

# THE STATE OF PRACTICE IN SOIL-STRUCTURE INTERACTION MODELLING IN NEW ZEALAND

Theo Hnat<sup>1</sup>, Christopher R. McGann<sup>2</sup> and  
Liam M. Wotherspoon<sup>3</sup>

(Submitted June 2022; Reviewed August 2022; Accepted January 2023)

## ABSTRACT

The current state of practice in soil-structure interaction (SSI) modelling in New Zealand was investigated through an industry-wide questionnaire. This used a mixed methods, sequential explanatory research design involving the collection of quantitative and qualitative questionnaire data, as well as follow-up focus groups. Several statistically significant relationships were observed for SSI modelling approaches between different engineering fields, company sizes, and years of experience.

The key findings from this study suggest that there is no consensus on the best SSI analysis methods, modelling strategies, or guidelines to be used. Overall, fixed base analysis remains the most popular method across all company sizes and number of years of industry experience. Engineers from large companies reported higher consideration for SSI modelling and use of performance-based design for design projects, which perhaps reflects the scale and complexity of projects carried out in those companies. However when SSI is considered, analyses are typically limited to nonlinear vertical springs under the foundation as part of a dynamic analysis. Use of SSI for buildings is typically limited to seismic assessments and complex or otherwise high importance structures. However, bridge engineers routinely used pushover analyses with linear and nonlinear springs and dynamic analyses with nonlinear springs, in contrast with the rest of the industry.

There is further room to improve on the quality of communication and interaction between structural and geotechnical engineers. A lack of specific guidance on when SSI should be considered was reported, alongside broader training issues to ensure that structural and geotechnical engineers fundamentally understand the requirements and input/output needs of each role.

<https://doi.org/10.5459/bnzsee.1609>

## INTRODUCTION

The response of a structure to earthquake shaking is affected by interaction between three linked systems: the structure, the foundation, and the soil underlying and surrounding the foundation [1]. Soil-structure interaction (SSI) analysis evaluates the collective response of these systems to a specified ground motion. SSI effects are absent for the theoretical condition of a rigid foundation supported on rigid soil. Accordingly, SSI accounts for the difference between the actual response of the structure and the response of the theoretical, fixed base condition.

Conventionally, SSI effects have been considered beneficial in reducing the structural response of buildings. A traditional approach is to modify the fundamental period and associated damping of the corresponding fixed-base system. Research by [2] and [3] demonstrates that SSI effects can significantly affect the dynamic response of structures. The authors show that the fundamental period of a single-storey building, as well as the amplitude of the equivalent input acceleration, always increases as a result of the dynamic coupling between the structure and the soil.

These effects were also observed in multi-storey buildings to a lesser extent, and were negligible in very tall structures. Further support to the argument of beneficial SSI effects stems from analytical studies of the seismic response on elastoplastic oscillators using both fixed-base [4] or flexible support approaches [5]. The authors show that an increase in the

fundamental period due to SSI can result in a decrease in ductility demand imposed on the elastoplastic oscillators.

Despite the omission of nonlinear soil behaviour in early studies of SSI, the assertion that these effects are beneficial in reducing the seismic response of structures forms the basis of past and current seismic design provisions [6–8]. The lack of a standard foundation design code in New Zealand is of significant concern [9], and the poor communication between structural and geotechnical engineers in the area of foundation design can lead to serious miscalculation of design factors of safety. In practice, factors of safety in the order of 1.1 are permitted [10], which may result in excessive rotations and unpredictable deformation at the foundation level.

Case studies from past New Zealand earthquakes can be used to demonstrate the significance of SSI effects. Differential settlement of structures was widely observed following the 2011 Canterbury Earthquake sequence. In the case of flexible foundation systems, this led to excessive induced stresses in the sub- and super-structure, as shown in Figure 1a. On the other hand, stiffer structures suffered from rigid body rotation, as shown in Figure 1b.

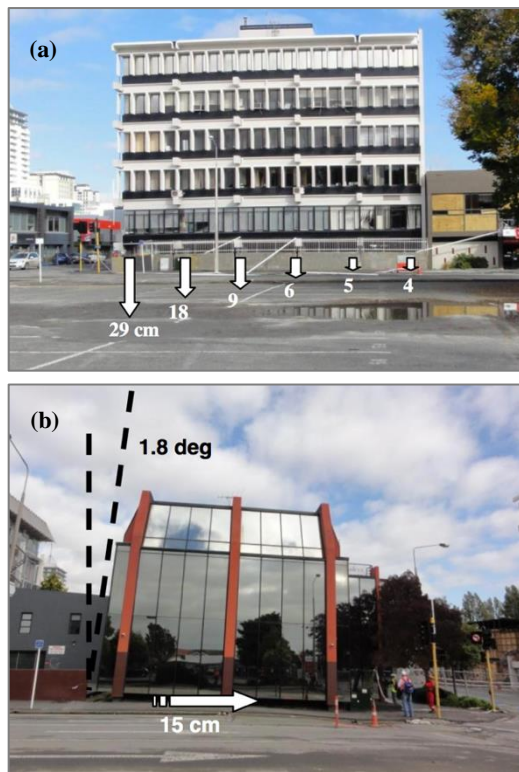
A recent investigation into the performance of the Statistics House in Wellington following the 2016 Kaikoura earthquake found that ground motion amplification led to the partial collapse of the flooring system. SSI effects and basin-edge amplification led to larger seismic demands on the structure [12]. Gazetas et al. [13] highlighted that the collapse of

<sup>1</sup> Corresponding Author, PhD Candidate, University of Canterbury, Christchurch, [tudor.hnat@pg.canterbury.ac.nz](mailto:tudor.hnat@pg.canterbury.ac.nz) (Member)

<sup>2</sup> Senior Lecturer, University of Canterbury, Christchurch, [christopher.mcgann@canterbury.ac.nz](mailto:christopher.mcgann@canterbury.ac.nz) (Member)

<sup>3</sup> Professor, University of Auckland, Auckland, [lwotherspoon@auckland.ac.nz](mailto:lwotherspoon@auckland.ac.nz) (Fellow)

expressway piers in the 1995 Kobe earthquake is likely to have been caused by similar site and SSI effects.



**Figure 1:** (a) Differential settlement leading to induced foundation and superstructure stress; and (b) rigid body rotation of a structure [11].

The primary objective of this paper is to answer the research question “What is the current New Zealand state of practice in SSI modelling?”. To achieve this, an industry-wide, online questionnaire was distributed via the Structural Engineering Society New Zealand (SESOC), the New Zealand Geotechnical Society (NZGS), and the New Zealand Society for Earthquake Engineering (NZSEE). The questionnaire was live from July to October 2020, and follow-up focus groups were held from November to December 2020. The resulting quantitative and qualitative data were analysed, providing insights into industry-wide trends in SSI modelling and their statistical significance.

## METHODOLOGY

To the authors’ knowledge, there have been no similar studies with regards to the state of practice in modelling SSI effects in New Zealand. The most relevant state of practice outreach in literature was conducted by NEHRP [14] with a focus on US practice, however, this was based on informal and anecdotal conversations with a small sample of targeted/selected individuals.

