Displaced But Not Moved: Performance-Based Foundation Design

L. Schmidt & I. Barbalich
Holmes NZ LP, Wellington, New Zealand

S. Moniz
Holmes NZ LP, Christchurch, New Zealand

ABSTRACT

Improved understanding of seismicity within New Zealand and globally has led to an increase in seismic hazard for many locations. High seismic acceleration demands (e.g. >1g) for buildings and infrastructure have led to challenges in foundation design and soil-structure interaction. As an alternative to traditional methods, we have utilised 1-Dimensional and 2-Dimensional Site Response Analyses (SRA) as key tools for designing efficient performance-based foundation systems under high seismic demands.

This paper provides an overview into 1D and 2D SRA methods for foundation design. Four case studies are presented where SRA has been utilised to add value to projects. Case Study 1 involves the design of a 300m bridge underlain by 40m of soft and liquefiable soils in which the use of SRA has resulted in a reduction in soil demands. This made the bridge design feasible without extensive ground improvement. Case Study 2 is an example where 1D SRA has been implemented to investigate a potential reduction in seismic acceleration demands for structural assessment of an existing building. Case Study 3 and Case Study 4 are examples where use of SRA has allowed for sliding shallow foundations to be implemented for the design of multiple structures, rather than resolving large lateral seismic demands through expensive piles.

This paper also outlines key assumptions regarding simplification of nonlinear soil strength and stiffness modelling for SRA.

Large scale friction interface testing for the design of cast in-situ shallow foundations on Wellington Greywacke bedrock is also discussed briefly for Case Study 4.

1 INTRODUCTION

In recent years, improved understanding of seismicity and adjustments of procedures in codes and guidelines has led to increased seismic accelerations (>0.6g) for the design of foundations in some cases. This is particularly relevant in high seismic regions like New Zealand, where accelerations previously being used for design are already significant. Many noteworthy projects in areas of high seismicity within New Zealand are facing design seismic accelerations of >1g. This has led to challenges in traditional foundation design and the application of soil-structure interaction concepts.

In particular, increased seismic accelerations for foundation design have led to challenges with respect to the resolution of lateral actions. We have often found that simple force-based designs cannot be resolved under high seismic demand. Additionally, commonly used simplified design concepts such as Mononobe-Okabe and some Newmark sliding methods are no longer applicable when large seismic accelerations are being considered. At high seismic accelerations, achieving equilibrium under sliding with a strength reduction factor of 0.8 becomes impossible for shallow foundations.

Resolving lateral components of these large seismic accelerations with piles or anchors is often not cost effective. Additionally, pile and anchor design can add complexity and reduce robustness of an otherwise simple and resilient shallow foundation design. In the past the focus of performance-based foundation design has been on settlement and laterally loaded piles. It is now apparent that an understanding of lateral performance of shallow foundations is also important.

2 APPROACH

The alternative approaches we have taken to traditional foundation design have required 1-Dimensional and 2-Dimensional Geotechnical Site Response Analyses (SRA) as a key tool for designing efficient performance-based foundation systems. This paper provides a brief overview of the processes involved in SRA.

1D and 2D SRA were used to inform alternative approaches to the design of structures with piled foundations as well as for existing structures. Section 3 provides details on Case Studies 1 and 2 where the authors have used SRA to add value to the projects involving piled foundations and existing structures.

SRA has also been used to inform alternative approaches for the design of shallow foundations. We have worked on multiple projects where shallow foundations have been designed to slide along the ground under seismic loading. Examples of these projects are presented for Case Study 3 and Case Study 4. An overview of key assumptions around friction requirements for sliding shallow foundation design is also presented in Section 4 for Case Study 4.

The key metric of interest we have focused on in all SRA case studies has been Peak Ground Acceleration (PGA). This is due to relevance for geotechnical design in New Zealand codes. However, we have also considered other metrics in our analyses, including but not limited to velocity, displacement, arias intensity, duration, and pseudo-spectral acceleration.

To evaluate whether the foundation related displacement demands that a structure experiences during a design earthquake are acceptable, a good understanding of the dynamic soil and soil/structure interface behaviour is important. With the large seismic acceleration demands mentioned, it has become evident that the fusion of geotechnical and structural engineering is more important than ever. However, fully integrated inter-discipline modelling has not been undertaken for the case studies mentioned in Section 3. This is due to difficulties combining geotechnical and structural design to code compliance in a single analysis, as well as due to cost and complexity considerations.

Generally, 1D SRA has been used to estimate uncoupled ground displacements and stress states, whereas 2D SRA has been used to estimate both uncoupled and coupled behaviour. In uncoupled analyses, the computation of the dynamic response of the ground and the plastic displacement of the structure are performed independently. However, in coupled analyses, the dynamic response of the ground and permanent displacement of the structure are modelled together, and the effect of plastic displacement of the structure on the ground response is considered (Jibson, 2011).

Earthquake ground motion record selection, scaling, and deconvolution are required for both 1D and 2D SRA. However, these topics are outside the scope of this paper. For more detail on these processes, refer to Kramer (1996) and Baker, Bradley and Stafford (2021).

3 SITE RESPONSE ANALYSES

3.1 1-Dimensional Site Response Analyses

3.1.1 1D SRA Overview

1-Dimensional Site Response Analysis (1D SRA) involves looking at behaviour of a soil column representative of the ground conditions at the site. We have used 1D SRA to assess the effects of material engineering behaviour on the response of ground motions as they are transmitted through the soil column from bedrock level to ground surface. We have primarily assessed the effect of soil column transmission on the ground motion intensity measures acceleration and response spectra. Other ground motion intensity measures including but not limited to velocity, displacement, arias intensity, duration have been considered in the authors' SRA methods.

