Seismic design for temporary works: Recommendations for a Temporary Works forum NZ design note

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ABSTRACT

The Temporary Works forum NZ (TWf NZ) aims to improve construction safety by addressing risk in the design and execution of temporary works. Anecdotal evidence suggests that seismic actions on temporary works are often inadequately considered by designers, or not considered at all. Similarly, many principles associated with robust seismic performance are not being followed in temporary works' design.

In this paper the seismic design of temporary works is examined to establish best practice, and to inform the development of a TWf NZ Guidance Note. The paper includes a literature review to establish international practice and current NZ code requirements, a discussion on seismic risk relating to temporary works, and discussion on the principles of efficient design as it relates to seismic performance of temporary works. Case studies explore how these principles have been applied on projects, some of which have been tested by earthquakes.

From our literature review and case studies, our recommendations for a TWf NZ design note are summarised as follows:

- The design process for all temporary works must consider earthquake loading and consequences of failure. This is a requirement of the NZ Building Code. NZS1170.5 provides the necessary seismic parameters for temporary works design. Consider elevated importance level where consequences of failure are high. Consider parts and components loading when appropriate.
- Principles of robust detailing and *design for uncertainty* are as important for temporary works as they are for permanent works design. Where possible, capacity design principles should be applied in temporary works design to reduce the risk of brittle failure.

1 INTRODUCTION

Currently there are no New Zealand standards specific to temporary works, and few international standards that address the design of temporary works for seismic loading. As such, design approach and quality are inconsistent, with disparity in how seismic risk is addressed in temporary works. As stated by Mark Hedley, following a major scaffold collapse at Panmure Bridge in 2017, '*It has been left to people's initiative to develop systems they think will be suitable and safe'* (Engineering NZ, 2019)

To improve the quality and consistency of seismic design for temporary works, the TWf NZ intends to prepare a Technical Guidance Note summarising best practice. In preparation for this design note, we have prepared this NZSEE conference paper to summarise our research and share our findings with the industry.

In the context of this paper, temporary works includes:

Temporary structures: Formwork and falsework; precast propping; temporary bracing to steelwork; fixed scaffolding; temporary bridges; site hoarding; protection gantries; temporary site offices and utilities.

Equipment and plant support: Bases and ties for tower cranes; bases and ties for construction hoists; support for cantilever loading decks and proprietary work platforms.

Earthworks: Support to trenches; temporary retaining walls.

Temporary conditions associated with construction: Existing or new permanent structures subject to construction loading or temporary conditions during construction; incomplete new permanent structures during the construction sequence. (TWf NZ, 2019).

2 SEISMIC DESIGN OF TEMPORARY WORKS: THE CONTEXT

2.1 Temporary works design versus permanent works design

There are significant differences between temporary works and permanent works design which must be considered when formulating design methods and parameters:

- Temporary works don't fit the definitions of a 'building' and it can be difficult to apply prescriptive rules, such as accidental eccentricities and definitions of regularity which have been formulated and written for multi-story buildings.
- Temporary works have short service lives. Exposure to infrequent environmental events is less likely than for permanent buildings.
- The consequences of failure for temporary works may have no relationship to the consequences of failure of the completed building.
- In temporary works design, consideration needs to be taken of intermediate construction stages, not just the 'wished in place' condition. Logistics and practical considerations often present the greatest design effort. Constructability and addressing immediate construction safety risks are normally the priority.
- Most (but not all) temporary works are used within controlled construction sites. Temporary works are not normally intended for public use, except for pedestrian gantries, hoardings, and the like. Arguably, there are lower expectations for the seismic performance of temporary works compared to permanent works. As stated by Hill (2004) '*Conditions on construction sites often reflect much greater risks of collapse than that associated with the completed structure'.* Ideally this would not be the case, but this situation is common and generally recognised by those working in construction.

2.2 Challenges associated with seismic design of temporary works

There are several challenges with incorporating good seismic design in temporary works:

- Contractors and clients are not necessarily aware of the requirement to design temporary works for seismic loads and there is a history of seismic risks being ignored. Allowances may not be included in tender costs or program for additional design or implementation of 'earthquake robust' temporary works.
- While permanent works designers should always consider construction methodology in their designs, this tends to be done with little thought to seismic resilience during construction. Well-considered permanent works design can substantially reduce the cost, complexity, and risk in the temporary works.
- Efficient temporary works make use of permanent works' load paths. It is often difficult to resolve where responsibilities lie between the permanent works engineer and temporary works engineer when load paths are a 'composite' of temporary works and permanent works.
- Conventional temporary works, such as diagonal props and braces, tend to be stiff and non-ductile. Stiff temporary works are often required to achieve tight construction tolerances, but stiffer structures tend to attract higher seismic loads. So, adding more props isn't always the right solution for the seismic load case. It can be difficult to find the right balance between strength and stiffness for temporary works.
- Temporary works need to have high construction tolerance. Many strategies for achieving tolerance such as slotted or oversized holes, stacked packing plates, jacks and the like, can create challenges with lateral and tension load paths.
- Post-installed anchors are commonly used for fixing temporary works to concrete since they don't require early coordination of cast-in items. Post-installed anchors can be governed by brittle failure modes such as shallow concrete cone failure. Only some anchors are seismically rated, and the reductions on anchor capacity are severe for seismic loading in cracked concrete.
- Most temporary works employ reusable proprietary products for all or part of the assembly. These proprietary products are typically designed and manufactured overseas to international standards. Supplier information is often incomplete and may not highlight key assumptions made by the supplier. Often the capacity of components is quantified by in-house testing by the manufacturer. In most cases seismic loading has not been considered in the design, detailing, or testing of the components. Typically, capacities are presented as 'safe working loads' which are not compatible with our load and resistance factored design (LRFD) standards. The case is similar for equipment such as hoists and cranes.