The current study used a mixed methods, sequential explanatory research design [15], incorporating an online questionnaire and follow-up focus group sessions. The next sections give an overview of mixed methods designs, including their advantages and disadvantages. This is followed by an outline of the mixed methods sequential explanatory design and the rationale behind why it was chosen for use in this survey.

### Mixed Methods Research

Mixed methods research designs are carried out to collect, analyse and integrate both quantitative and qualitative data with the aim of gaining an in-depth understanding behind the

research questions [16]. Quantitative data is usually represented numerically and is interpreted via statistical analyses. However, qualitative data is typically more descriptive and can provide further insights into the research problem. The overarching goal of mixed methods research design is to expand one’s understanding and gain depth of insight into the topic being studied, as opposed to corroborating findings within one study [17]. The benefit of combining both quantitative and qualitative data into a single study is to take advantage of the strengths of each method and to therefore develop a more comprehensive overview of the topic being studied [15]. Disadvantages of mixed methods designs typically relate to the length of time needed to undertake the research and the complexity of analysis [18].

### Sequential Explanatory Design

Sequential explanatory design is perhaps the most popular strategy for mixed methods research in the field of education [19]. This design is characterised by two distinct phases, the first being quantitative and the second being qualitative [18]. The qualitative data collected in the second phase helps to explain and elaborate on the quantitative data collected in the first phase. This strategy typically gives more weight to the quantitative data, with these results informing the qualitative data collection. The qualitative component of the research is usually smaller and explores a few cases out of those studied in the quantitative phase.

The mixed methods sequential explanatory design allows for the strengths of both quantitative and qualitative research methods to be utilised in combination, without the occurrence of overlapping weaknesses between the two techniques [20]. Furthermore, this design can be particularly useful when quantitative data provides unexpected results, as the second stage can be used to examine the results of the first stage in greater detail. Some of the challenges of using this type of mixed methods design include determining how much priority should be given to the quantitative data and how to select the sample that is to be studied in the qualitative phase [15].

### Questionnaire

The questionnaire was structured in three distinct parts. Part 1 contained an introduction and instructions page, and comprised of general questions such as:

- “Which engineering field do you most associate with?”;
- “Which region of New Zealand do you predominantly work in?”; and
- “How many employees work at your company?”.

The answers were either multiple-choice selections or drop-down fields. These types of questions and their answers were used to identify groups and subgroups within the data, with a view of investigating inter-group relationships. As the questionnaire was completed anonymously, company size was thought to be an important proxy for items such as the type and value of projects, or availability of modelling resources.

Part 2 of the questionnaire opened with a definition of SSI and comprised of quantitative and qualitative questions relating to each participant’s use of SSI. Two such examples for the former were “How often do you use performance-based design?” and “How often is SSI considered for projects you are involved in?”, with their answers consisting of seven-point Likert-type scales [21] covering a range of Never (1) to Always (7). Qualitative questions included:

- “What types of projects typically demand SSI consideration?”;
- “Which aspects of SSI do you typically consider?”; and

- “What codes and / or guidelines do you follow?”.

Answers to these types of questions were entered as short-form text by participants. This section also included a binary filter question: “Do you have experience in applying soil-structure interaction (SSI) analyses to design projects?”. Participants who selected “No” would finish the survey upon completion of Part 2, while those who selected “Yes” would carry on to the final section.

Part 3 of the questionnaire contained mostly quantitative questions relating to analysis methods, familiarity with implementing specific SSI models, and perceived barriers to implementing these. The referenced models are similar to those used by NEHRP [14] and range from fixed base, structure only to a full substructure model with horizontal and vertical springs, dashpots, foundation rotation, and multi-support excitation.

There were no selection or exclusion criteria applied for participating in the questionnaire, aside from the fact that the survey was only distributed through New Zealand professional engineering societies SESOC, NZGS, and NZSEE. The questionnaire could be completed anonymously, with an option to opt-in to follow-up focus group participation. Due to the sample size and make-up of the questions, it was not possible for the research team to infer specific identities of any of the participants.

### Focus Groups

Groups of four to five participants who opted-in through the questionnaire gathered to discuss some of the emerging themes. No prior preparation was required before attending a focus group, and no attempt was made to link any questionnaire results to participants. Each session was recorded, transcribed, and anonymised of personal information. The focus groups made use of the Chatham House Rule [22] to aid free discussion of the topic without revealing the identity or affiliation of the speakers or participants. Transcripts of the focus group discussions were not linked to any personal details of the participants to maintain confidentiality of the responses. Participant lists were not retained following the completion of the sessions.

## RESULTS AND DISCUSSION

### Quantitative Questionnaire Data

In carrying out the proceeding statistical analyses, left-censoring [23] was used for the company size and years of experience variables, as their highest values were open-ended which would introduce a level of subjectivity in choosing an appropriate midpoint of the censoring interval [24]. Tests of significance and measures of association were conducted on the quantitative data by treating Likert scales, company sizes, and years of experience as ordinal variables [25]. Kendall’s Tau-b has been predominantly used in this study, as it is a nonparametric measure of the strength and direction of association between two variables measured on at least one ordinal scale [26, 27].

### Overview and Descriptive Statistics

A total of 142 responses were recorded for the questionnaire, however small discrepancies in total numbers are due to incomplete fields in participant data. The number of participants by engineering field and company discipline are

shown in Figure 2. From a regional split, 102 participants reported as working in the North Island, compared to 36 in the South Island. This is shown in Figure 3, along with the self-reported years of experience in their engineering field. Figure 4 shows the reported company size for each participant.

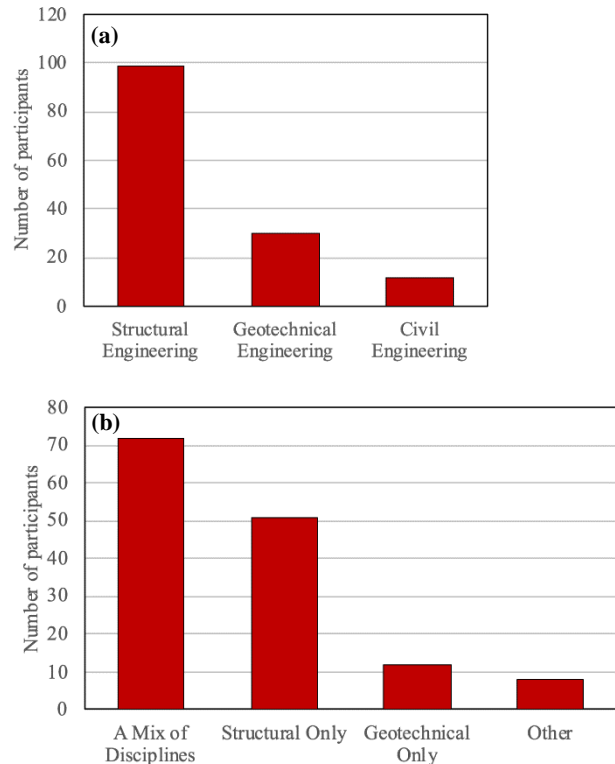


Figure 2: Number of participants by (a) engineering field and (b) company discipline(s).

