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Design Philosophy for Improving Horizontal Infrastructure Seismic Resilience

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ABSTRACT

The Canterbury Earthquake Sequence of 2010/2011 severely damaged horizontal infrastructure in Christchurch, New Zealand. This paper presents a design philosophy for optimisation of resilience, which has been developed from first hand practical experience of assessment and design during the horizontal infrastructure rebuild. Determination of the appropriate level of seismic resilience to maximise asset value is a multi-discipline process. Assessment requires consideration of failure mechanisms and anticipated seismic performance, network criticality and probability of occurrence. Capital cost for resilience is balanced against how palatable the corresponding post disaster functionality and repair economics are to the Asset Owner. Maximum value is achieved through focusing on resilience during the planning and concept design phases. Early geotechnical engineering advice is necessary to identify geological hazards/risks and opportunities to limit effects. Project examples demonstrate implementation and benefits of incorporating an appropriate level of seismic resilience into design of horizontal infrastructure.

Introduction

The horizontal infrastructure of Christchurch City was severely damaged by the extensive liquefaction and strong ground motion from a series of significant earthquakes during the Canterbury Earthquake Sequence (CES) of 2010/2011. The Stronger Christchurch Infrastructure Rebuild Team (SCIRT) was established in response to the extensive damage sustained during the 22 February 2011 earthquake. This alliance comprises the New Zealand Government (CERA and NZTA), Christchurch City Council (CCC), five civil contractors, with support from an integrated design office of engineers from 14 local engineering consultants. SCIRT was tasked with performing assessment, design, and delivery of the $2.5b infrastructure rebuild. Horizontal infrastructure repaired included; wastewater, stormwater, water supply, roads and associated structures. Lessons learned from observation and back analysis of seismic performance have been an indispensable resource to understand typical failure mechanisms and assist with development of resilient infrastructure designs. Designers focused on balancing seismic resilience for assets against cost through providing an appropriate level of anticipated seismic performance and post disaster functionality. This focus assisted with maximising the overall value of the rebuild. This paper provides a philosophy for designing to improve earthquake resilience from the perspective of the geotechnical engineer and engineering geologist.

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Definition of Earthquake Resilience

SCIRT considered resilience as being an improvement in the seismic performance of Christchurch's infrastructure and post disaster network functionality, to improve the speed and ease of the emergency response and recovery following future earthquakes. The definition of earthquake resilience varies between people and organisations. Prior to commencing design it is important that the design team discusses, understands and agrees on what resilience means for the Asset Owner. This serves as the foundation for the design philosophy.

Designing for Resilience

Assessment of resilience should be undertaken during all stages of design, commencing at the feasibility or concept stage. The greatest level of resilience can be achieved for the lowest cost, or no cost, during the early planning and design phases of a project where the overall strategy is developed. The ability to improve resilience for an asset or sector of a network diminishes rapidly as the design process progresses, and the costs to implement feasible improvements in resilience increase exponentially. Figure 1 provides a schematic representation of the improvement in generalised feasible level of resilience versus the associated costs.

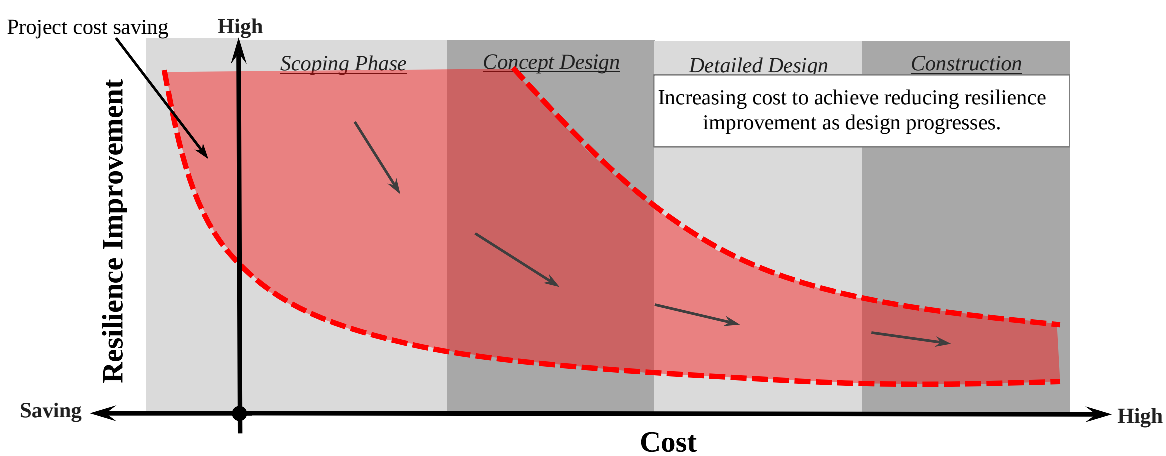

Figure 1. Schematic generalisation of feasible resilience improvement versus cost to implement