2.3 Seismic risk for temporary works in New Zealand

2.3.1 Uncertainty in earthquake engineering

New Zealand's updated National Seismic Hazard Model (NSHM) was released on the 4th of October 2022 (GNS, 2022). In their press release, GNS Science stated that *'Forecast ground shaking hazard has increased across New Zealand with an average increase of about 50% or more'*. (Mitchell, 2022).

The release of the new NSHM was a reminder of the uncertainty in estimating earthquake hazard. NZSEE, SESOC and the NZGS published an advisory *Earthquake design for uncertainty* in August 2022 in anticipation of the new NSHM. The key message of the advisory was that with good design, seismic uncertainty can be mitigated to achieve significant risk reduction with minimal cost implications. (NZSEE, 2022).

2.3.2 Past performance of temporary works in earthquakes

There are several examples of tower cranes collapsing in earthquake, including two cranes that collapsed at the Taipei Financial Centre (Taipei 101) in Taiwan in March 2002 during the M7.1 Hualien earthquake. The epicentre was approximately 100km from Taipei at a depth of 32km (OCHA ReliefWeb, 2002). Five people were killed, including both crane drivers, and over 20 people were injured in the event. (Cranes today, 2002).

During the 2016 M7.8 Kaikoura earthquake there was a significant temporary works collapse on a construction site in Wellington as shown in Figure 1 (left). The lessons learnt were presented to the TWf NZ, however, due to commercial sensitivities we cannot provide specific details. Eight double-t flooring units collapsed due to loss of seating during the earthquake. Shoring towers rocked, causing the supporting beams to pull away from the double-t units. Had this earthquake happened during working hours, serious injuries or fatalities could have occurred.

Photos from the February 2011 Christchurch earthquake show several collapsed scaffolds as shown in Figure 1 (right) below.

Figure 1: Left: Collapse of precast flooring units on a Wellington construction site during the November 2016 Kaikoura earthquake 2016 (Source confidential, 2016). Right: Collapsed scaffold following the February 2011 Christchurch Earthquake (Coxhead, 2011).

Aside from these examples, there appears to be few observations recorded of the performance of temporary works in earthquakes. Reconnaissance and clearinghouse records tend to be focused on permanent structures and geotechnical hazards. In the future it would be beneficial to have a TWf NZ delegate attend reconnaissance trips for gathering information on the performance of temporary works in a major earthquake. This information could be incorporated into a technical note on the performance of temporary works details to better inform the design of temporary works in the future.

3 LITERATURE REVIEW

3.1 New Zealand regulations, standards, and guidelines

3.1.1 NZ Building Code

Temporary works are covered under Part B1 of the Building Code which includes explicit requirements for consideration of earthquake loading for sitework under B1.3.3: *Account shall be taken of all physical conditions likely to affect the stability of buildings, building elements and* ***sitework****, including:..(f) Earthquake…* B1.3.4 requires '*Due allowance shall be made for: (a) The consequences of failure…'* and B1.3.6 requires that '*Sitework, where necessary, shall be carried out to… provide stability for construction on the site…'* (MBIE, 2014).

The Building Code is contained within Schedule 1 of the Building Regulations 1992. As such, it is a legal requirement to consider earthquake actions and the consequences of failure in the design of temporary works.

3.1.2 NZS 1170.0 and NZS 1170.5

The NZS1170 'Structural design actions' suite of standards, is cited under Verification Method B1/VM1 of the NZ Building Code (MBIE, 2014). This makes NZS1170 the most direct way of complying with the building code with respect to estimating earthquake loading on temporary works.

- **NZS 1170.0 Part 0: General principles** provides a method for determining importance levels, which are related to the consequences of failure. Table 3.3 provides the annual probability of exceedance (APE) for earthquake actions for construction equipment with importance level IL2. (Standards New Zealand, 2002)
- **NZS 1170.5 Part 5: Earthquake actions – New Zealand** provides methods to estimate earthquake actions, which can be applied to temporary works design. Typically, the 'equivalent static' method is applied to temporary structures fixed to ground, and the 'parts and components' method is applied to temporary structures or parts fixed to the permanents works above ground. (Standards New Zealand, 2004)

3.1.3 Materials standards cited by the NZ Building Code

The following materials standards used in temporary works design are cited in B1/VM1 of the NZ Building Code. These can be used for demonstrating compliance of temporary structures in these materials, and for checking permanent works members that are part of temporary load paths.

- **NZS 3404:1997 Steel structures standard**
- **NZS 3101:2006 Concrete structures standard**
- **NZS 3603:1993 Timber structures standard** (soon to be superseded by AS/NZS 1720:2022).

All have methods and rules related to designing for earthquake actions. They provide detailing rules for achieving seismic resilience in structures for elastic to fully ductile response. However, even for elastic design, these standards do not allow a brittle failure to govern. Associated cited standards cover materials and construction requirements that also apply to temporary works design.

3.1.4 Other New Zealand standards and guidelines

- **Temporary Works forum NZ guidelines.** Since its inception, the TWf NZ has published several good practice guides which includes:
  - **Temporary works procedural control (2019).** The guide mentions earthquake loads as a consideration in temporary works design. Assessment of the consequences of failure is integral in temporary works procedural control. (TWf NZ, 2019)
  - **Temporary works in a marine environment (2022).** The guide recommends consideration of seismic loads for fixed temporary works in accordance with AS/NZS1170. (TWf NZ, 2022)
  - **Precast panel propping design (2022).** The guide recommends calculating seismic loads to NZS 1170.5 for 1/100 APE event, for elastic loads. Recommends the use of seismically rated fixings for precast props, prohibits deformation-controlled (drop-in) anchors, and requires proof testing for chemical anchors (TWf NZ, 2022).
- **Worksafe good practice guidelines: Safe work with precast concrete (2018).** The guide refers structural designers to NZS 1170.5 for determining seismic loads. It refers to 'Parts and Components' section of NZS 1170.5 for multi-story buildings. (Worksafe NZ, 2018)
- **Worksafe good practice guidelines: Scaffolding in New Zealand (2016).** The guide mentions earthquake loads as an environmental load that must be considered and cites NZS 1170.5 for earthquake actions. It suggests seeking advice from a CPEng for assessment of environmental loads. (Worksafe NZ, 2016).