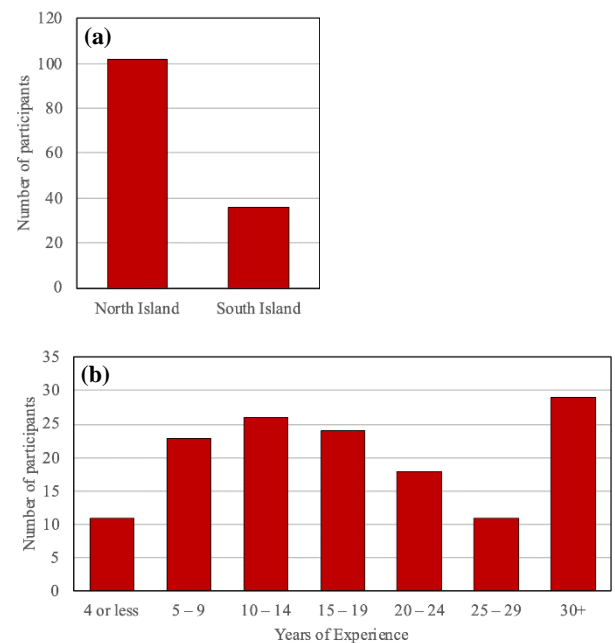


Figure 3: Number of participants by (a) location; and (b) years of experience in engineering field.

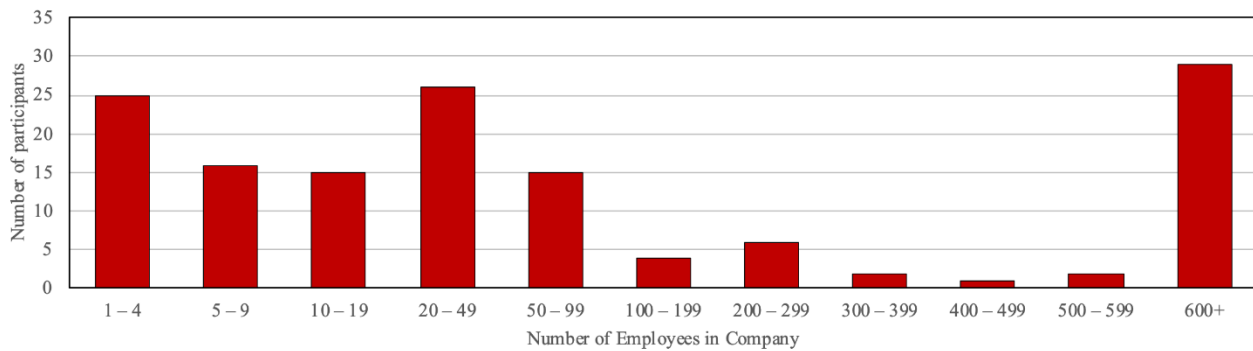


Figure 4: Number of participants by company size.

While it is not possible to directly calculate the total number of SSI practitioners in New Zealand, there are some hints within the data that the questionnaire captured a large proportion of engineers that commonly consider SSI. In fact, 83% of participants answered “Yes” when asked “Do you have experience in applying soil-structure interaction (SSI) analyses to design projects?”. It would be unreasonable to assume the same proportion applies to the entire New Zealand earthquake engineering community. Based on the focus group discussions with senior members of large engineering firms, it appeared that “not so many people, ... a handful” carry out any form of SSI design in those companies. This apparent bias in the respondents’ familiarity with SSI analyses appears natural, as individuals who have never worked with SSI may have ignored the survey requests or may have otherwise felt like they had nothing to contribute and therefore opted not to participate.

The engineering field (i.e., structural, geotechnical, civil) was viewed as an evident starting point to observe potential differences in response between groups of engineers. A sample set of five questions are shown in Table 1 along with their mean ( $M$ ), standard deviation ( $SD$ ), and number of participants ( $N$ ). The numerical values for  $M$  are representative of the Likert Scale used for each question. An example of the seven-point scale used for the first two questions is 1 (never), 2 (rarely), 3 (sometimes), 4 (about half the time), 5 (reasonably often), 6 (most of the time), and 7 (always). Higher values reflect a more affirmative answer to a question. For each question, Student  $T$ -

Tests were carried out to establish statistically significant differences in answers from structural, geotechnical, and civil engineers. Except for the question “How often do you use performance-based design?”, there were no statistically significant differences (using a  $p$ -value of 5%) between how the three groups of engineers answered the questionnaire. As such, the following sections use data for all engineering fields in investigating relationships between subgroups, except in cases where performance-based design is also a variable.

#### Use of Performance-Based Design

Performance-based design (PBD) is an integral part of SSI analyses, particularly through the implementation of displacement or deformation limit states [28]. As shown in Table 1, it was observed that there was a statistically significant difference between structural and geotechnical engineers’ frequency of use of PBD. Comparing the group of 97 structural engineers ( $M = 2.77$ ,  $SD = 1.66$ ) and 29 geotechnical engineers ( $M = 3.67$ ,  $SD = 1.42$ ) demonstrated significantly lower use of PBD by the structural participants relative to the geotechnical participants ( $t(124) = 2.6$ ,  $p = .009$ ). These differences are visualised in Figure 5.

In a qualitative sense, the calculated averages spanned between “sometimes” and “about half the time” for geotechnical engineers. For structural engineers in comparison, the calculated averages ranged between “rarely” and “sometimes”.

Table 1: Summary of descriptive statistics for five key questionnaire items.

Question (Likert scale number of points)	Structural (99 participants)			Geotechnical (30 participants)			Civil (12 participants)		
	$M$	$SD$	$N$	$M$	$SD$	$N$	$M$	$SD$	$N$
How often do you use performance-based design? (7)	2.77	1.66	97	3.67	1.42	29	3.50	1.73	11
How often is SSI considered for projects you are involved in? (7)	3.33	1.66	70	3.88	1.71	16	4.10	2.07	5
How familiar are you at implementing SSI analyses? (5)	2.32	0.65	51	2.75	0.89	8	1.90	1.14	5
How well do you think that SSI analyses represent real-world performance? (5)	2.46	0.67	50	2.63	0.64	8	3.00	1.29	4
If simple SSI modelling tools were available, how likely are you to apply them in future projects? (7)	5.68	1.16	51	5.25	0.89	8	4.75	2.22	4

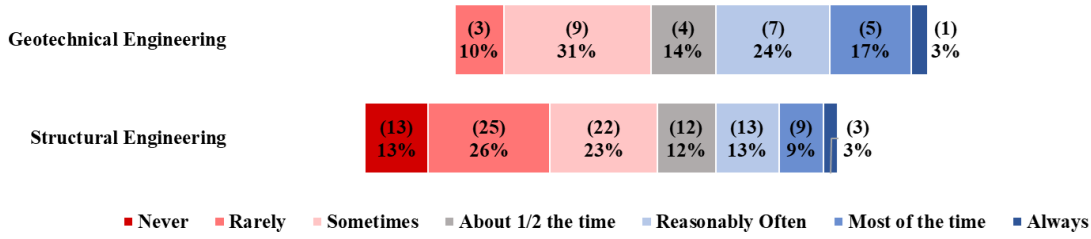


Figure 5: Comparison between structural and geotechnical engineers in frequency of use of PBD (bracketed numbers represent individual questionnaire answers).

