures. Work is currently underway to prepare a new 3rd edition of BM based on recent advance in bridge design practice in New Zealand and worldwide, and also the NZTA's experience of the performance of bridges during the Canterbury earthquakes. In the current 2nd edition of the BM various geotechnical design requirements are included in a number of different sections of the Manual: Section 2: "General Requirements" covers site investigations, influence of bridge approaches; Section 3 "Design Loading" deals with earth loads, settlement, subsidence and ground deformation; Section 4: "Analysis and Design Criteria" gives recommendations on loads for foundations and earth retaining systems, design standards including strength reduction factors and factors of safety, foundation capacity, requirements for anchors, embankments and cuttings, construction control, liquefaction and ground improvement.

In the new 3rd edition, Section 2 “Design - General Requirements” gives classification of importance level and recommends annual probabilities of exceedance for storm, floodwater and earthquake actions for bridges, retaining structures and earth slopes (depending on their importance category). Section 5 “Earthquake Resistant Design of Structures” specifies seismic performance and design requirements for structures. A new section, Section 6 “Site Stability, Foundations, Earthworks and Retaining Walls” now combines most of the geotechnical design requirements and deals with the geotechnical design of bridges, other highway structures; and natural cut and fill slopes as well as retaining walls and mechanically stabilised earth structures.

The new edition of the BM has been developed by Opus International Consultants with inputs from GNS Science, and in consultation with and for NZTA. Peer review inputs were provided by a number of New Zealand consulting companies during the development of the amendments. This paper highlights key changes in the structure and content of the BM relating to geotechnical engineering. The new edition of the BM was issued for industry use in early June 2013.

2 CATEGORISATION OF BRIDGES, RETAINING STRUCTURES AND EARTH SLOPES

In Section 2 of the new edition of the BM, bridges, earth retaining structures and earth slopes are categorised into four different importance levels, with Level 1 being low importance and Level 4 being high importance. Depending on the level of importance, annual probabilities of exceedance for wind, snow, floodwater and earthquake actions are assigned. Retaining structures and earth slopes affecting route security, and retaining structures and earth slopes providing protection to adjacent property are considered separately. Similar classifications are given for bridge structures and earth retaining structures associated with bridges. Both, the structure and non-structural elements are required to remain undamaged following wind, snow and flood events up to an SLS 1 event, and the bridge or earth retaining structure should remain operationally functional for all traffic during and following flood events up to an SLS 2 event. SLS 1 and SLS 2 events are serviceability limit state events defined by the specified annual probabilities of exceedance. Seismic performance requirements for bridges and retaining walls associated with bridges are given in Section 5 of the BM and are presented in Table 1, where R_u is the return period factor for the ultimate limit state.

Table 1: Seismic performance requirements

Earthquake severity	Minor earthquake Return period factor = $R_u/4$	Design level earthquake Return period factor = R_u (ULS event)	Extreme earthquake Return period factor = $1.5R_u$
Post-earthquake function - immediate	No disruption to traffic	Usable by emergency traffic	Usable by emergency traffic after temporary repair
Post-earthquake function – after reinstatement	Minimal reinstatement necessary to cater for all design-level actions	Feasible to reinstate to cater for all design-level actions, including a repeat design-level earthquake	Capable of permanent repair, but possibly with reduced load capacity
Acceptable damage	Damage minor	Damage possible; temporary repair may be required	Damage may be extensive; collapse is prevented

Effects of the design ULS seismic displacement on any affected structures should be assessed and compared against the performance criteria for these structures specified in the BM. Allowance should be made for the cumulative displacement arising from at least two design ultimate limit state seismic events occurring in sequence.

3 SERVICEABILITY LIMIT STATE FOR SOIL STRUCTURES

In addition to the ultimate limit state conditions, serviceability limit state requirements have been introduced for soil structures. These requirements include the following:

- Where the serviceability of structures (bridges, major culverts, major sign gantries, etc.) is dependent on, or influenced by associated or adjacent soil structures, the soil structures should be designed to ensure that their performance does not deleteriously affect the structure from satisfying its serviceability requirements.

- All soil structures associated with roads should remain undamaged following earthquake events with an annual exceedance probability of 1/25. The operational continuity of routes should not be significantly impeded following earthquake events of relatively high annual exceedance probabilities.