- **Department of Labour: Approved code of practice for cranes (2009, 3rd Ed.)** The ACoP Explicitly requires designers to consider seismic design and cites NZS 1170.5. It includes a method for checking seismic actions; however, this method has several apparent shortcomings:.
  - It is not in accordance with NZS 1170.5. It appears to be a permissible stress method. The method is not referenced – it is unclear from where the method has been derived.
  - Applies a blanket 'Zone Factor' of 1.2 for all cranes, irrespective of location. The Zone Factor is not a parameter that is defined in NZ standards. It is not the same as the hazard factor Z in NZS 1170.5.
  - It is relevant only for 'rigid and intermediate' subsoils with no guidance on the definitions of these terms (presumably they are equivalent to site subsoil class B/C)
  - The seismic design coefficient curves incorporate ductile response from the crane tower. Assumes as a minimum that diagonal bracing members of cranes are capable of plastic deformation in tension.
  - P-delta allowances are highly prescriptive with a questionable relationship to the physics of second-order p-delta effects.
  - The method is relevant only to freestanding cranes. (Department of Labour, 2009)

  For these reasons, we recommend that NZS1170.5 is used for assessing seismic actions on cranes with allowances for P-delta actions from relevant methods given in the standards.
- **Ministry of Works and Development: Code of practice for falsework Vol. 1 (1980)** This code of practice is out of date; however, the design philosophies remain valid. In the authors' opinion, this code provides the most considered treatment of seismic loads in temporary works compared to other references reviewed. Part of the seismic loading calculation includes an exposure period factor F_e. There is also a factor, F_c, that accounts for the consequences of failure.
- **Waka Kotahi NZTA Bridge Manual (2022, 4th Ed.)** The fourth edition provides a detailed set of load combinations for construction cases. A minimum return period of 100 years is recommended for seismic loads with higher return periods if appropriate, and lower return periods for short duration situations (NZ Transport Agency, 2022). We note that the Bridge Manual combinations are intended for assessing the permanent bridge works for construction scenarios, and not for designing temporary works.
- **MBIE earthquake geotechnical engineering practice series.** Module 6: 'Earthquake resistant retaining wall design' provides methods of estimating seismic soil loads on retaining structures. Worked example 4 provides methods of design that can be applied to propped and tied-back walls. Peak ground acceleration (PGA) 'a_{max}' is obtained for the relevant site and return period from Module 1, Appendix A.
- **NZSEE et al Earthquake design for uncertainty**. The principles of designing for uncertainty described in the advisory also apply to temporary works design:
  - Provide simple, 'regular' structures with clear load paths and redundancy. Ensure elements are properly tied together and consider deformation compatibility between different load paths.
  - Avoid details with limited displacement capacity – choose details that can maintain strength after yielding instead of details that may lose strength if pushed past their theoretical capacity. Use capacity design and choose robust details that suppress brittle failure modes.

3.2 International standards and guidelines

There are few countries with similar seismic hazard and seismic design standards to NZ. As such, the availability of international guidance for seismic design of temporary works is limited. The following section summarises seismic design guidance found in international references.

3.2.1 USA

- **ASCE 37-14: Design loads on structures during construction**. The standard refers to ASCE/SEI 7-10 (equivalent to NZS1170) for estimating earthquake loading on the basis that *'All structures shall be* *treated as Risk Category II… regardless of the group classification of the completed structure.'* Risk Category II is equivalent to Importance Level 2 in NZS1170.0. The standard allows the use of a reduction factor on the ASCE/SEI 7-10 mapped values. The factor is essentially a return period factor for exposure period corresponding to a mean recurrence interval of about 50 years (2% chance of exceedance in one year). The standard exempts consideration of earthquake loading '*where large earthquakes are infrequent or not considered probable.'*. Also exempt is *construction of detached one- and two-family lightly framed dwellings not exceeding two stories in height…'*. (ASCE, 2015) (ASCE/SEI, 2010)

- **CALTRANS Falsework manual** requires consideration of lateral load with a minimum horizontal load of 2%. It does not require earthquake loads to be considered for falsework for bridges, but directs designers to *consider a reduced earthquake loading on partially completed structures over or adjacent to traffic as stated in Memo to Designers (MTD) 20-2.* The memo requires earthquake design based on 1/100 APE for temporary works with design life less than 5 years. 'Important' and 'Nonstandard' bridges require 'project-specific approaches' (CALTRANS, 2011) (CALTRANS, 2021)

3.2.2 UK and Europe

Europe generally has low seismic hazard except for countries in the South-East including Italy, Greece, Albania, Romania and Turkey. The Eurocode standards are main source of seismic design information.