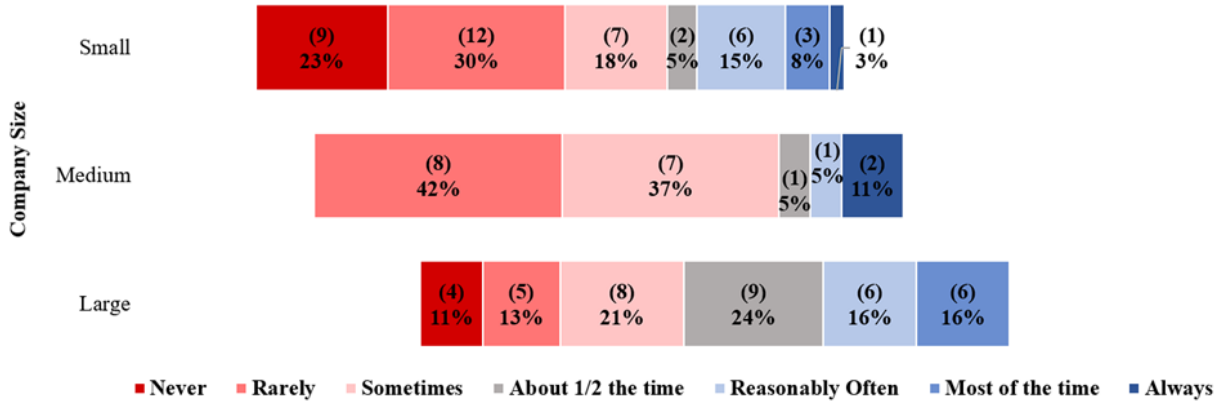


Figure 6: Relationship between the prevalence in use of performance-based design and company size for structural engineers (bracketed numbers represent individual questionnaire answers).

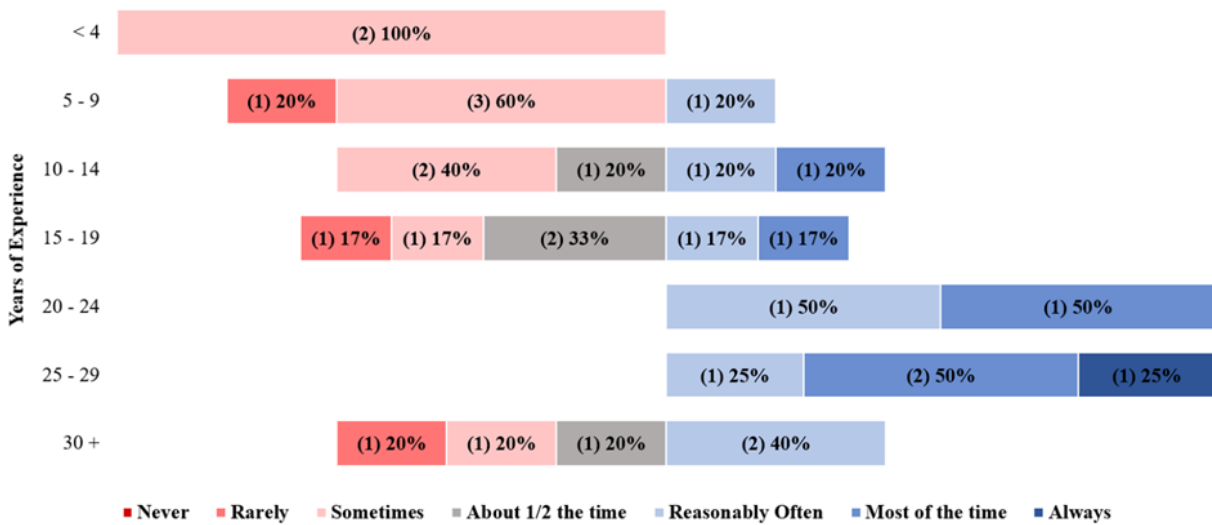


Figure 7: Relationship between the prevalence in use of performance-based design and years of experience for geotechnical engineers (bracketed numbers represent individual questionnaire answers).

A statistically significant, weak positive association was seen for structural engineers between the prevalence in use of PBD and company size,  $r_t = .176$ ,  $p < 0.026$  (Figure 6). Here  $r_t$  is the Kendall rank correlation coefficient, adjusting for ties (Tau-b) and  $p$  is the level of statistical significance (set to  $< 5\%$  for this study). The company sizes were distributed into three size categories: small (0 to 19 employees), medium (20 to 49 employees), and large (50 or more employees). These definitions were based on the Ministry of Business, Innovation and Employment guidelines [29]. There was no measurable increase in use of PBD with years of experience for structural engineers.

A statistically significant, strong positive association was observed for Geotechnical Engineers between the prevalence in PBD and years of experience,  $r_t = .302$ ,  $p < 0.043$  (Figure 7). There was a notable drop in use of PBD for geotechnical engineers with over 30 years of experience, suggesting it is not used as consistently across that category. Perhaps this is partly due to the timing of when the concept of PBD was formalised in the early 1990s [30]. When compared to structural engineers, there was no observed increase in use of PBD with company size for geotechnical engineers.

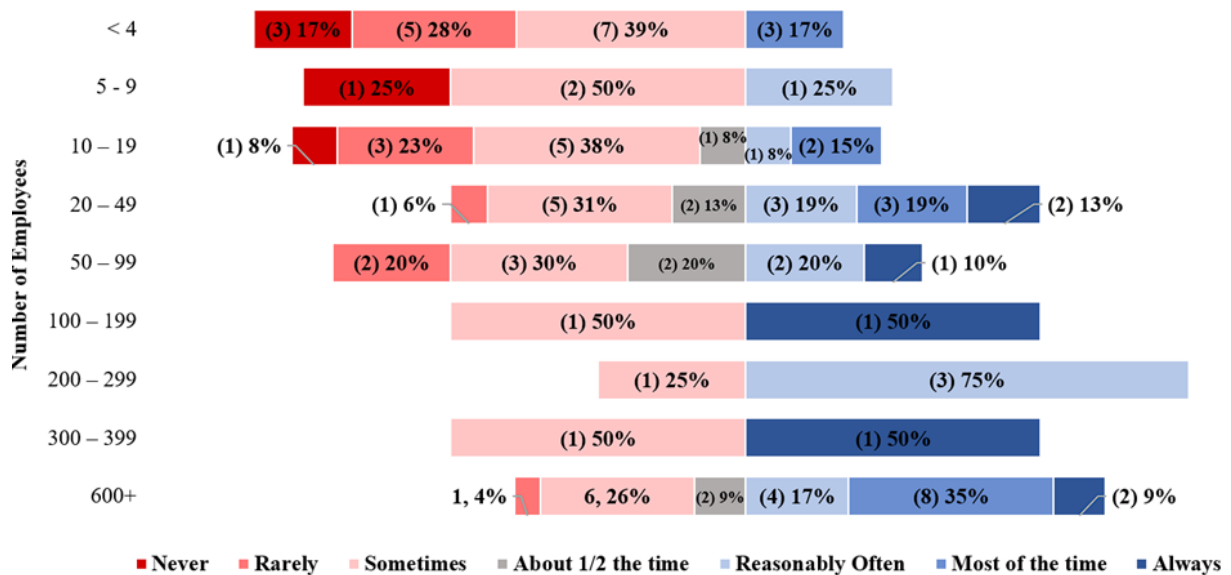


Figure 8: Relationship between the level of SSI consideration in projects and company size (bracketed numbers represent individual questionnaire answers).