Response spectra are developed by applying a ground motion acceleration time series to the base of a single-degree-of-freedom system, measuring the resulting displacement, and using this to inform the pseudo-spectral acceleration, SA(T). Therefore, response spectra represent the peak response of simplified structures or systems. Readers should note that the use of response spectra as a variable for indicating ground motion behaviour may not always be appropriate for representation of complex, multi-layered soil systems.

We have primarily used the program DEEPSOIL V7 for 1D SRA. Analysis methods in DEEPSOIL may be linear, nonlinear or equivalent linear. For most of our analyses nonlinear methods have been used to fully define large-strain behaviour of materials. Relationships used by the authors to represent nonlinear material behaviour under large strain in 1D SRA is discussed in more detail in Section 3.3. 1D SRA was a key analysis method for two projects that we have undertaken.

3.1.2 1D SRA in Case Study 1

In the design of a 300m road bridge (Case Study 1) underlain by 40m of soft and liquefiable soils, 1D SRA was used to investigate potential damping of earthquake ground motions from bedrock to ground surface, as well as to investigate the potential for liquefaction triggering in a layer of interest. It was found that a high reduction in strength and stiffness of the materials due to the extremely soft and liquefiable materials led to a reduction in the PGAs from bedrock level to the ground surface. This is shown in Figure 1, in which a variety of ground motion record PGAs have been plotted versus depth

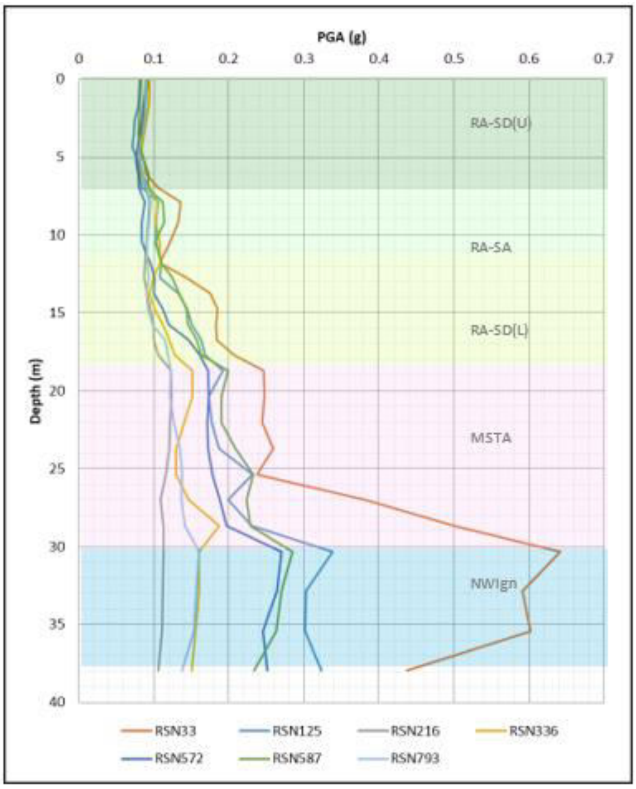

Figure 1. 1D SRA Case Study 1. Peak Ground Acceleration versus depth below ground level

as each ground motion is propagated up through the ground profile from bedrock (~38mbgl) to ground surface. This trend of acceleration de-amplification is in accordance with accelerations recorded on soft soil sites versus rock sites.

In Case Study 1, simplified liquefaction triggering methods suggested liquefaction potential in multiple layers at the site. One of these layers with liquefaction potential, marked up in pink in Figure 1, started at a depth of almost 20m below ground level. 1D SRA was utilised to further investigate liquefaction potential of this layer. The SRA helped to inform a reduction in the liquefaction risk for a section of this deep layer. This reduction in liquefaction risk led to decreased soil demands on the bridge piles.

The concept design for this bridge involved extensive ground improvement due to an expectation of high lateral soil demands on the piles using simplified calculation methods. The reduction in lateral soil demands on the bridge piles due to decreased liquefaction risk allowed for the piles to be designed without ground improvement.

The use of 2D SRA for Case Study 1 is discussed in Section 3.2.2.

3.1.3 1D SRA in Case Study 2

In the assessment of a multi-storey building in Christchurch (Case Study 2), 1D SRA was used to investigate a potential reduction in the surface accelerations used for structural assessment. This potential reduction was due to liquefaction and cyclic softening in the ground profile (classified as Site Class D). For this case study, the structural engineers had initially been using surface accelerations provided in NZS1170.5 for the structural assessment of the building. We hypothesised that consideration of liquefaction and cyclic softening in the ground profile may lead to a reduction in surface accelerations compared to codified accelerations. Following the Canterbury Earthquake Series, indications of liquefaction occurrence at the Case Study 2 site such as sand boils were apparent. To better reflect the design level earthquake shaking for the building, we undertook 1D SRA. The predicted trend was similar to that indicated for Case Study 1 in Figure 1 – a reduction in PGAs from bedrock level to ground surface due to the presence of soft and liquefiable soils.