- **BS5975 Code of practice for temporary works procedures and the permissible stress design of falsework** is silent on earthquake loading. It is included here since it is a standard commonly cited and used by temporary works designers and suppliers internationally. (BSI, 2019)
- **EN 1991-1-6 Eurocode 1 – Actions on structures Part 1-6: General actions – Actions during execution** briefly covers seismic actions. It refers designers to EN 1998 Eurocode 8: Design of structures for earthquake resistance. (CEN, 2005)
- **EN 1998 Eurocode 8: Design of structures for earthquake resistance** provides seismic design parameters with consideration for the reference return period of the considered transient situation, and the importance factor. Seismic actions are scaled based on the duration of the construction phase and the acceptable probability of exceedance. This method essentially provides a variable return period factor that can be calculated for any exposure period or probability of exceedance. (CEN, 2013)
- **EN 12811: Temporary works equipment: Scaffolds** does not cover seismic loading. (CEN, 2003).
- **EN12812: Falsework – Performance requirements and general design** states that *'Allowance shall be made for seismic effects',* referring to EN 1998 for the applicable seismic parameters. The standard provides good guidance on load combinations including seismic effects which explicitly excludes the wet concrete weight case from the seismic combination. (CEN, 2004)
- **EN 81-77 Lifts subject to seismic conditions** is applicable for construction hoists. The authors have seen this standard used by hoist suppliers to verify the tie capacity for hoists in NZ. The standard refers to EN 1998 and states that lifts must be considered 'non-structural elements' according to EN 1998-1 which is equivalent to parts and components loading in NZ terminology (CEN, 2013).

3.2.3 Other

- **AS3610: Formwork for concrete (Australia)** requires consideration of earthquake loads to AS1170.4 where formwork remains in place for more than 6 months. (Standards Australia, 1995)
- **ISO 11031: Cranes – Principles for seismically resistant design** provides methods for estimating seismic forces for cranes. It suggests a recurrence interval of 100 years for *'cranes intended for temporary use at different sites'*. It provides detailed methods for determining response spectra, including 'response amplification factor' analogous to our parts coefficient under NZS1170.5. Methods are given for equivalent static, modal, and time-history analysis of cranes. (ISO, 2016)

3.3 Research by Others

The topic of seismic design for temporary works has been reviewed in the past by several authors. Papers of note include the following:

- **Hill (2004) Rational and irrational design loads for 'Temporary' structures.** Discusses risks and exposure for structures with short design life. The author argues that shorter design life does not equal reduced risk from a reliability or safety perspective, and that it is irrational to reduce loads (such as seismic demands) due to design life alone. This is at odds with many guidelines and codes that have 'exposure factors'. Hill argues that a more rational basis for load reduction for temporary works is by: (i) conditional occupancy - occupancy during construction is limited to those trained and experienced in construction hazards; (ii) accepted risk - higher risks during construction are generally accepted compared to the risks associated with the finished structure. (Hill, 2004)
- **Beale (2014) Scaffold research – a review** notes that there is limited research on the response of scaffold structures during earthquakes but cites several studies including Blair and Woods (1990) who suggest scaffold should be allowed to slide (walk) during earthquake, provided the scaffold doesn't overturn. Beale also references shake table tests of scaffolding up to 12ft by Lindley et al (2001) that concluded damping was high and the scaffolding showed good resilience in tests with no structural failures. (Beale, 2014)

3.4 Discussion

- All reviewed NZ guidelines require consideration of seismic loads in the design of temporary works. No designer or supplier of temporary works should consider that seismic design is optional.
- It can be argued that the NZS1170.5 approach of applying a blanket IL2 to construction equipment is not compliant with the intent of the NZ Building Code which states '*due allowance shall be made for… the consequences of failure*'. Similarly, the NZS1170.5 approach is not in line with the TWf NZ temporary works procedural control in which the consequences of failure are integral to risk management.
- The only reference that explicitly considers the consequence of failure in temporary works is the 1980 Ministry of Works code of practice for falsework. Other guides such as those by ASCE and CALTRANS implicitly consider consequences via exemptions from seismic design in low-risk situations.
- Designers should incorporate consequences of failure into temporary works design by assessing the importance level according to NZS1170 and selecting the required design APE for the appropriate design life (< 6 months, typically). In this way the temporary works is designed for loads commensurate to the risk of failure to the public and neighbouring assets at risk from the construction.
- From our review of international standards and guidelines several themes emerged:
  - All standards consider a reduced design return period for temporary works structures (in the order of 50-100 years). The design return period for temporary works design in NZ (100 years) is broadly in line with international standards.
  - Many international references contain thresholds for when seismic actions need not be considered. In the case of Europe and the US, the geographical spread is such that there are regions that can be considered 'non-seismic' for the purposes of structural design. In the authors' opinion, such a threshold should not be applied for New Zealand. Our seismic standards already consider seismic risk in the hazard factors for different locations. Implementing an arbitrary threshold will not produce consistent or rational designs.
- For falsework design, seismic loading should always be considered; however, in many cases it can be justified that a design earthquake occurring while the concrete is still wet has *sufficiently low probability of occurrence* that they need not be considered in combination. This is consistent with EN12812 and the

1980 code of practice for falsework design. However, in the weeks leading up to the pour, falsework will be supporting formwork, a significant mass of reinforcing steel, personnel, and equipment. It may also support precast elements. These should be considered in the seismic design.

- Most sources on scaffold design either don't address seismic design or they mention consideration of seismic loading briefly and non-specifically. This may reflect the fact that most lightweight free-standing access scaffolds are governed by wind actions, although this isn't necessarily the case for scaffolds tied to, or suspended from, buildings.
- There is NZ and international guidance available for all common types of temporary works, including hoists and tower cranes; however, the industry would benefit from a dedicated standard for temporary works design in NZ.

4 CASE STUDIES

The following case studies present examples of temporary works that incorporate seismic design to NZ standards, following the principles of robust seismic design. In several cases the temporary structures were exposed to significant earthquakes while in use.