Effects of Company Size on the Frequency of SSI Consideration

A very statistically significant, strong positive association between consideration of SSI in projects and company size was observed,  $r_t = .336, p < 0.001$  (Figure 8). This data suggests that SSI is considered more often in larger companies; in a qualitative sense, companies with less than 20 employees only consider SSI analyses “sometimes”, while this increases to “reasonably often” for companies with many hundreds of employees. This perhaps reflects the types and scale of projects carried out in large companies.

In small companies, technical expertise or resourcing constraints may contribute to SSI being considered less. This could result in a negative feedback loop for small companies, whereby SSI is not considered due to the types of projects and therefore expertise is not needed or acquired, and vice versa for large companies.

The qualitative data analysis highlighted that financial constraints featured heavily for engineers in large companies; 46% of those participants mentioned at least one cost-related category as a key obstacles to implementing SSI analyses more

often. Similar constraints were reported in small- and medium-sized companies, however to a lesser extent at 23% and 27% mentions, respectively.

Effects of Familiarity on the Frequency of SSI Consideration

A very significant, strong positive association between consideration of SSI in projects and familiarity at implementing SSI analyses was observed,  $r_t = .317, p < 0.003$  (Figure 9). This is perhaps the most intuitive association observed in the dataset. In other words, an engineer already accustomed to carrying out SSI modelling is more likely to consider implementing SSI analyses in projects they are involved in. This was also reflected in the focus group conversations that “[in] buildings it’s considered not very often. It’s only really considered if the person leading the design is proactive sorting it out.” Furthermore, several focus group participants noted that “most senior engineers would know it and understand it, but potentially wouldn’t have the experience actually applying it.” Similar comments regarding graduate engineers suggested that “young engineers [have] an appreciation for how it is important, but not necessarily how to implement it.”

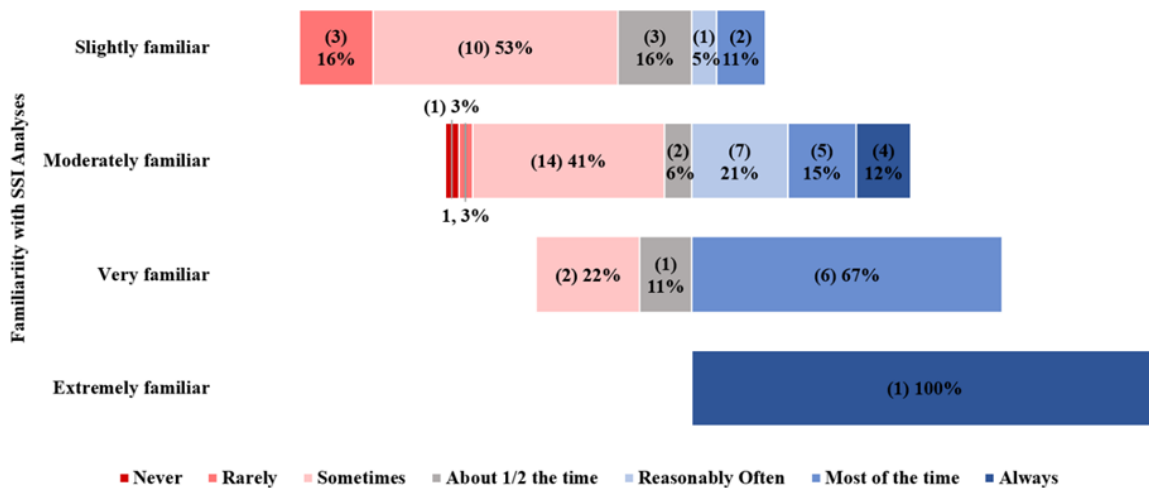
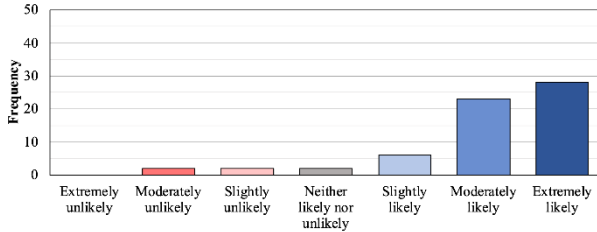


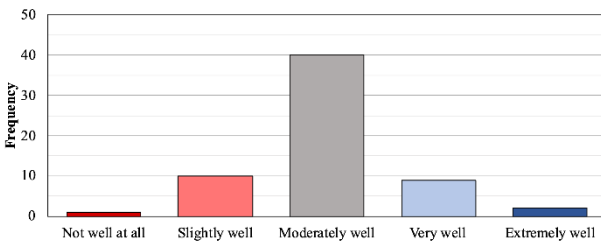
Figure 9: Relationship between the level of SSI consideration in projects and the familiarity in implementing SSI analyses (bracketed numbers represent individual questionnaire answers).

*Insights into the Use of Simplified SSI Tools and SSI Modelling Accuracy*

Other notable questionnaire results were the likelihood to use simple modelling tools ( $M = 6.06, SD = 1.21$ ), and how well modelling tools were perceived to reflect real-world performance ( $M = 3.02, SD = 0.713$ ), shown in Figures 10 and 11 respectively. This data suggests that participants are highly likely to adopt simplified SSI tools, where available, and the general perception is that SSI analyses reflect real-world performance “moderately well”. These findings are consistent with focus group comments suggesting that engineers would be “very likely” to use “simple guidelines [that] allow you to improve what you’re doing, without being unsafe”.