- The road controlling authority should be consulted and should define the operational performance expectations for the section of road to be designed, taking into consideration the redundancy in the regional road network, and the resilience required for the proposed road to ensure the desired functionality of the road network. This should provide the access resilience expectations in terms of degree of access required on the road after different levels of events and the time for restoration of access. The following default values are provided in the absence of such considered definition:
  - 1/100 for routes of importance Level 3 and 4 as identified in the BM;
  - 1/50 for routes of importance Level 2, being a route not falling into other levels;
  - 1/25 for minor routes of importance Level 1, being no exit or loop rural roads, not serving a through route function and serving populations of < 50.

  (These annual probabilities of exceedance correspond approximately to "Minor earthquakes" in Table 1.)

Based on the seismic performance requirements expressed in Table 1, operational continuity has been defined as::

- full live load capacity is maintained
- vehicle access is restorable within 24 hours
- any necessary repairs should be of such a nature that they can be completed within one month

4 DESIGN EARTHQUAKE LOADING FOR SOIL STRUCTURES

The term "soil structures" used in the new edition of the BM combines cut and fill slopes (including stabilised slopes), embankments, and earth retaining structures (including Mechanically Stabilised Earth). In NZS 1170.5:2004 duration of shaking (related to earthquake magnitude) is accounted for implicitly within the design PGA values by a procedure of magnitude weighting, whereby earthquake sources of magnitude M less than 7.5 are given lower weighting in computing the site spectra because the duration of shaking and thus damage potential is reduced for lower magnitude earthquakes. Where design procedures require specific input values for magnitude M (e.g. all common liquefaction assessment procedures), the value M = 7.5 is normally adopted if values of PGA from NZS 1170.5:2004 (NZS, 2004) are used. However, given that the performance of soils, earth structures, slopes and retaining walls exhibit a step-wise behaviour (where a critical acceleration results in liquefaction and/or a sudden loss of stability, i.e. dramatic change in behaviour), use of these values may be unconservative. A lot of geotechnical design procedures such as, for example, assessment of liquefaction potential of soils, use the magnitude scaling factor. Therefore, it would be more appropriate to use unweighted PGA and expected magnitude of the design seismic event. In the new edition of the

BM, unweighted PGAs have been adopted. Based on recommendations developed by GNS Science, the unweighted PGAs are derived for the relevant return period as follows:

For site subsoil classes A strong rock, B rock and C shallow soil site:

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For site subsoil classes D deep or soft soil and E very soft soil:

— — , where

= 1000 year return period PGA coefficient for a Class A or B rock site derived from Figure 1A, developed by GNS Science;

= return period factor at the ultimate limit state derived from Section 2 of the BM and from NZS 1170.5 table 3.5 (Standards NZ, 2004); for a 1500 year return period is recommended to be taken as 1.5;

= site subsoil class factor, where = 1.0 for a Class A strong rock or Class B rock site;
= 1.33 for a Class C shallow soil site.