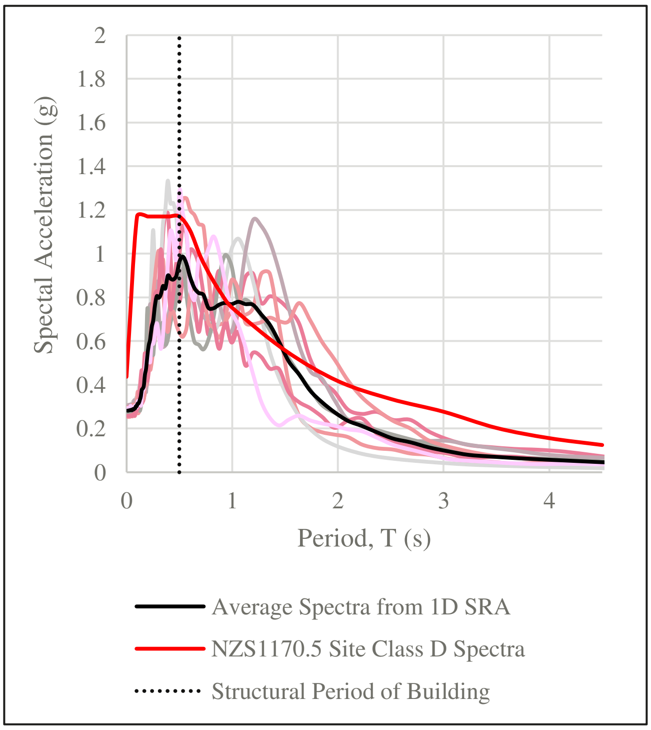

Figure 2. Response spectra from 1D SRA compared to NZS1170.5 Site Class D Spectra

The ground profile at the site of Case Study 2 consists of interbedded silts, sands and gravels to 30m, underlain by Riccarton gravels to bedrock (assumed 400mbgl). Limited information for the site was available at depths greater than 30mbgl. Multichannel Analysis of Surface Waves (MASW) data available for the site indicated that the shear wave velocity of Riccarton Gravels was ≥ 500m/s. For the purposes of these analyses, the Riccarton gravels level was taken as a proxy for Site Class B bedrock level.

A 1D soil column was set up in DEEPSOIL. We selected and scaled a group of records to the spectra provided in NZS1170.5 for Site Class A/B (with Vs30 of selected records ranging between 500 – 700m/s). We assumed that the spectra for Site Class A/B was similar to that at bedrock level and Riccarton gravels level for the site of Case Study 2. The ground motion records were input into the DEEPSOIL model at bedrock level. As the ground motions propagated through the 1D soil column, behaviour of the materials and indicators of the ground motion were observed. The resulting surface response spectra was compared to an NZS1170.5 spectra for Site Class D. A slight reduction in the surface accelerations was observed at the building period due to the presence of soft and liquefiable soils, as shown in Figure 2.

The reduction in surface accelerations indicated by the 1D SRA resulted in reduced seismic acceleration demands being used for the structural assessment of the existing building. This effect on structural response led to savings in the suggested structural remediations for this building, therefore benefitting the project.

An additional verification process was undertaken for the 1D soil column specifically using ground motion records from the Canterbury Earthquake Series. Site Class A/B ground motions recorded at Lyttleton Port (LPCC) were used to verify the 1D soil column. The resulting surface response spectra was extracted and compared to observed ground motion recordings at locations close to the site in Christchurch City Centre for the same event in the Canterbury Earthquake Sequence. These results are presented in Figure 3.

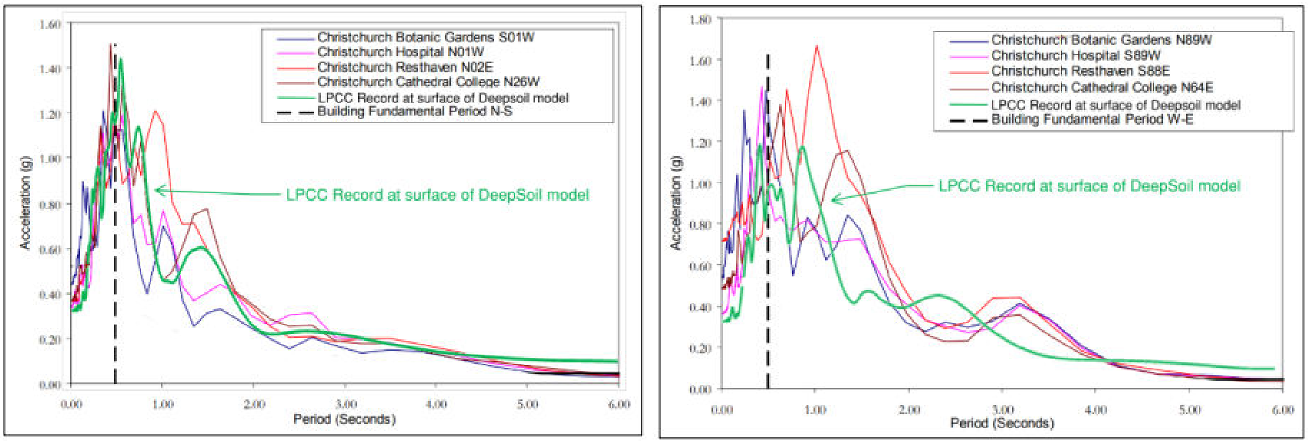

Figure 3. 1D SRA Case Study 2. LPCC record response spectra at surface of 1D soil column overlain with recorded ground motion spectra at nearby sites. A) North-South direction, B) East-West direction

In Figure 3 the response spectra obtained from the 1D SRA verification is indicated in green, with response spectra from four nearby recorded motions also presented. Figure 3 indicates that the results of the 1D SRA are well aligned with the recordings at the four ground motion stations close to the site of Case Study 2. The 1D SRA appears to capture the main response features well, including similar levels of acceleration for the building fundamental period, a secondary peak in the N-S direction between 1-2s, and the secondary peaks in the E-W direction between 3-4s. Because the results of the 1D SRA exhibited similar seismic featured to those recorded at nearby sites, this provides additional confidence that the 1D soil column is representative of actual ground response and can be used as a reasonable proxy to produce revised surface spectra for the site.