**Figure 10: Likelihood to use simple SSI modelling tools among survey participants.**



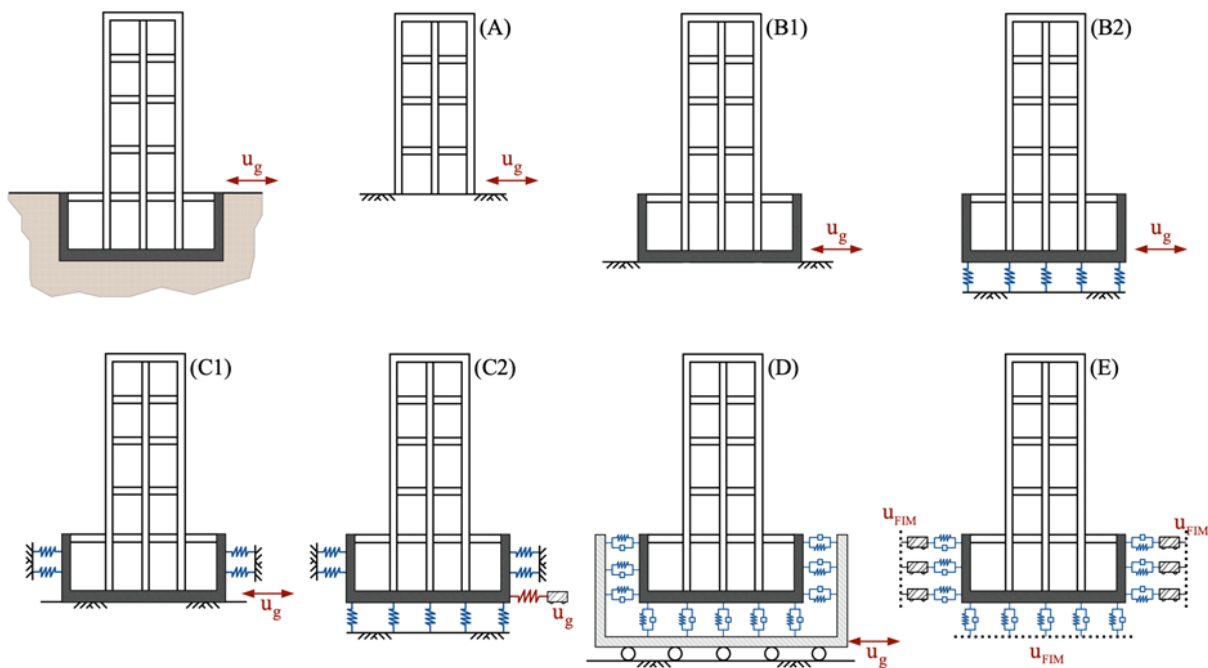
**Figure 11: Participants' perception of how well SSI analyses represent real-world performance.**

*SSI Modelling Preferences*

In the third part of the questionnaire, two questions are used to gain an insight into a participant’s typical approach to SSI modelling. The first question, “With reference to the following modelling strategies, how often would you use each option?”, requests a general self-assessment on how often a participant would use a theoretical analysis method, ranging from fixed base to the use of nonlinear springs as part of a dynamic analysis. The second question requests a participant to self-assess how often they would use a specific model presented, relating to a hypothetical building with a basement (Figure 12). This exercise was reproduced from the NEHRP study on the use of SSI in US engineering practice [14]. Although a logical increase in analysis complexity exists for both questions, the choices were randomised through the survey software in order to minimise the effect of question order on responses [31].

The general approach to the data analysis involving the two SSI modelling questions was to first investigate general trends by engineering field, company size, and years of experience. Following that, specific sub-trends were explored in conjunction with the qualitative data gathered from the long-format questionnaire questions and the focus groups.

A series of multiple linear regressions were carried out on the questionnaire data from both modelling questions. It should be noted that the results for bridge engineers are excluded from the following analyses and will be discussed separately due to differences in use of models when compared to non-bridge engineers. The modelling axis was represented by a set of dummy variables named analysis complexity (AC) or model complexity (MC), depending on the respective question. The numerical value corresponds directly to the represented analysis or model, as shown in Tables 2 and 3. Pushover analyses with linear and nonlinear springs were combined into AC2 despite having individual questions, after it became apparent that linear springs were rarely used in comparison to nonlinear springs.



**Figure 12: Example modelling options for a hypothetical multi-storey building with a basement, reproduced from the NEHRP study on the use of SSI in US engineering practice [14].**

**Table 2: Analysis complexity definitions (see Figure 13).**

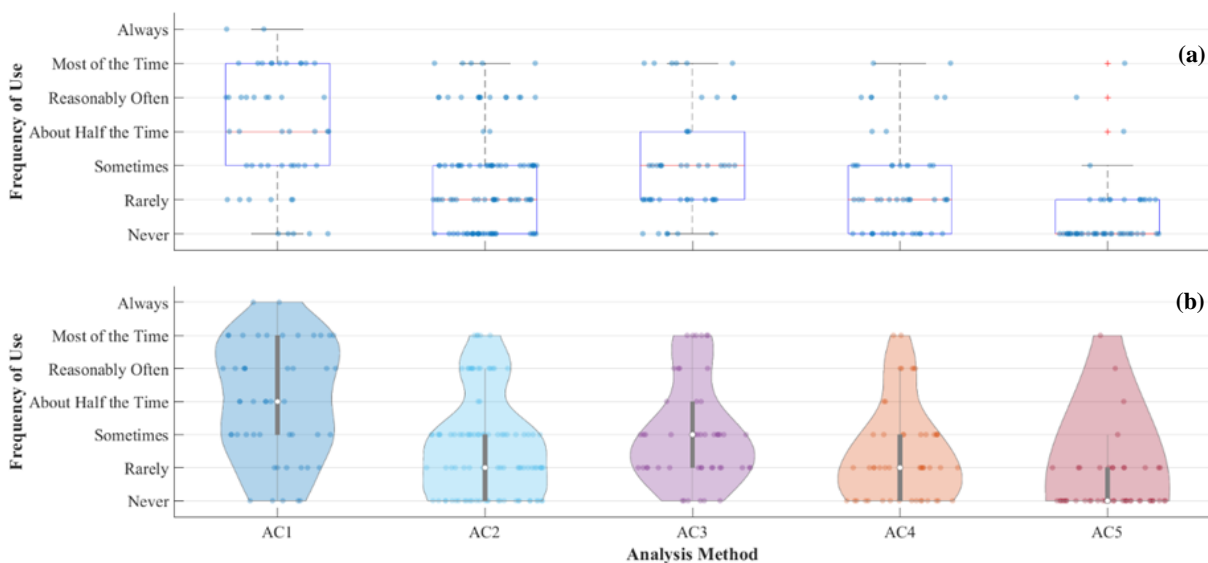
Analysis Complexity	Analysis Method
AC1	Fixed base
AC2	Pushover analysis with either linear or nonlinear springs
AC3	Dynamic analysis with linear springs and damping
AC4	Dynamic analysis with nonlinear springs and damping
AC5	Nonlinear springs and damping linked to a free-field column, with inputs from a site response analysis

**Table 3: Modelling complexity definitions (see Figure 14).**

Model Complexity	Modelling Approach
MC1	Model A. Fixed base, structure only. Basement and foundation considered separately
MC2	Model B1. Basement is explicitly modelled, with retained soil ignored. Fixed base.
MC3	Model B2. Basement is explicitly modelled, with retained soil ignored. Vertical springs used under the foundation.
MC4	Model C1. Horizontal springs with fixed ends, ground motion input at the base of the model. Fixed vertically.
MC5	Model C2. Horizontal springs with fixed ends, ground motion input at the base of the model. Vertical springs used under the foundation.
MC6	Model D. Horizontal and vertical springs attached to rigid walls and base (i.e., “bathtub model”). Ground motion is applied to the bathtub.
MC7	Model E. Full substructure model with horizontal and vertical springs, dashpots, foundation rotation, and multi-support excitation.