SCIRT identified during the Christchurch rebuild the importance of a complete multi-disciplinary approach to design, with a focus on seeking technical and planning advice from the Asset Owner, field operations teams, designers and construction team. The geotechnical engineer was a critical member of the SCIRT design team, actively involved in all design phases. This commenced with strategy and planning of project scope, through to identifying key geotechnical hazards and performance risks which were continually reassessed as the design evolved. The knowledge civil designers gained from this early interaction aided optimisation of infrastructure design and spatial layout, further improving resilience. Collaboration and knowledge sharing between academia and engineering practitioners improved the wider understanding of seismic performance and practical methods to improve resilience. Figure 2 provides a simplified flow diagram of the design process, describing the key activities and actions to be performed by team members while considering and optimising resilience for the project.

Scoping Phase

Phase 1

- ➢ *Understand importance of asset, and how it interacts with other elements within the wider network.*
- ➢ *Determine an appropriate level of design resilience.*

- Understand project scope and Asset Owner objectives.
- Identify legal requirements and obligations.
- Determine minimum seismic performance and post disaster functionality required by Asset Owner.
- Understand acceptable levels of damage for post-disaster repair.
- Determine importance of the infrastructure element within wider network to prioritise resilience.
- Identify and consider key areas of asset vulnerability.

Concept Design Phase

Phase 2

- ➢ *Strategically plan asset design considering the wider network, to optimise resilience.*
- ➢ *Achieve significant improvements in resilience at low to moderate cost.*

- Select appropriate design standards, guidelines, and loading scenarios and earthquake characteristics for design.
- Assess site conditions; geological deposition processes, ground conditions, topography.
- Assess geotechnical risks and hazards; e.g. liquefaction, lateral spread, seismic settlement, slope instability and rockfall.
- Review strategies to adjust spatial alignment or location of project to avoid major project risks.
- Understand interdependencies between the project assets and the wider network, to refine asset importance.
- Consider a range of engineering solutions including completely alternative strategies – network wide assessment.
- Assess anticipated seismic performance; identify vulnerabilities and key areas of focus for resilient design.
- Optioneer solutions; overall resilience, post-disaster functionality and total life cycle costs to maximise value.
- Identify potential modification to design strategy that can provide significant resilience improvement at low cost.

Detailed Design Phase

Phase 3

- ➢ *Assess failure mechanisms, consequence and prioritisation for improving resilience and to optimise value.*
- ➢ *Achieve improvements in resilience at moderate to high cost*

- Develop design, focusing on resilience, functionality and interaction with adjacent infrastructure.
- Constantly innovate; review solutions and approaches by others, and consider alternative or new solutions.
- Implement a multi-disciplinary design approach, including Asset Owner, operators and key stakeholders.
- Seek detailed geotechnical engineering review; quantify risk and identify opportunities to limit adverse performance.
- Identify potential failure mechanisms and effect on functionality to develop a prioritisation for resilient design.
- Utilise prioritisation ranking to mitigate or improve performance, commencing with the greatest performance risks.
- Focus on low cost resilience improvements that provide a step change of performance with effective design detailing.
- Design to control severity and extent of earthquake damage, future proof to reduce cost and difficulty of repair.
- Constantly look for opportunities to adjust the Concept Design strategy if these become evident.
- Perform early multi-disciplinary design and contractor involvement (ECI) reviews to optimise resilience.
- Provide resilience compatibility for associated infrastructure, services and utilities, critical to maintain functionality.
- Review overall value provided by project, check appropriate considering design objectives and prioritisation ranking.
- Focus on safety in design considering constructability, future maintenance, repair and demotion.

Construction Phase

Phase 4

- ➢ Field verify design assumptions, and identify potential opportunities to improve resilience
- ➢ *Focus on construction quality and correct execution of design*

	• Perform best practice construction, ensure that design intent is achieved, and prevent degradation of the ground. • Monitor construction to field verify design assumptions.