4.1 Hayward's Interchange pedestrian bridge girder support, Wellington (2016)

4.1.1 Design Features

The permanent structure is a four-span pedestrian bridge that crosses four lanes of SH2 and the Wairarapa and Hutt Valley rail lines. Both assets remained in use during the works. The bridge spans are single super-t girders integral with the piers. The lateral load paths were not complete until the pier heads were cast. The temporary works solution was as follows:

- The importance level of the temporary works was increased to IL3 to match the importance of the state highway are rail assets. The design return period in this case was 250 years.
- Temporary brackets were installed on the faces of the piers with through-bolts. Bolts passing through the piers provided a robust load path into the piers. Similarly, temporary brackets were fixed to the super-t girders prior to lifting (see Figure 2). Once placed, these brackets could be quickly bolted together.
- The permanent works load path was used as the temporary load path with temporary works designed to replicate the permanent load path to the pier head. While the loading condition was not identical (no continuity of the bridge spans in the temporary case), the piers worked as cantilevers for the 1/250 APE.

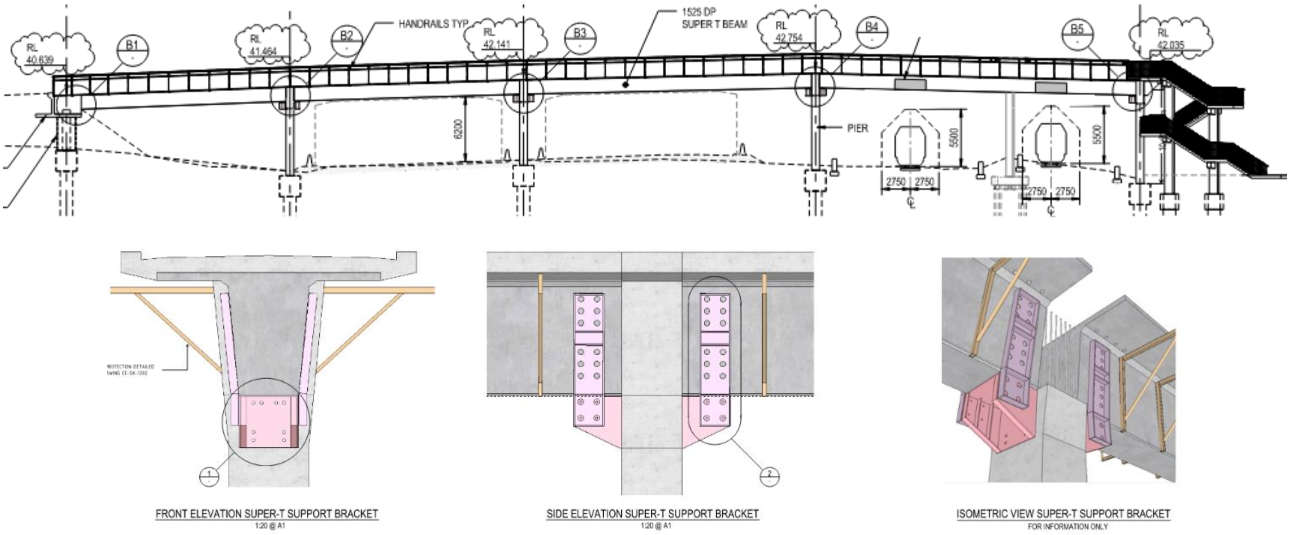

Figure 2: Elevation of the bridge and conceptual details of the temporary works supporting the girders.

4.1.2 Observed Seismic Performance

One month after installation, and prior to the pier heads being completed, the M7.8 Kaikoura earthquake struck Wellington. Inspections showed no damage and minimal movement in the temporary works.

4.2 Super-t girder support system (various projects), Wellington (2016-2020)

4.2.1 Design Features

The permanent works structures were super-t girder bridges for the Transmission Gully and Peka Peka to Ōtaki projects. Several bridges crossed SH1 and the NIMT rail line. These were design with an elevated IL3 importance level for 250-year return period. Girder depths were between 1025mm and 1525mm with weights up to 60T. The design challenges and solution was as follows:

- Initial calculations showed that the lateral loads were greater than what could be easily resisted by diagonally bracing the girders. Generally, the connections presented the greatest difficulty in achieving the required capacity based on elastic seismic loading.
- Many existing solutions for precast girder support involve bracing the girders together, or tying the flanges together, to prevent overturning – but this leaves the first girder vulnerable. Since some bridges crossed SH1 with significant pier cross-fall, this presented an unacceptable risk.
- The solution was to provide efficient girder ties that clamp the girder onto the supporting structure. Under lateral load tension is induced in the ties, mobilising their tension capacity. As the tie tension increases, so too does the normal force across the friction interface between the girder and its seating. Friction calculations showed the overturning mode was most likely – although the tension ties can still be effective if sliding occurs, with some permanent translation of the girder.
- The girder ties were threaded grade 500E rebar (ReidBrace™) fixed into the supporting structure via cast-in hooked bars with couplers or chemical anchors, both designed to develop the yield strength of the bars.
- This solution was simpler and less expensive to implement than conventional girder bracing systems, and each girder with ties was 'self-stable'. Adopting connections that could fully develop the yield capacity of the ties provided further robustness.

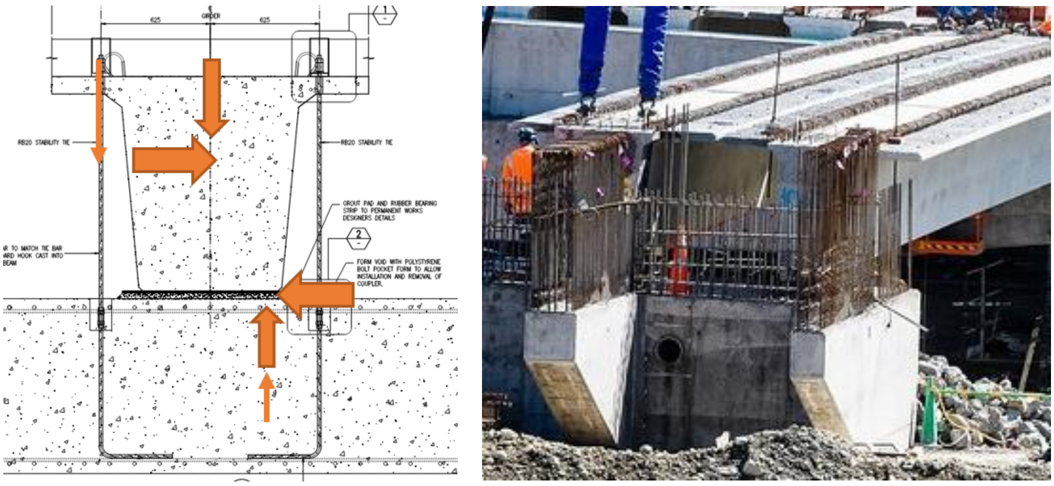

Figure 3: Super-t girder 'stability tie' system is very efficient while providing enhanced robustness over conventional girder bracing strategies.