3.2 2-Dimensional Site Response Analyses

3.2.1 2D SRA Overview

The finite element program RS2 by Rocscience has been used to undertake 2-Dimensional Site Response Analyses (2D SRA). We have used the program to set up ground models of sites to expected bedrock depth. Ground motion acceleration time histories were then applied at the base of the model (bedrock level). In order to examine the results of the 2D analyses, stresses and deformations throughout the ground profile at various times throughout the ground motion application were examined.

Simplified elastic-plastic methods have generally been used to represent nonlinear strength and stiffness of materials in 2D SRA. This is discussed in more detail in Section 3.3. Behaviour of materials prone to liquefaction of cyclic softening has also been considered by the authors in 2D SRA and is discussed in Section 3.3.

3.2.2 2D SRA in Case Study 1

2D SRA has been used by the authors to assess the displacement of a 300m road bridge underlain by 40m of soft and liquefiable soils. This project is the same case study as described in Section 3.1.2. 2D SRA was also undertaken for this project to assess displacement demands on the proposed bridge piles in a design seismic event. These analyses included considerations of cyclic softening and liquefaction.

Figure 5 shows the 2D setup of these analyses in RS2. The project consisted of geogrid reinforced embankments sitting on top of layers of soft and liquefiable ground to bedrock ~40m below the ground surface. Vertical dashed lines indicate proposed bridge pile locations.

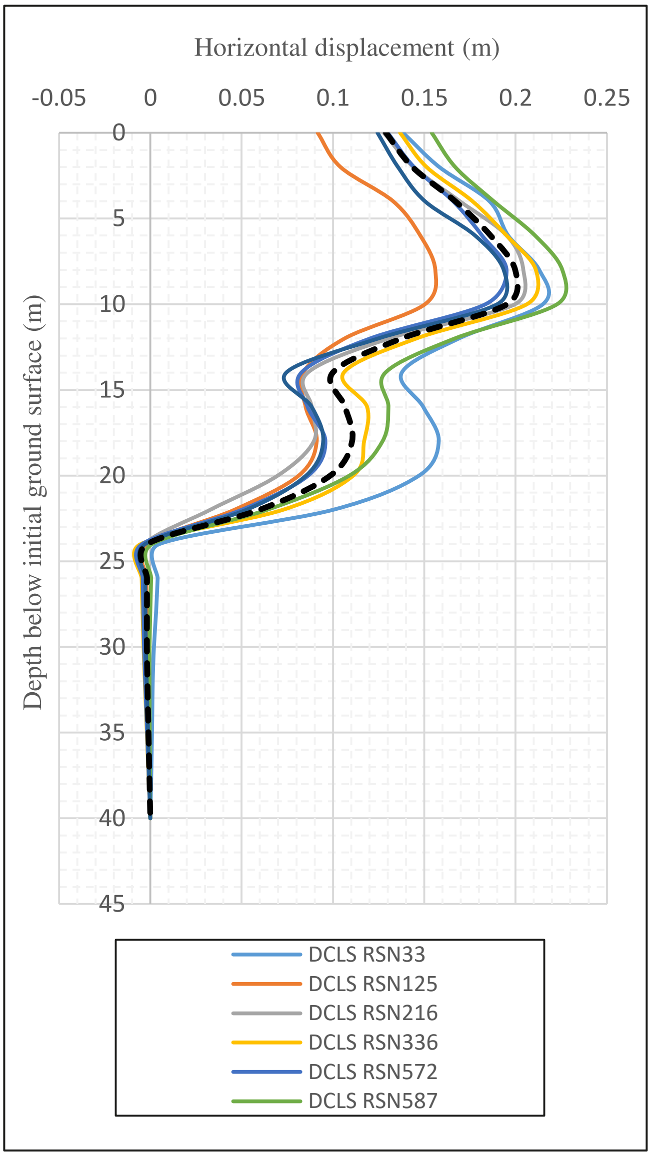

Figure 4. Example soil displacement profile at pile location obtained from 2D SRA. Case Study 1.

Dynamic analyses were undertaken for this 2D model, and soil displacement profiles under design seismic loads at the pile locations were provided to the structural engineers for pile design. As mentioned in Section 3.1.2, before 2D SRA was utilised the concept design for this bridge involved extensive ground improvement due to an expectation of high lateral soil demands on the piles using simplified calculation methods. The use of soil displacement profiles obtained from the 2D SRA allowed the lateral soil demands on the piles to be reduced, thus making the design feasible without extensive ground improvement. Figure 4 shows an example of soil displacement profiles provided to the structural engineers for one pile location.

We are aware that cyclic softening and liquefaction triggering is unlikely to occur in a consistent manner across a site. For all SRA where cyclic softening and/or liquefaction are factors, we recommend undertaking sensitivity checks on all relevant modelling options to ensure a viable range of results is obtained for the ground conditions at the site. In these case studies, this has included performing full analyses considering no liquefaction and no cyclic softening, as well as analyses considering the full extent of liquefaction and cyclic softening. We believe that performing analyses that capture both “ends of the spectrum” in regard to liquefaction and cyclic softening will ensure the designer is conservatively considering all potential site behaviour.