Figure 2. Simplified strategy to optimise resilience though the design process

Within SCIRT, geotechnical engineers assisted civil designers in assessing and designing repairs for the “three waters” catchments. Early understanding of geotechnical hazards and relative severity at prospective pump station sites, critical pipeline routes and sub-catchments assisted with resilience optimisation of the network. The spatial layout was adjusted to avoid land of elevated geotechnical risk where technically and economically feasible. Technologies with higher intrinsic resilience such as pressure sewer and vacuum sewer wastewater systems were considered within areas of high geotechnical risk. Often significant step changes in resilience were achieved, and in some cases the early optimisation of the design strategy provided a net cost saving in addition to providing a network with lower vulnerability to earthquakes.

Determination of an appropriate level of resilience

Designing to prevent damage may not be technically feasible or necessary to achieve the objectives of the Asset Owner, and is typically a low value solution. The key to good design is to provide an appropriate level of resilience in the right locations. Determination of an appropriate level of resilience for an asset is generally through application of engineering judgment supported by technical analysis and review of case histories. Optimising resilience is a complex engineering problem which has many variables. Assessment considers influence of geotechnical hazards, consequences of anticipated performance, and probability of a significant earthquake. A multi-disciplinary approach is required for assessing and agreeing the level of resilience for asset design in order to provide a robust solution. The level of resilience adopted must be compatible with associated infrastructure and objectives of the Asset Owner.

Table 1. Key considerations when reviewing appropriate level of resilience

Items	Details for consideration
Requirements and responsibilities of the Asset Owner	• Legal obligations • Budget constraints • Asset Owner requirements of post disaster functionality and prioritisation
Influence of spatial location	• Significance of the asset within the wider network, and resulting consequences to dependent infrastructure
Earthquake hazard	• Earthquake severity and annual probability of exceedance
Failure mechanisms and consequence	• Geotechnical hazards at the site and influence on asset performance. • Identify likely modes of failure and severity/consequence within the wider network and within the specific asset • Prioritise hazards and failure mechanisms for resilience improvement
Engineering solutions to improve resilience	• Technical feasibility, reliability and complexity of resilient solutions, • Ability to exhibit improved resilience for multiple earthquakes
Value	• Estimate improvement in seismic performance and post disaster functionality and compare to requirements. • Identify critical drivers for resilience, being cost, seismic performance and/or post disaster functionality. • Demonstrate efficient use of capital considering the net present value of the asset for a range of synthetic earthquake scenarios.

The level of resilience appropriate for a particular asset in a specific network is directly proportional to the percentage of the total network that relies upon the asset maintaining functionality. This can be quantified through establishment of importance ratings which are directly proportional to the percentage of the total network which is dependent on each asset. In the case of a wastewater network the sewage treatment facility, terminal pump stations and major trunk sewers will generally require the highest level of resilience, while lower performance associated with discrete failures of less critical wastewater pipes servicing a block of houses is more palatable to the Asset Owner.

Resilience Prioritisation Method

Design for resilience should aim to control failure mechanisms and limit the extent and/or severity of damage as best practicable to satisfy minimum functional requirements and enable timely, cost-efficient, repair. A generic resilience prioritisation method was developed for the selection and incorporation of additional resilience measures into infrastructure design within SCIRT projects. The resilience prioritisation method is a structured process of assessment and design; it can be summarised into the following key design components:

1. Determine appropriate level of resilience to the overall asset, and for sub components.
2. Identify geotechnical hazards, infrastructure vulnerability and key failure mechanisms, considering influence on overall seismic performance and impact on post disaster functionality.
3. Develop engineering solutions to mitigate or limit extent and severity of earthquake

damage, commencing with reducing the highest priority risks and vulnerabilities.
4. Consider improvement in performance provided by each design solution and overall value provided. Initial design focuses on low cost / high value solutions.
5. Check that the completed design satisfies project objectives and Asset Owner resilience requirements.

Gibson, Green, Holmes and Newby (2013) discusses and applies the resilience prioritisation method in designing earthquake resilience into pump station foundations, and demonstrates its application for design of a terminal wastewater pump station.

Geotechnical Assessment

The geotechnical engineer is a critical member of the project team, responsible for assessing and communicating geotechnical hazards and associated failure mechanisms affecting the asset. The first stage of geotechnical assessment often commences with a high level desktop study; available geotechnical information is collated to develop understanding of ground conditions, geotechnical hazards and anticipated levels of seismic performance. Review of case histories of seismic performance is essential for understanding critical failure mechanisms and infrastructure vulnerabilities. The Canterbury Geotechnical Database which was established following the Canterbury earthquakes promoted collaborative exchange of factual geotechnical information to assist in such assessments.