A negative relationship between analysis methods and modelling approach with respect to model complexity was found in both cases. These are shown in Figures 13 and 14 through a series of box and whisker plots and violin plots. The latter aids the visualisation of the distribution shape of the data by showing the kernel density estimation of each variable. For example, wider sections of the violin plot represent a higher density of data.

Fixed base (AC1) and dynamic analysis with linear springs and damping (MC3) were reported as the most utilised analysis methods, with scores typically ranging from “sometimes” to “most of the time” for AC1, and “rarely” to “about half the time” for AC3. The analysis methods AC2, AC4, and AC5 were used on average “rarely” or “never”.



**Figure 13: Analysis methods (see Table 2) used in NZ structural and geotechnical engineering companies (a) box plot; and (b) violin plot.**

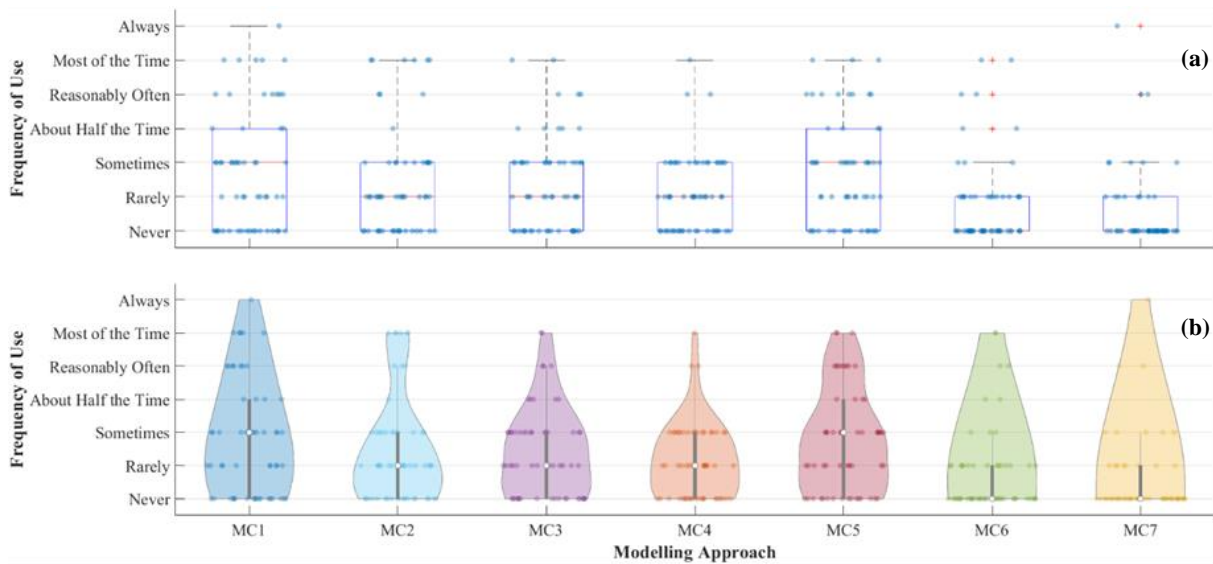


Figure 14: Modelling approaches (see Table 3) used in NZ structural and geotechnical engineering companies (a) box plot; and (b) violin plot.

Relating to the hypothetical basement building, the results showed a similar preference for models MC1 (fixed base) and MC5 (horizontal springs with fixed ends and vertical springs under the foundation), as shown in Figure 14. MC2, MC3, and MC4 were reported similarly in terms of frequency of use, typically used “rarely”. From the SSI modelling approach, models MC6 and MC7 were either “never” or “rarely” used. It was considered to combine the previous groups due to their response similarities, however the data for each model is shown for completeness.

These results reflect the qualitative data analysis well, where it was found that “Soil / Spring Stiffness” was the most-considered aspect in SSI modelling. The focus group discussion also reinforced the view that for “most new designs, people generally avoid it [in reference to soil spring models], you do fixed base at the best”, or when more complex analysis methods

are chosen, “using regular springs or something like that, is probably used at least 90% of the time.”

*Effects of Experience on the Use of SSI Modelling*

Some interesting observations were made when analysing each model with consideration for the participants’ years of experience. Applying this approach to most of the model complexity cases did not reveal any particular trends. However, MC5 saw higher use among engineers with 5 – 19 years of experience (as comprised by the categories with 5-9, 10-14, and 15-19 years of experience), and relatively infrequent use outside that range, as shown in Figure 15. This spike contributed to the higher average use of MC5 seen in Figure 13. These findings are consistent with focus group comments suggesting that “most senior engineers would know it and understand it, but potentially wouldn’t have the experience actually applying it.”