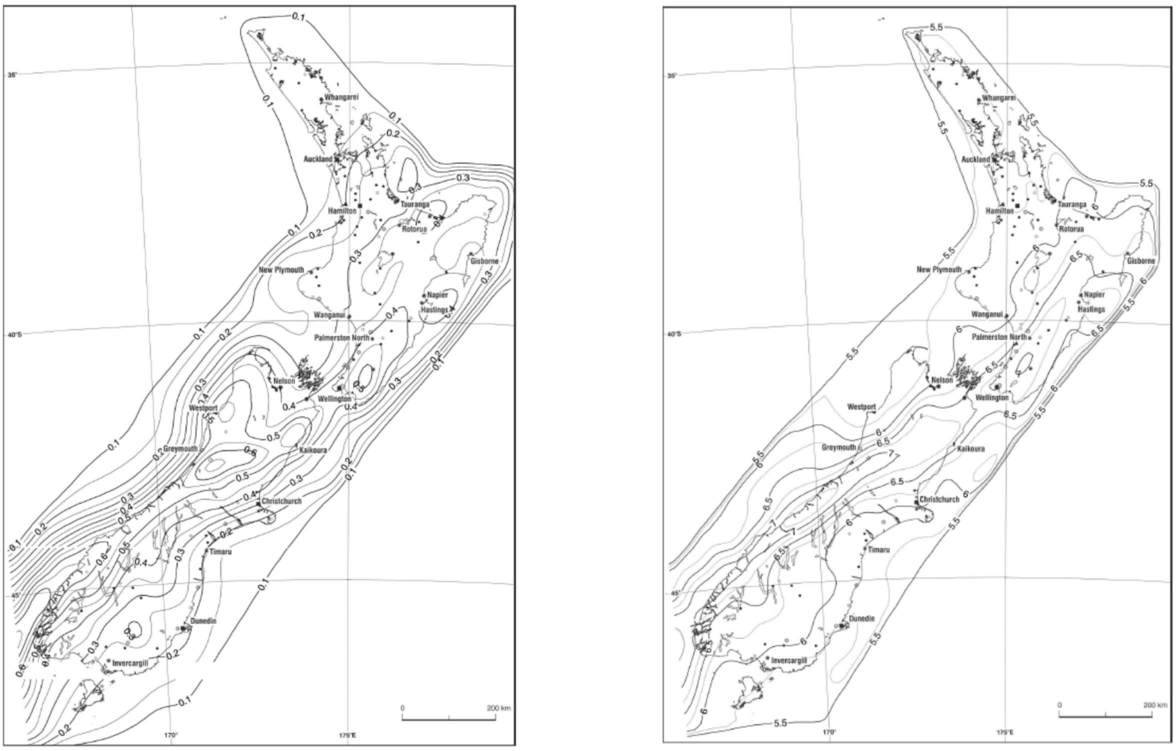

Figure 1: (A) - Unweighted peak ground acceleration coefficients, , corresponding to a 1000 year return at a subsoil class A or B rock site (B) - Effective magnitudes for use with unweighted peak ground accelerations (1000 year return period)

The earthquake magnitude should be derived for the relevant return period from the figures showing contours of magnitudes developed by GNS Science and included in Section 6 of the BM. An example image of the magnitude contours is shown on Figure 1B. The effective magnitudes presented by Figure 1B have been derived from the NZS 1170.5 hazard analysis results for the overall set of earthquakes affecting each location by inverting the PGA magnitude weighting equation on which the magnitude weighted PGAs presented in NZS 1170.5 are based. In addition, to ensure robust designs, a minimum nominal earthquake load has been specified for zones of low seismicity. As a lower bound, the effects to be designed for should not be taken to be less than those due to a 6.5 magnitude earthquake at 20km distance from the project site, for which the recommended peak ground acceleration coefficients have been specified.

5 EARTHQAUKE SCENARIOS AND SITE SPECIFIC SEISMIC STUDIES

At any given site the actual seismic hazard based on a probabilistic seismic hazard analysis may vary from the hazard specified in Section 6. In the new edition of the BM the need for site specific studies is governed by understanding of seismic hazard, consequences of failure, importance level of bridges, retaining walls and earth slopes and project cost. Dependent on the value of the project, soil structures and earthworks to be designed for earthquake resistance, a site specific seismic hazard study should be undertaken as a special study, as follows:

- less than $3 million – a site specific study is not required
- $3 million to $7 million – a site specific study is advisable
- more than $7 million – a site specific study is mandatory (values at December 2012)

Where the site is comprised of potentially liquefiable materials, NZTA may instruct the designer to carry out a site specific seismic hazard study for projects with values of less than $7 million, especially for soil structures with Importance Levels 3 and 4.

Where site specific seismic hazard studies are undertaken, deaggregation of seismic hazard should be carried out and individual sources contributing the most to the seismic hazard of the site should be considered. The PGA and magnitude values representing realistic ground motions that could actually occur at the site due to known active faults in the area should be used in the assessment of liquefaction. This process may yield more than one magnitude-PGA pair for liquefaction analysis in some areas of New Zealand. Each magnitude-PGA pair should be evaluated individually in the liquefaction analysis. If liquefaction is estimated for any given magnitude -PGA pair, the evaluation of that pair should be continued through the slope stability and lateral deformation evaluation processes.

Also, the stability of the supporting ground to bridge structures (either slopes or retained ground) should be such as to ensure that the collapse of bridge structures should be avoided under a maximum considered event (MCE) with a peak ground acceleration of 1.5 times the maximum design peak ground acceleration derived as above. 1.5 is the margin between MCE and ULS generally inherent in the NZS 1170.5 spectra and applied in deriving site specific spectra A map of New Zealand displaying magnitudes of MCE has been prepared by GNS Science and included in the new edition of the BM.