Failure Mechanisms

Observations and experience from historic earthquakes provide an invaluable resource for the assessment and quantifying criticality of failure mechanisms. The extensive set of geotechnical information available gave SCIRT designers improved confidence in ground conditions, and informed detailed back analysis of infrastructure seismic performance during the CES, to inform and improve design for the rebuild. Figure 3 provides a visual schematic, summary of generic failure mechanisms, including the typical effects on horizontal infrastructure.

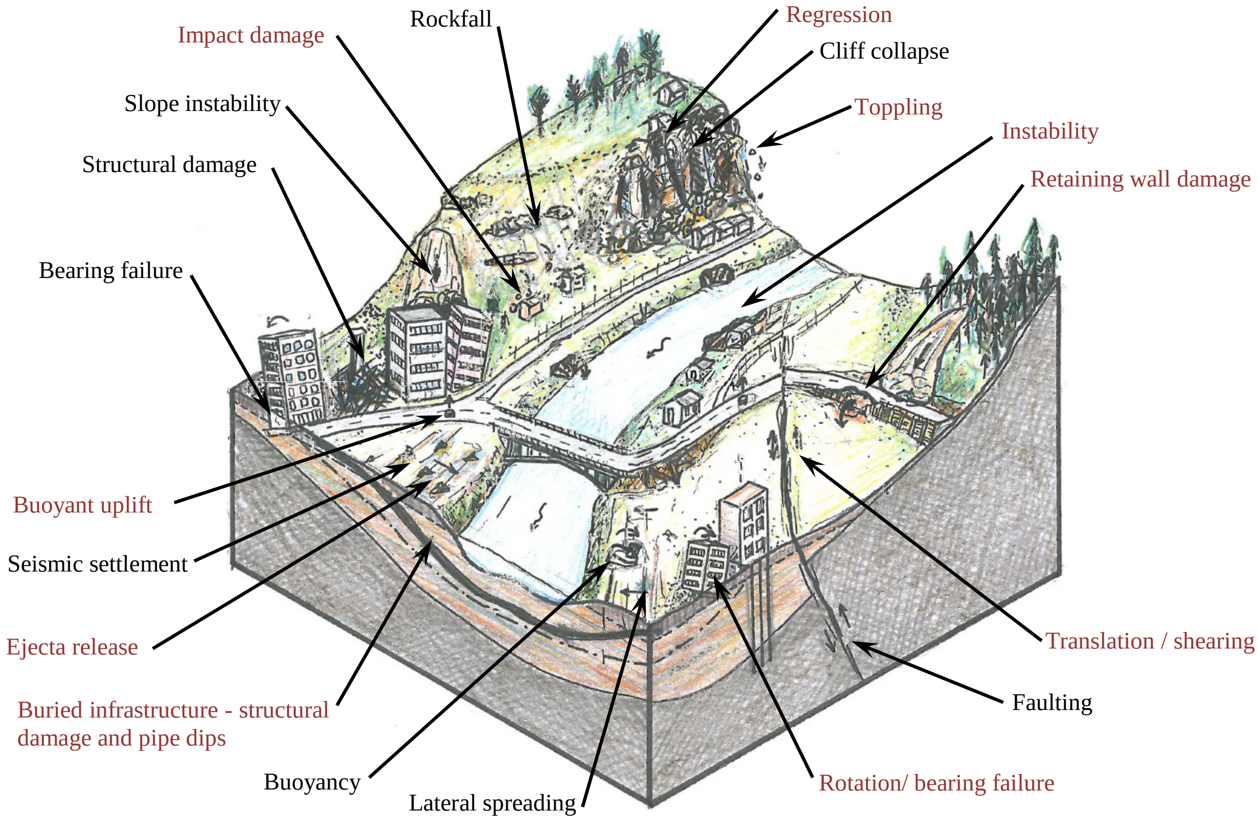

Figure 3. Schematic representation of typical geological and geotechnical hazards

Focus on design detailing

Observations during the CES identified that the design aspects that had the greatest vulnerability resulting in poor post disaster functionality were associated with design detailing and minor components rather than the overall design philosophy. Functionality of an asset is controlled by the weakest link and it is important that compatibility of levels of resilience between components of an asset are maintained. Cost savings by incorporation of lower levels of resilience for components is only feasible where their influence on functionality is limited. The SCIRT focus on resilient design was in the details, especially relating to mechanisms of failure. This was incorporated into SCIRT standard details and designer guidelines. Selected examples of simple low cost engineering solutions that can provide a step change in earthquake resilience, while optimising overall infrastructure value are provided in Table 3.