4.2.2 Observed Seismic Performance

Temporary works for bridges BR01 and BR05 at Peka Peka to Ōtaki experienced the M5.4 earthquake on the 25th May 2020 which occurred off the Levin coast. Temporary works for these two bridges were designed for IL2 based on a 100-year return period design event. Maximum peak ground acceleration recorded was 0.15g. No damage or movement was observed following the earthquake and subsequent M5.0 aftershock.

4.3 Peka Peka to Otaki bridge BR08 propping, Otaki (2020)

4.3.1 Design Features

Bridge BR08 on the Peka Peka to Ōtaki expressway is an 80m long steel girder bridge that crosses SH1 and the NIMT rail line. The temporary works were designed for IL3 and hence 250-year design return period. The completed bridge was designed to span between abutments, with the central piers providing only nominal lateral resistance for free-float bearings. The main challenge with the temporary works was to ensure lateral loads could be taken to ground prior to the bridge deck (diaphragm) being completed. The exposure period was significant while the deck was constructed, and the deck design used heavy precast concrete planks as permanent formwork which offered no contribution to bracing. Design features of the temporary works included:

- Provision of additional diaphragm bracing to the bridge girders, which were incorporated into the permanent works.
- Inputs into the deck construction sequence to ensure a portion of the deck and the back walls were constructed early, to anchor the bridge into the abutments prior to landing the majority of the precast deck panels.
- A substantial propping tower was provided at the central pier to augment the permanent works. This propping tower provided vertical support to the girders prior to the free-float bearings being grouted, and lateral support to bridge prior to deck diaphragm being completed.
- It proved impractical to provide 100% of the required lateral resistance via the temporary propping tower. The permanent works piers were robustly detailed by the bridge designer for an accidental lateral load. The lateral resistance of the piers was used together with the temporary tower to provide the necessary lateral resistance. Modelling confirmed the stiffness compatibility between the temporary works and piers, and additional checks were done to ensure 'no cracking' up to SLS1 loading.

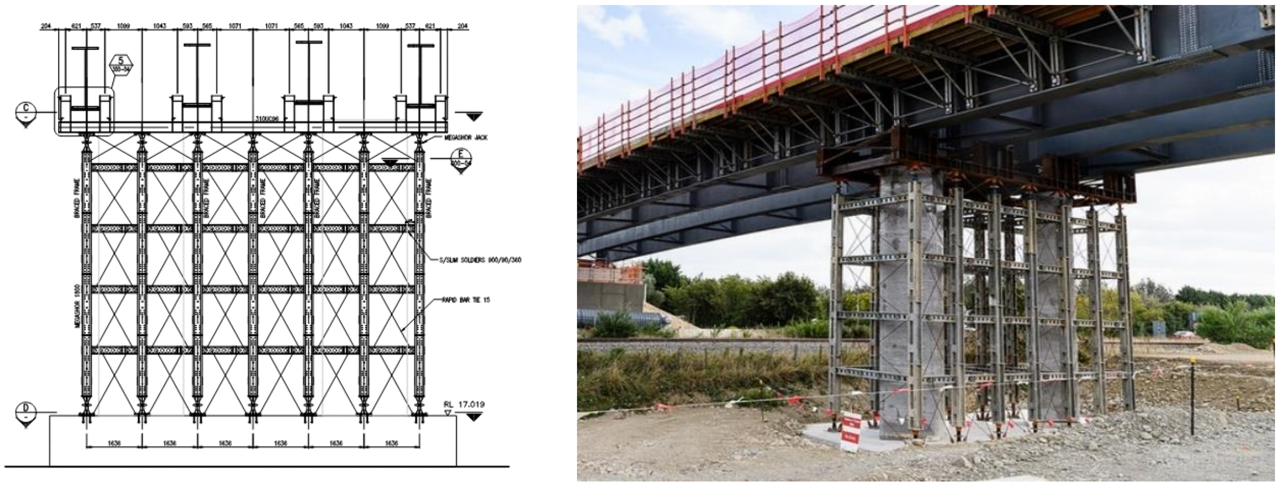

Figure 4: Bridge BR08 propping at Peka Peka to Ōtaki showing 'composite' temporary/ permanent load path. Photo credit: Mark Coote.

4.3.2 Observed Seismic Performance

The bridge was partially constructed during M5.4 earthquake on the 25th of May 2020 which occurred off the Levin coast. No damage or movement was observed following the earthquake. All the columns were uncracked.

4.4 Ductile ties for construction hoist (various projects) Wellington (2019-2023)

4.4.1 Design Features

Construction hoists have masts that are tied the building at 6-10m centres. When ‘parts and components’ loads are considered, the lateral load on ties can be significant. Designing for elastic loads results in ties out of proportion to the mast. This leads to a potentially non-robust solution where the mast may fail before the ties.