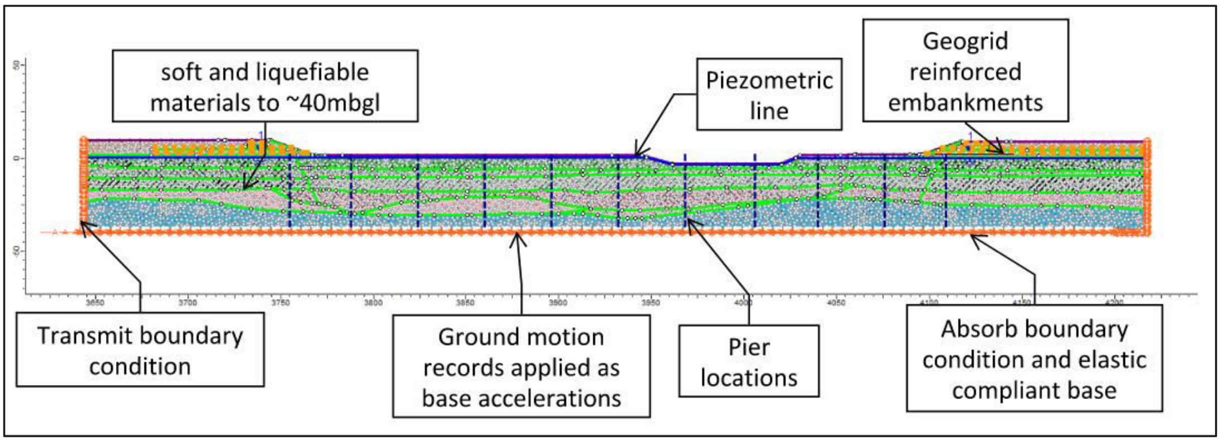

Figure 5. 2D SRA Setup for Case Study 1.

3.2.3 2D SRA in Case Study 3

2D SRA has also been used by the authors to assess a potential sliding failure mechanism forming under shallow founded buildings. One of these projects involving multiple shallow-founded buildings with a potential sliding failure mechanism is Case Study 3.

The ground profile for this project consists of interbedded colluvium and alluvium approximately 70m down to bedrock level. The 2D SRA was used to assess stresses and displacements throughout the ground profile under design seismic loading. The analyses were also used to investigate the potential magnitude of shallow foundation sliding that could occur under the design seismic loading.

We have used simplified methods for representing structural elements of the building in the 2D SRA. Generally, the buildings have been represented as blocks of material below the ground where building mass is reflected by material density. We have tried to keep the focus on the foundation / ground interface, and on replication of realistic seismic actions propagating to the foundation system.

Building material parameters for this project were developed in conjunction with structural engineers. An example of a simplified building modelled in the 2D SRA is presented in Figure 6. Plastic slip joints have been modelled representing a frictional interface between structural and geotechnical elements to allow permanent deformation of the building to occur in the 2D model. Frictional interface values obtained from testing are discussed in Section 4. Hence, the 2D SRA predicts permanent slipping displacement of the structure under seismic loading.

We have also attempted to account for the inertia load of overlying building storeys under design seismic loading by applying additional mass and force to the modelled building and adjusting the underlying joint friction boundary accordingly. We are aware that this method does not fully capture out-of-phase shaking actions between the ground and the building, and in this case study the full structural inertia has been applied in the same direction as ground shaking. However, for displacement performance purposes it has been assumed that in-phase performance (which is captured by this simplified modelling method) would present conservative results in terms of shallow foundation sliding.

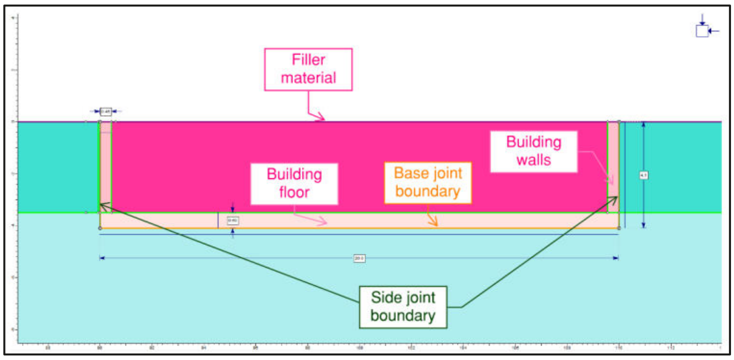

Figure 6. Example of simplified building modelled in Case Study 3.

The use of 2D SRA for predicting permanent slipping displacement of the structures under design seismic loading for Case Study 3 allowed for the design of shallow foundation systems to be pursued for the buildings rather than piled foundation systems. This led to significant cost savings for the project.

3.2.4 2D SRA in Case Study 4

2D SRA was also used by the authors to assess sliding failure forming underneath a shallow founded water tank. The ground profile for the site of Case Study 4 consists of Wellington Greywacke bedrock.

The concept design for the water tank, measuring 12m in height and 70m in diameter, consisted of large shear keys to prevent sliding of the shallow founded structure. 2D SRA was used to assess the potential displacements associated with a design seismic event if the shear keys were removed. The 2D SRA approach described for Case Study 3 was also used for Case Study 4. It was found that the displacement of the shallow founded tank would be tolerable in a design seismic event. This allowed for the shear keys to be removed from the design, leading to significant cost savings for the project.