Table 3. SCIRT examples demonstrating a range of methods to improve infrastructure resilience

Asset Type	Brief summary of select SCIRT examples to improve resilience
Wastewater, Stormwater and Water supply networks	• SCIRT reviewed the performance of pre-earthquake CCC standard design details during the CES to improve and develop new details to improve future resilience. Standard design details must have an appropriate level of resilience suitable for the majority for the network. Vulnerabilities in standard details can have a cumulative impact over the wider network • Geotechnical hazards were considered when developing wider network strategy Routes were adjusted away from greatest geotechnical risks when feasible • Use of flexible and durable materials such as polyethylene • Steepen pipe grades and incorporate more lift stations or pump stations • Consideration of influence of lateral spread and channel heave at pressure main crossings beneath rivers, designing to limit influence of ground deformation • SCIRT adopted pressure sewer and vacuum sewer wastewater systems which exhibit improved resilience to differential settlement, and the shallow pipes improve the ease of repair compared to the existing deep gravity network
Below ground chambers and pump stations	• Ground improvement or piles to mitigate effects of liquefaction • Resilient foundations to mitigate buoyant uplift and differential seismic settlements though; well graded backfill, extended foundation slab, piles, adding mass, permeable backfills to relieve excess pore pressures or ground improvement • Over-steepening the gravity inlet to accommodate differential settlement of the catchment relative to pump station settlement • Provide flexible pipe and service connections to accommodate differential settlements and minor to moderate lateral stretch • Locate pump stations away from free faces • Uniformity in foundation level and limit eccentric loading • Structural and backfill design to accommodate anticipated soil loadings • Multiple smaller structures distributed in parallel throughout the catchment can reduce the consequence of failure • Use of horizontal pumps allowed design of robust but lightweight shallow structures designed to maintain functionality with moderate lateral spread and differential settlements. Resilience associated with low cost and ease of repair
Bridges	• Ground improvement at abutments to limit deformation • Design of robust piles to resist lateral spread, accepting damage to approaches
Seawalls and Retaining Walls	• Use of flexible riprap seawalls to accommodate moderate to severe lateral spread deformation while maintaining coastal protection and low repair costs • New Zealand Building Code requirements controlled retaining wall design

Design and loading standards, such as NZS 1170, generally focus on “protecting life” and limiting the extent and severity of the post-earthquake repair. Structures of high importance have an elevated design seismic loading, which typically results in a robust stiff structure attracting greater loading. The designer should ensure that adequate ductility and design detailing is provided to limit and control severe damage. Controlling the location and nature of failure through detailing incorporating ‘fuses’ (replaceable components designed to fail) can simplify repair, improving resilience. All designs should be kept simple, as complexity increases the potential for construction and design errors leading to unexpected performance or failure.

Value assessment

Asset value is optimised through prioritising and balancing project objectives, minimum requirements for earthquake resilience, and total life cycle cost. This assessment is performed during all phases of design, with increased focus during concept design. Total life cycle cost of various design solutions is assessed considering net present value of the cost for capital works, operation and maintenance, and potential earthquake repair over the asset life. Assessment of the cost of earthquake repair considers synthetic earthquake scenarios, and evaluating anticipated seismic performance and associated costs to repair damage. Within SCIRT this was performed by two methods; (1) selecting earthquake characteristics and nominating year of occurrence, (2) probabilistic assessment of earthquake occurrence and intensity. Earthquake characterisation and frequency of occurrence was informed by the earthquake hazard model for the location.

Conclusions

Observations and experience from the rebuild of earthquake-damaged horizontal infrastructure in Christchurch by SCIRT have formed the basis for this philosophy of earthquake resilient design. Optimisation of design resilience is achieved through a multi-disciplinary assessment considering the anticipated mechanisms of failure, infrastructure vulnerability, and wider network consequences. Satisfying Asset Owner objectives and requirements for post disaster functionality and acceptable levels of damage is of priority. The ability to improve asset resilience decreases as the design progresses though to construction; simultaneously the relative cost for resilience improvements increases. Maximum value is achieved though implementing a focus on resilience during the planning and concept design phases where there is focus is on strategy. Significant improvements in resilience can be achieved at low cost through a focus on optimising spatial layout to minimise the influence of geotechnical hazards, and design detailing to mitigate potential vulnerability and controlling failure. Theoretical future earthquake repair costs can be balanced against the capital cost for improvement in resilience. This can be achieved through calculating the net present value of the life cycle costs including synthetic earthquake scenarios, in order to maximise overall project value. Early input by geotechnical engineers is invaluable in identifying geotechnical hazards, prioritisation of failure mechanisms, soil structure interactions, probability of occurrence, and influence on overall asset performance.

Acknowledgments

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