6 SLOPE AND LAND STABILITY IN EARTHQUAKES

Potential slope instability and displacements should be assessed using geotechnical principles, as follows. The factor of safety against instability should be assessed using conventional slope stability analysis with load and strength reduction factors of one, and the relevant earthquake accelerations. Average groundwater conditions or maximum tide levels should be assumed for this assessment. If the factor of safety is less than 1 and the failure mechanism is not brittle (such as in rocks where the initiation of failure could substantially reduce the strength of the materials), then the critical ground acceleration at which the factor of safety is one should be assessed using large strain soil parameters consistent with the likely displacements due to earthquake shaking. The displacement likely at the design ULS seismic response, and under the MCE event associated with bridge collapse avoidance, should be assessed using moderately conservative soil strengths consistent with the anticipated strain and a Newmark sliding block displacement approach. Displacements may be assessed using the methods described in Geotechnical earthquake engineering practice, module 1 – Guideline for the identification, assessment and mitigation of liquefaction hazards (NZGS, 2012) using relevant peak ground accelerations, and the distance to the dominant earthquake sources in the area. Where a Newmark sliding block method is applied, the 84th percentile displacement should be derived for ULS events and 50th percentile for MCE events. Due to substantial discrepancies in displacements predicted by different methods, at least three different commonly accepted methods for the assessment of the displacement should be used and the range of predicted displacements (rather than a single value) should be used in the design process. The effects of the design ultimate limit state seismic response displacement on any affected structures, should be assessed, and compared against the performance criteria specified in the BM. Allowance should be made for the cumulative displacement arising from at least two design ULS seismic events occurring in sequence.

7 LIQUEFACTION AND GROUND IMPROVEMENT

The new edition of the BM requires that liquefaction of saturated predominantly cohesionless soils (generally sands and loose sandy gravels) and cyclic softening of clays and plastic silts during strong earthquake shaking be taken into consideration in the design of structures, including highway bridges and their approaches, retaining walls and embankments**.** Where liquefaction susceptible soils containing gravels are present and static cone penetration tests and standard penetration test results can be influenced by gravel particles, the use of in-situ shear wave velocity tests is now recommended. It is also recommended to consider the use of dynamic triaxial tests if the potential for liquefaction or cyclic softening is uncertain but is critical to the performance of a significant structure.

The design should mitigate the risks associated with potential damage to the highway and associated structures from liquefaction, cyclic softening or site instability, through ground improvement or provision of sufficient strength and / or ductility in the structures to resist liquefaction and site instability effects, so that the performance requirements of the BM are achieved, unless agreed with the road controlling authorities to be impractical or uneconomic.
It is recognised that ground improvement is costly. On some NZTA projects the cost of ground improvement has been higher than the cost of the bridge structures. Where liquefaction or cyclic softening problems are identified as potentially causing lateral spreads that may damage the structure, the following options should be considered:

- For new structures: relocate the structure to another less vulnerable site. This option should be considered at the concept design stage. If the risk of liquefaction or cyclic mobility is identified for a proposed route, alternative routes with better ground conditions at structure sites should be considered.

- For new and existing structures on liquefiable sites: soil- structure interaction analysis should be undertaken to determine whether the deformation and load capacity of the foundation/structure system is adequate to accommodate the ground deformation demands without collapse (assuming no ground improvement) in the ultimate limit state earthquake and can meet performance criteria in the serviceability limit state earthquake; and where the foundation/structure system is found to be inadequate the most cost-efficient of the two following options should be used:
  - foundation/structure system should be strengthened to accommodate and withstand the predicted liquefaction and related ground deformation demands;
  - ground improvement should be undertaken to reduce the liquefaction potential of the soils and minimise the ground displacement to acceptable levels.