During the construction of this shallow founded tank, large-scale testing was undertaken to determine the friction angle of the sliding interface between the underside of the tank and the top of the in-situ Greywacke bedrock. This testing is described in more detail in Section 4.

3.3 Nonlinear Material Properties

3.3.1 Overview

When undertaking SRA, it is often necessary to represent material strength and stiffness nonlinearly in order to capture the likely behaviour of geological materials under seismic conditions. Additionally, in the case studies discussed, the ground profiles have contained materials prone to liquefaction or cyclic softening.

3.3.2 Nonlinear Stiffness

Fully nonlinear stiffness relationships are available in both the 1D and 2D SRA methods discussed. For 1D SRA, DEEPSOIL offers a variety of relationships for modelling nonlinear stiffness, damping and shear strength. The program includes pre-defined relationships for sands and clays, as well as a user-defined option. We have commonly used the Darendeli (2001) reference curve for 1D SRA.

A variety of options to stiffness are available on RS2 for 2D SRA. The program contains several relationships for nonlinear isotropic stiffness. One of these nonlinear isotropic stiffness relationships is presented in Equation 1.

$$G = G_{max}\left(1 + \alpha\frac{\gamma}{\gamma_y}\right)^r \tag{1}$$

where G = shear modulus; G_{max} = maximum shear modulus; γ = deviatoric strain, and α, γ_y and r are material parameters. To simulate degradation, r should be less than zero.

Figure 7 shows an example of a nonlinear strain relationship using Equations 1 and 2 which has been fitted to the Seed & Idriss (1970) nonlinear stiffness degradation curves. In this example, G_{max} is known and α, γ_y and r have been varied to allow a fit within the bounds imposed by the Seed & Idriss (1970) curves.

$$E = 2G(1 + v) \tag{2}$$

where E = Young's modulus; v = Poisson's ratio

This plot in Figure 7 shows the small strain E value. This value is calculated through small strain measurement techniques such as shear wave velocity measurements. The large strain E value has also been plotted. For this material, the large strain E was estimated through large strain measurement techniques such as penetration and dilatometer tests. The large strain E is similar to E at ~1% shear strain from Equations 1 and 2 and from Seed & Idriss (1970). If large strain E values are not available for the material of interest, the relationships in Figure 7 indicate that the value at 1% shear strain is approximately 5% of small strain E. Hence, a simplified approximation is expressed in Equation 3.

$$E_{large\ strain} = 0.05E_{small\ strain} \quad (3)$$

For the purposes of simplified analyses, we have expressed this relationship using $E_{peak} = E_{\text{small strain}}$ and $E_{residual} = E_{large\ strain}$, and therefore have been able to model the nonlinear stiffness of materials in the 2D SRA using a simple elastic-plastic relationship.

We undertook sensitivity studies comparing the effects of modelling a fully nonlinear isotropic relationship (such as that plotted in Figure 7) to a simplified elastic-plastic relationship. The results in our sensitivity studies indicated negligible difference in stress and displacement of the 2D SRA. We consider that this simplification is relevant for seismic loads that are likely to produce shear strains in the order of 1%. When undertaking 2D SRA in RS2, the user can check the strain level of each geological material to ensure it is within the appropriate range for a simplified stiffness model. The user can also check element failure in RS2 to determine whether residual stiffness is being utilised for a model element.

When modelling liquefied materials, Poulos (2012) has been used to estimate liquefied material stiffness.

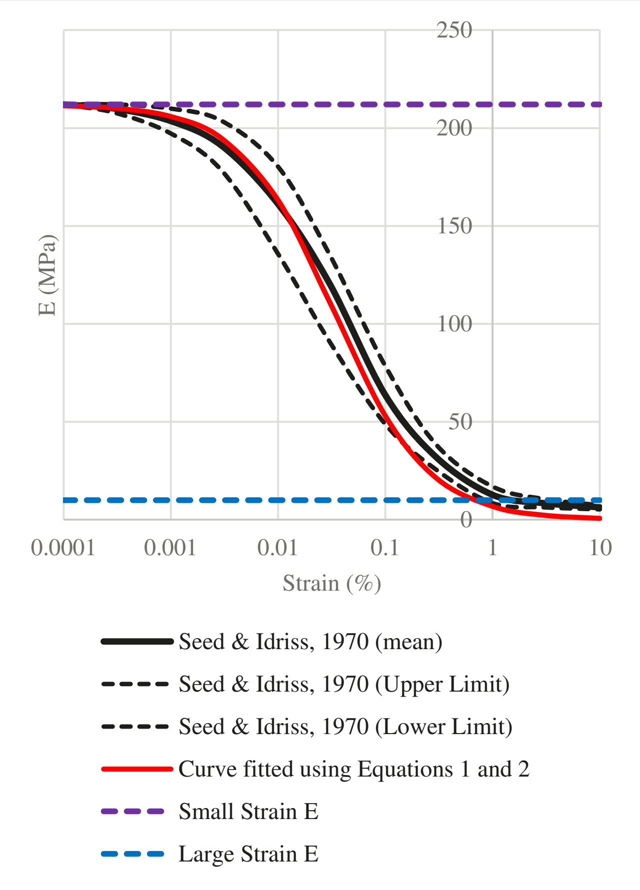

Figure 7. Nonlinear stiffness degradation with strain

3.3.3 Nonlinear Strength

Various models are available on RS2 for modelling strength of geological materials. In the case studies mentioned we used the Vertical Stress Ratio model to represent liquefied material strength and Mohr-Coulomb and Hoek Brown models for representing non-liquefied material strength. We have modelled material strength using a simplified elastic-plastic model and assigning peak and residual strength properties.