While it would be unfortunate for an earthquake to happen while the hoist was in use, the consequences of failure are high for those using the hoist, and on many sites, the hoist and mast could fall across public areas. One example is at Bowen House in Wellington which overlooks the Beehive and the Treasury. To provide robustness a ‘ductile hoist tie’ solution was developed to protect the hoist components from excessive seismic loads, and to reduce the demands on fixings (see Figure 5 (left)). Naylor Love developed a similar solution for a project at Wellington East Girls College, as shown in Figure 5 (right). These solutions have the following design features:

- The engineered component was ductile. In one case the ductile element was a moment frame designed to form plastic hinges in the legs. In the other case ductile tension-only RB12 bars were used.
- All other components, such as the fixing to the building, were designed for the overstrength of the hinging mechanism. Robust fixings were used that can develop the overstrength of the ductile component.
- Lateral seismic demands were estimated using the parts and components method with $\mu = 3.0$. Detailing of the ties met the requirements of NZS3404 for the necessary member categories. The ductile frame limited the lateral load that could be transferred to the hoist within its rated wind capacity.

Figure 5: Left - Ductile hoist tie at Bowen House, Wellington. Right – Ductile hoist tie at Wellington East Girls College (courtesy of Naylor Love).

5 RECOMMENDATIONS FOR THE TWF NZ DESIGN NOTE: GOOD PRACTICE SEISMIC DESIGN FOR TEMPORARY WORKS IN NEW ZEALAND

Based on the literature review and case studies presented above, we recommend the following points are considered for the TWf NZ design note for the seismic design of temporary works.

5.1 Consider the consequences of failure

Consideration of the consequences of failure is a requirement of the NZ Building Code for sitework, and it is integral in temporary works procedural control. The TWf NZ guideline provides recommendations on assessing the consequences of failure to determine check categories. The categories are minor; insignificant; major; and catastrophic. These broadly fit NZS1170.0 and NZ Building Code importance levels: IL1 (low), IL2 (ordinary), IL3 (high) and IL4 (exceptional), respectively. The designer can assess the check category to the TWf NZ good practice guideline and select the corresponding importance level from NZS1170.0.

Do not assume all temporary works and construction equipment are IL2. Use the appropriate importance level with the design working life of the temporary works to determine the required APE from Table 3.3 from NZS1170.0. When assessing the consequences of failure, consider whether the public and other buildings or assets are at risk. Temporary works associated with tall buildings may fall outside the site. Temporary works for bridges constructed over or adjacent to roads and rail may also put those assets at risk. Conversely, it may be appropriate to adopt IL1 for low-risk temporary works where failure is not likely to endanger human life.

For retaining walls or underpinning works, the seismic performance of the temporary works needs to match or exceed the performance requirements of what it is supporting.

5.2 Adopt check (peer review) categories of the TWf NZ procedural control guide

The first recommendation of the *Earthquake design for uncertainty* advisory is to get designs peer reviewed. Peer review is a useful tool for reducing design risk. The TWf NZ procedural control guide provides recommendations for independent checking appropriate to the consequences of failure. We recommend that the guide is used by all temporary works designers to select an appropriate level of checking.

5.3 Use appropriate standards and methods

5.3.1 Adopt NZS1170.5

Generally, NZS1170.5 should be used to determine seismic parameters with the appropriate APE associated with the importance level for the temporary works. In most cases the equivalent static method can be used to estimate seismic inertia loads applied to the temporary works. For temporary works fixed to, or supported on, the permanent works, apply the parts and components method. This includes determination of tie forces for ‘tied back’ temporary works such as hoists, scaffolding, and tower cranes (where ties are used). It also includes propping for precast panels supported on suspended parts of the permanent structure.

5.3.2 Consider displacement compatibility

Ensure temporary and permanent works are compatible from a lateral stiffness perspective and consider their relative stiffness when apportioning seismic load. Temporary works should not straddle movement joints or base isolation planes unless specifically designed to cope with the anticipated movements. If in doubt, seek input from the permanent works engineer.

5.3.3 Take care with proprietary products

It is important for the designer to understand how the supplier has presented capacities. Similarly, it is important for suppliers to clearly communicate to designers how the product capacities have been derived. The capacity of proprietary products and components will typically be presented as a working load limit. Suppliers can normally supply the safety factors associate with the working load limit (WLL). NZS1170.5 provides ULS seismic loads, so a conversion from WLL to *design capacity* is often required. Use strength reduction factors consistent with NZS3404 for steel components. Apply further reduction factors, if necessary, to account for wear and tear.

For hoists and tower cranes reference to international standards may be required. Seek input from the supplier wherever possible – discussions with suppliers about seismic risk can only improve awareness and understanding between suppliers and users of the equipment.

5.3.4 Retaining walls and underpinning

Use MBIE earthquake geotechnical engineering practice guidelines (Module 6) to estimate seismic soil loads for the appropriate APE. Use Module 1 to determine peak ground acceleration for the required return period, not NZS1170.5. When designing temporary retaining walls or underpinning, understand the impact of settlement or wall movement on the supported structure.

5.4 Apply principles of robust seismic design to temporary works: Design for uncertainty

Seismic loads are a 'best estimate' for design and they carry significant uncertainty. Temporary works design should follow the principles of designing for uncertainty, following the advice provided by the NZSEE et al. Structures should have clear, simple loads paths, and be well tied together. Other key principles, as applied to temporary works, are summarised below:

5.4.1 Provide robust connections

The most important principle is to ensure connections are robust. The following hierarchy of robustness can be used for selecting fixings for temporary works:

- Not OK: Seismically rated anchors are not used, or brittle connection failure governs. Shallow embedment with brittle concrete breakout/ pull-out mechanism is most likely.
- OK: Seismically rated/tested anchors are used with elastic demands, and the effect of cracking is considered in assessment. Chemical anchors are load-tested, drop-in 'displacement controlled' anchors are not used.
- Good: Deep seismically rated anchors are designed to develop the tension capacity of the fixing i.e., the steel failure mode governs and shear-friction mechanisms can develop as the anchor yields.
- Good: Ductile through-bolts (typically G4.6 threaded rod) pass through the connected slab or beam with an oversized washer (bearing plate) on the reverse side. Bolts can yield in tension. Bolts transfer shear in dowel action and/or shear friction if the bolt yields.
- Best: The above 'good' options are used, and they are protected from overload via capacity design.