This analysis will require close interaction between the structural and the geotechnical designers and should be undertaken in accordance with ATC/MCEER Liquefaction study report guidelines (ATC/MCEER, 2003) or similar methodology approved by the road controlling authority. The ATC/ MCEER methodology requires that pile pinning effect and associated reduction in lateral displacement be taken into account in the analysis of the bridge abutments. Where ground improvement is specified by the structure designer, the road controlling authority will require the designer to submit evidence of ground improvement optimisation analysis in accordance with this methodology. For projects where the cost of ground improvement is more than $1 million (price at December 2012), consideration should be given to the use of inelastic time history finite element analysis of soil - foundation - structure interaction to optimise the extent of ground improvement. Our experience indicates that where the stiffness of the bridge structure is taken into account, substantial cost savings can be achieved due to reduction in the extent of ground improvement. For design and construct type projects on sites prone to liquefaction, cyclic mobility and/or lateral spreading, optimisation of ground improvement should be carried out at the stage of specimen design and clear requirements should be included in the Principal's Requirements for the project.

Early next year the BM will be further complemented by results from a NZTA Research Project to develop design guidelines for bridges and other highway structures located on sites prone to liquefaction and lateral spreading. This research project is being currently carried out by Opus, University of Auckland and University of Canterbury.

8 FOUNDATIONS

The new edition of the BM recommends to use the strength reduction factors derived using the risk based methodology set out in section 4.3of AS 2159. The strength reduction factors adopted for bearing capacity of shallow foundations should be taken as $Ø_g = Ø_{gb,}$ where $Ø_{gb}$ is the basic geotechnical strength reduction factor from AS 2159 and $Ø_g$ should not exceed a maximum value of $Ø_g = 0.6$ for all load combinations. An exception to this is when engaging in capacity design for earthquake resistance, in designing for actions arising from yielding of elements developing their overstrength, when higher strength reduction factors, up to $Ø_g = 0.75$, may be adopted. Strength reduction factors adopted, for both shallow and piled foundations, should not exceed a maximum value of $Ø_g = 0.75$, regardless of whether static, dynamic, or gravitational loading, or seismic loading induced by overstrength capacities developing are being considered.

The foundations should not compromise the seismic performance of the superstructure (i. e. above foundation level structure). The foundations must be capable of transmitting the largest feasible actions to the supporting soil, and the soils must be capable of resisting the pressures applied by the foundations, otherwise the intended seismic response of the superstructure cannot eventuate. For structures designed using capacity design principles, the capacity of the footings, piles or caissons should be such that deformations developed in the supporting soil under actions corresponding to the over-strength of the superstructure are limited in terms of their magnitude, so that the intended seismic response of the superstructure can eventuate. In general, foundation systems should be designed to preclude foundation failure, or uplift of an entire foundation element, at loadings corresponding to yielding of the earthquake energy dissipating elements, taking concurrency effects into account where applicable. Where it is intended to allow the rocking of foundations, inelastic time history analyses should be performed to study the structure's behaviour and bearing areas within the foundation should be so proportioned as to protect the soil against excessive plastic deformations that would be difficult to predict and which may result in premature misalignment of the otherwise undamaged superstructure.

9 OTHER ADDITIONS

A number of additional requirements for geosynthetic soil reinforcement have been added. Most of these requirements are based on the design guidelines for geosynthetic-reinforced soil structures (Murashev, 2003). Also, a brief section on the design of geofoam (polystyrene) road embankments has also been added. The requirements of this section are consistent with the following documents:

- Guidelines for geofoam applications in slope stability projects, Final Report for Project No. 24-11(02), National Cooperative Highway Research Programme, Transportation Research Board of the National Academies, US, 2011
- Guideline and recommended standard for geofoam applications in highway embankments, Report No. 529, National Cooperative Highway Research Programme, Transportation Research Board, Washington DC, 2004
- Geofoam applications in the design and construction of highway embankments, National Cooperative Highway Research Program, NCHRP Web Document 65 (Project 24-11), Transportation Research Board of the National Academies, US, 2004

10 CONCLUSIONS

The NZTA BM has been updated based on recent advancements in bridge design practice in New Zealand and worldwide, and also the NZTA's experience on the performance of bridges during the Canterbury earthquakes. A new Section 6 "Site Stability, Foundations, Earthworks and Retaining Walls" now combines most of the geotechnical design requirements. More detailed and updated geotechnical design criteria have been introduced. As a result, uniformity of geotechnical design standards applied on NZTA projects will be improved and better resilience of the road network should be achieved. The new edition of the BM emphasises the importance of communication between geotechnical and structural designers and encourages soil – bridge structure interaction analysis to optimise design solutions and to reduce the extent of ground improvement through more detailed analysis and/or through NZTA accepting higher risk where appropriate.

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