The case studies mentioned have included materials prone to liquefaction and cyclic softening. We encountered difficulty when modelling materials that were expected to liquefy or soften part-way through dynamic analyses. Therefore, we undertook analyses with liquefied or softened parameters applied throughout the entirety of dynamic analyses. When taking this approach, a sensitivity study should be performed with non-liquefied and non-softened material parameters in order to capture the appropriate amount of conservatism in the SRA.

4 SHALLOW FOUNDATION FRICTION INTERFACE

A key assumption for the design of sliding shallow foundations, such as those mentioned in Case Study 3 and Case Study 4, is the friction interface between the structure foundations and the ground. McManus and Burdon (2001) investigated foundation shear capacity and friction interface values with regards to low normal stress.

In Case Study 4 large scale testing was undertaken to estimate friction interface values on the underside of cast in-situ shallow foundations on Wellington Greywacke bedrock. This testing has also considered friction interface values when HDPE membranes are lain underneath the cast in-situ foundations. This testing was carried out for a range of higher normal stress values compared to those presented in McManus and Burdon (2001). Further details of this testing will be covered in a different paper. However, the test setup and a summary of the testing results are presented in Figures 8 - 10.

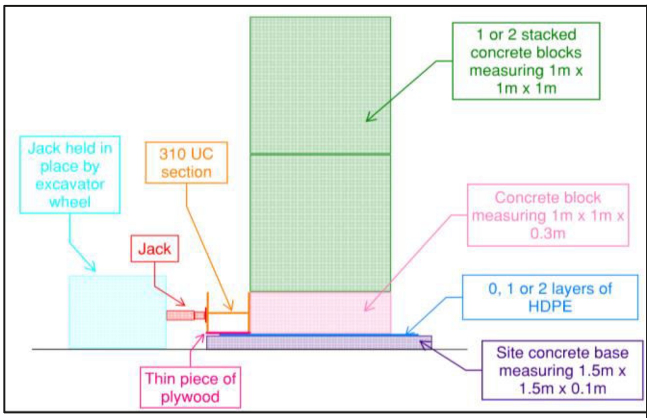

Figure 10. Case Study 4. Friction testing test setup

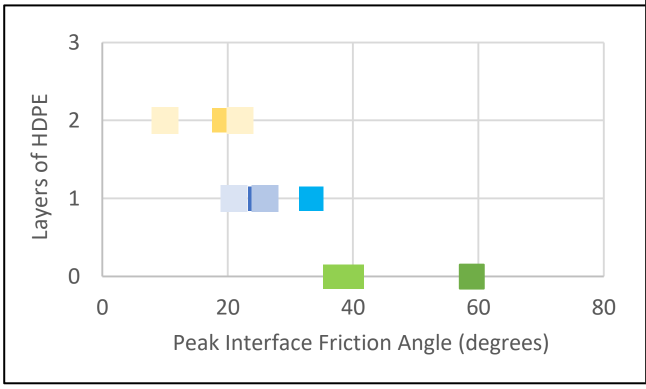

Figure 9. Friction Testing Results

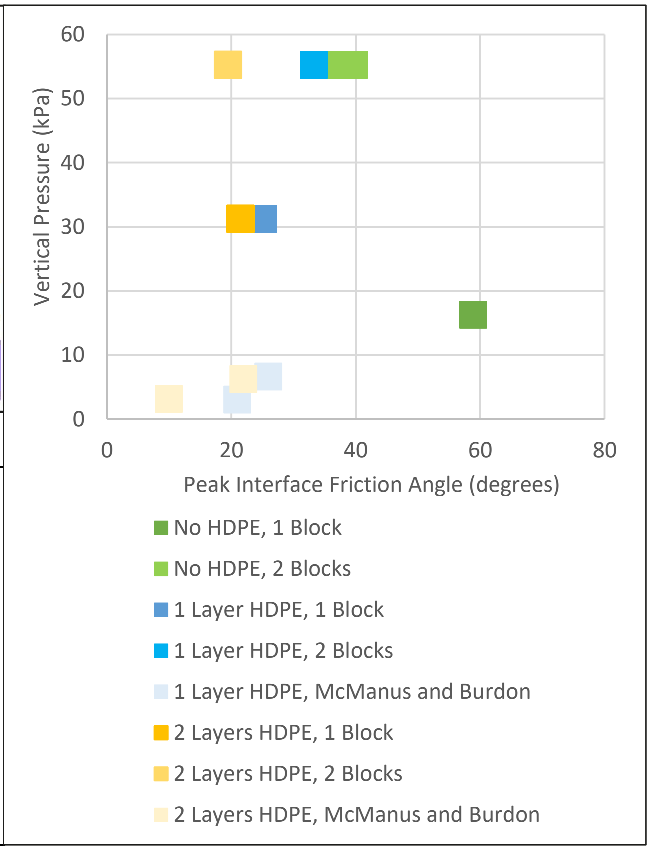

Figure 8. Friction Testing Results

5 DISCUSSION AND CONCLUSION

The case studies and methods presented in Section 3 show how site response analysis can be utilised in smart performance-based design. This can help the designer overcome design challenges without significantly increasing construction costs. In many cases, this also leads to increased resilience and a reduction in the conservatism that often comes with simplified foundation design methods. The 1D and 2D SRA undertaken for Case Study 1 allowed for a reduction in soil demands for pile design. Hence, the design of this 300m bridge was feasible without extensive ground improvement. This has led to significant construction savings for the project.