5.4.2 Understand and apply capacity design principles (where possible)

The following principles should be understood by all design engineers and applied to temporary works if possible:

- Identify desirable and undesirable failure mechanisms by considering the ductile elements that can yield and displace without significant loss of strength of the lateral system.
- Apply capacity design principles. Size the ductile part for the required seismic load and design all other parts (connections etc.) for the overstrength capacity of the ductile part. Refer to NZS3404 and/or product literature for the appropriate overstrength factors.
- The simplest ductile (or potentially ductile) component in temporary works is proprietary tension-only bracing with ductility demonstrated by testing:
    - ReidBrace™: ductility confirmed by testing completed at the University of Auckland. Achievable ductility is dependent on bar size and cleat thickness – refer to supplier literature.
    - Donobrace™: tested to achieve nominal ductility $\mu = 1.25$.

- Check details and material requirements. Follow the rules of NZS3404 Section 12 if ductility is adopted for the temporary works. For checking permanent works refer to the appropriate materials standard and seek input from the permanent works designer.
- Consider p-delta actions, especially if using flexible, ductile tension braces.

5.5 Designing temporary works that is efficient and seismically robust

As stated in the *Earthquake design for uncertainty* advisory, good design can achieve seismic resilience with minimal cost implications. The below strategies can help designer to achieve cost effective temporary works that is seismically robust:

5.5.1 Use the permanent works – modify the construction sequence if possible

The least efficient form of temporary works bypasses or ignores perfectly adequate lateral load paths in the permanent works. Provided the load paths are understood at intermediate construction stages, permanent works can provide the most efficient load path for temporary loads. The permanent works will be designed for at least a 1/500 APE event for the permanent case, and the lateral system should have seismically robust detailing in the completed condition.

Prior to beginning design of temporary works, review the construction sequence to see if construction of useful permanent structure can be brought forward in the program. In this way, the permanent lateral system (or parts of) can be constructed early, and gravity systems can take support from that structure. Take care when considering incomplete structures, without diaphragms or fly-bracing for example, which may be necessary to achieve robust seismic response.

This approach of modifying the construction sequence was taken on the Peka Peka to Ōtaki BR08 propping (see case study) in which construction of the end walls and end sections of the deck were brought forward to lock the bridge into its abutments as early as possible in the construction program.

Care needs to be taken when making use of permanent works. In many cases the permanent works will need to be assessed to ensure it can take the necessary loads in the temporary condition. It is always a good idea to engage with the permanent works engineer to discuss the strategy and understand how the permanent works have been designed. Similarly, it is best to openly discuss and formalise the responsibilities and risks with the permanent works engineers and clients.

5.5.2 Consider consequences of individual failure modes

The aim for robust temporary works design is primarily to prevent collapse that may lead to safety risks for workers or the public (special cases notwithstanding). Ordinarily, damage and/or movement are acceptable for the Ultimate Limit State provided these do not lead to collapse or other safety hazards (such as crushing or impact).

All failure modes are not created equal. Designers should consider the actual consequences of certain failure modes since some may be innocuous, others catastrophic. For example, sliding of a foundation or base plate will not necessarily lead to collapse. Blair and Woods (1990) arrived at this conclusion when reviewing seismic design of scaffolding for nuclear facilities. By allowing a scaffold to ‘walk’, they could demonstrate that overturning was unlikely based on an upper-bound estimate of the friction coefficient. This is essentially capacity design: protect the catastrophic overturning failure mode by allowing sliding to occur first.

5.5.3 Loading and other assumptions

The following approaches can help to achieve more efficient seismic design while maintaining a suitably low probability of collapse:

- When checking proprietary products, convert working load limits into design loads. NZS1170 provides ULS seismic loads, while most suppliers of proprietary systems quote capacities as working loads. If you are comparing ultimate loads to working loads, you are essentially double-counting the safety factor. Engage with the supplier if safety factors are not given in their technical literature.
- When designing falsework, it is not common practice to design for ULS earthquake while the concrete is still fluid, provided the concrete, once hardened, locks the element into the permanent works. Concrete begins to cure and has sufficient strength to transfer diaphragm loads to permanent load paths in a matter of hours. The scenario of an ultimate earthquake occurring during or immediately following a pour, while possible, is deemed a 'sufficiently low probability event' akin to both ULS wind and seismic events happening simultaneously. The temporary works designer should carefully consider how the load paths change when the concrete hardens and design the temporary works accordingly.
- Friction can be used in temporary works for seismic cases, provided the consequences of movement are considered. While friction cannot be completely relied upon to prevent sliding, in many cases sliding has low risk of leading to collapse. Eurocode EN12812 provides upper and lower bound friction coefficients at the interface of common construction materials which can be used to assess friction resistance and failure hierarchy.

6 CONCLUSION

This paper provides a starting point for developing concise, practical guidance for designers on how to achieve compliant and seismically resilient temporary works designs. Following the NZSEE conference we will seek feedback to incorporate into a Temporary Works forum NZ guidance note. We expect the key messages of the guidance will be:

- The design process for temporary works must consider earthquake actions and the consequences of failure.
- Temporary works designer should estimate earthquake loading using NZS1170 and consider parts and components loading as required.
- Principles of robust detailing and *design for uncertainty* are as important for temporary works design as they are for permanent works design. Good design of temporary works can achieve seismic resilience with minimal cost implications.

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