The 1D SRA undertaken for Case Study 2 allowed for a reduction in the seismic acceleration demands for structural assessment of the existing building. This effect on structural response led to savings in the suggested structural remediations for this building.

The 2D SRA undertaken for Case Study 3 and Case Study 4 allowed for design of shallow foundations to be pursued for multiple buildings and a large water tank. The cost savings associated with founding the buildings on shallow foundations rather than piles for Case Study 3 were significant. The cost savings associated with removing shear keys from the design in Case Study 4 were also significant.

Learnings from Case Study 3, Case Study 4, and other similar projects shows that a good understanding of the actual base friction coefficient for shallow foundation design is very important. We have done some work to investigate friction relationships in addition to the work carried out by McManus and Burdon (2001). This is briefly discussed for Case Study 4 in Section 4. It would be beneficial for our industry to continue to investigate and publish such information where the opportunity arises.

We recommend that the use of SRA for sites prone to high seismic accelerations should be carefully assessed on a case-by-case basis. The case studies discussed in Section 3 are examples of projects where SRA has added value to the project. SRA will not always be appropriate for design or remediation of structures.

Our next steps in the use of SRA for design are:

- Continue to investigate the sensitivity of SRA to geotechnical input parameters (particularly with respect to nonlinear strength and stiffness properties).
- Improve understanding of base friction and shear stiffness underneath shallow foundations cast in-situ.
- Investigate the use of simplified analysis methods (i.e. use of a modified Newmark sliding block approach) for verification of results obtained from SRA.
- Improve our understanding of soil damping under large seismic loads.
- Continue to utilise the beneficial effects of SRA to refine seismic actions for design of new structures or remediation of existing structures.

6 ACKNOWLEDGEMENTS

We would like to extend a special thanks to Gopal Adhikari for his significant contribution in developing the SRA methods discussed.

Thank you to the team at Holmes NZ LP for their contribution to the case studies discussed in this paper. We would also like to acknowledge HEB Construction for their contribution to the testing discussed for Case Study 4.

7 REFERENCES

American Society of Civil Engineers (2014). *Seismic Design of Piers and Wharves.* ASCE 61-14. American Society of Civil Engineers, Reston, Virginia, 75pp. Available at www.asce.org/pubs

American Society of Civil Engineers (2017). *Seismic Evaluation and Retrofit of Existing Buildings.* ASCE 41-17. American Society of Civil Engineers, Reston, Virginia, 576pp. Available at www.asce.org/pubs

American Society of Civil Engineers (2022). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures.* ASCE 7-22. American Society of Civil Engineers, Reston, Virginia. Available at www.asce.org/pubs

Baker, J.W., Bradley, B.A., Stafford, P.J (2021). *Seismic Hazard and Risk Analysis*. ISBN 978-1-108-42505-6, Cambridge University Press, Cambridge, 582pp.

Boulanger and Idriss (2014). *2nd Ishihara Lecture: SPT- and CPT-based relationships for the residual shear strength of liquefied soils.* Journal of Soil Dynamics and Earthquake Engineering 68 (2015) 57-68.

Hashash, Y.M.A., Musgrove, M.I., Harmon, J.A., Ilhan, O., Xing, G., Numanoglu, O., Groholski, D.R., Phillips, C.a., and Park, D. (2020) "DEEPSOIL 7.0, User Manual". Urbana, IL, Board of Trustees of University of Illinois at Urbana-Champaign.

Jibson, R.W., 2011, *Methods for assessing the stability of slopes during earthquakes—A retrospective*: Engineering Geology, v. 122, p. 43-50.

Kayen, Thompson, Moss and Seed (2013) *Shear-wave velocity-based probabilistic and deterministic assessment of seismic soil liquefaction potential.* Journal of Geotechnical and Geoenvironmental Engineering 139(3):407-419

Kramer, S. L., (1996). *Geotechnical Earthquake Engineering*. ISBN 8131707180, 9788131707180. Prentice Hall, 653pp.

McManus, K.J., and Burdon, N.R.R. (2001). *Lateral Resistance of Shallow Foundations.* Paper No. 6.03.01, NZSEE 2001 Conference.

Poulos, H.G., (2013). Practical approaches to seismic design of deep foundations. *Proc. 19th NZGS Geotechnical Symposium.* 2013, Queenstown. Available at https://www.nzgs.org/libraries/practical-approaches-to-seismic-design-of-deep-foundations/

Rocscience (2021). *RS2 Dynamic Theory Manual.* Rocscience Inc. Available at https://www.rocscience.com/help/rs2/verification-theory/theory-manuals/dynamic-analysis

Standards New Zealand (2004). *NZS170.5: Structural Design Actions. Part 5: Earthquake actions – New Zealand*. Standards New Zealand, Wellington, 76pp. Available at https://www.standards.govt.nz/sponsored-standards/building-standards/NZS1170-5

Seed and Idriss (1970) *Soil Moduli and Damping Factors for Dynamic Response Analyses*. Report EERC 70-10, Earthquake Engineering Research Centre, University of California, Berkeley.

Waka Kotahi (2022). *Bridge Manual Third Edition, Amendment 4.* ISBN978-0-478-37161-1 (online). Waka Kotahi NZ Transport Agency, Wellington. Available at www.nzta.govt.nz