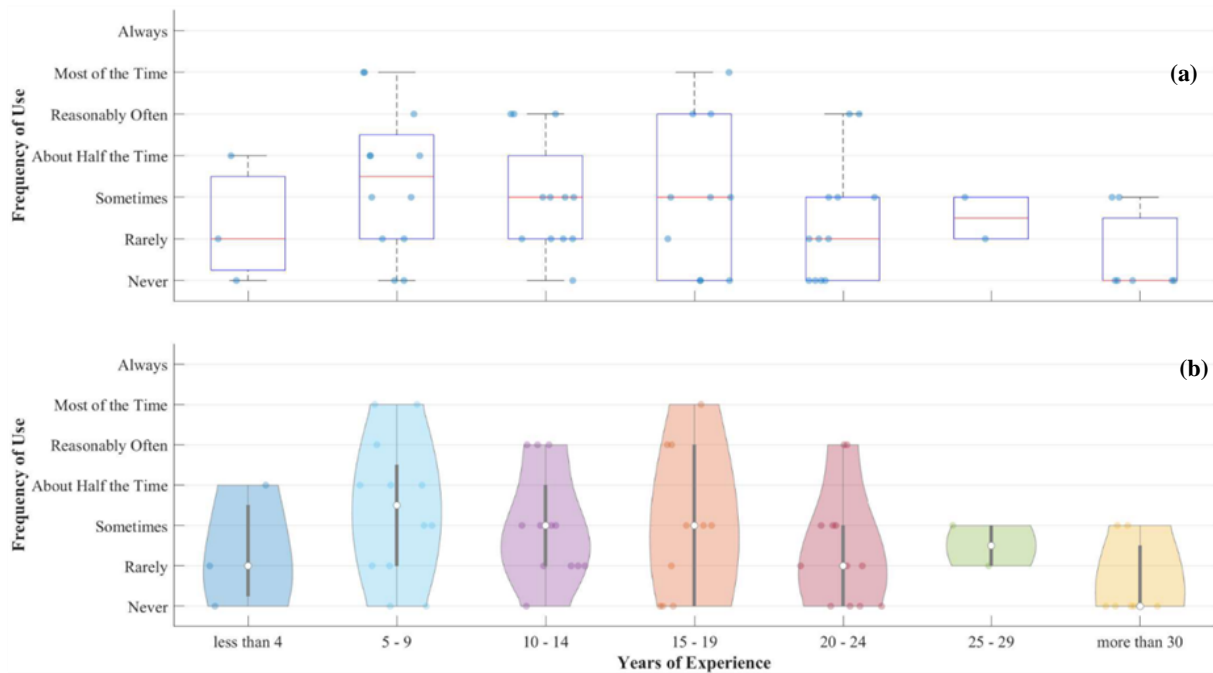


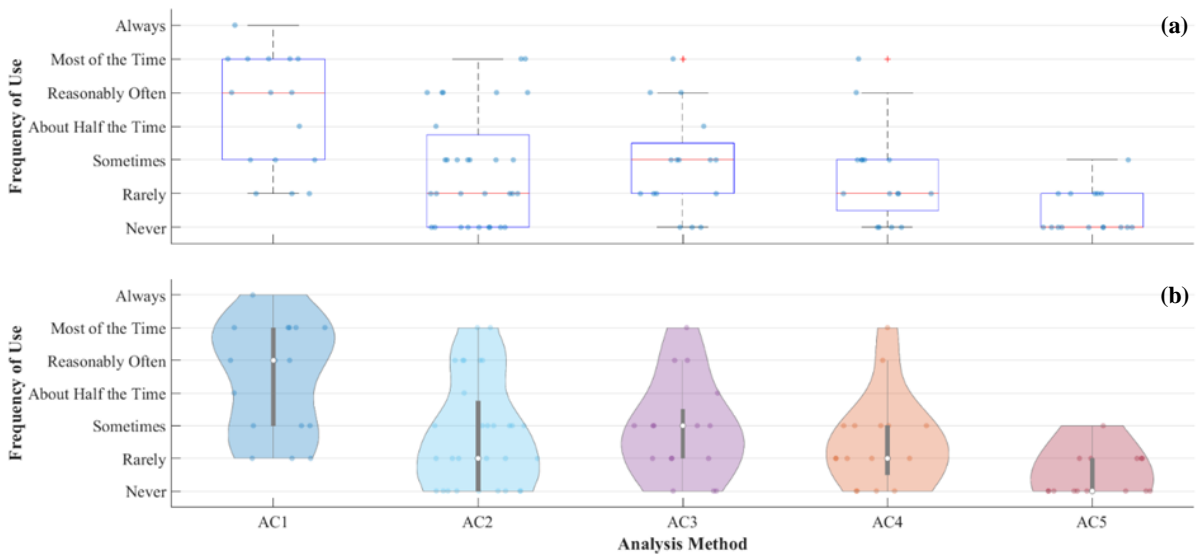
Figure 15: Variation in use of MC5 by years of experience (a) box plot and (b) violin plot.

*Effects of Company Size on the Use of SSI Modelling*

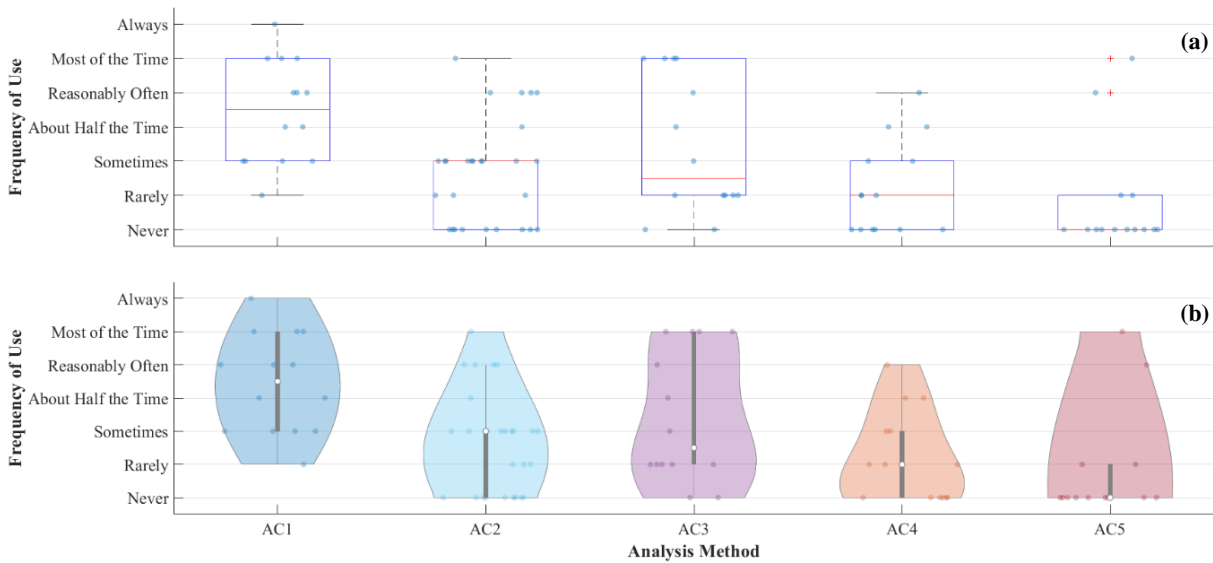
Dummy variables were created to represent three size categories: small (0 to 19 employees), medium (20 to 49 employees), and large (50 or more employees), based on the Ministry of Business, Innovation and Employment guidelines [29]. Within each company size category, linear regression analyses were calculated to compare the predictions of participants' frequency of use based on a particular model.

When looking at the effect of company size on the use of analysis methods, all cases showed a significant negative linear regression, with the effect being more prominent for small and medium-sized companies. For small companies, a significant regression was found  $F(1, 93) = 25.123, p < 0.001$ , with an  $R^2$  of 0.213.  $F$  denotes the ratio of mean square values, with 1 regression and 93 residual degrees of freedom respectively; the

test has a statistical significance of 0.1%, with  $R^2$  denoting a regression model fit of 21.3%, the latter being included for completeness as many social sciences studies exhibit low  $R^2$  values [32]. Participants' frequency of use reduced by -0.574 points on the Likert scale for each increase in model complexity (Figure 16). For medium companies, a significant regression was found  $F(1, 82) = 14.647, p < 0.001$ , with an  $R^2$  of 0.152. Participants' frequency of use reduced by -0.513 points on the Likert scale for each increase in model complexity (Figure 17). In a qualitative sense, for every two step increases in model complexity there was approximately a single reduction in likelihood as measured on the Likert scale. In other words, for small and medium-sized companies, if AC1 is reported as being used "reasonably often", AC5 would be used approximately "rarely".



**Figure 16: Analysis methods used in small sized companies (< 20 employees), (a) box plot and (b) violin plot.**



**Figure 17: Analysis methods used in medium sized companies (20 – 49 employees), (a) box plot and (b) violin plot.**

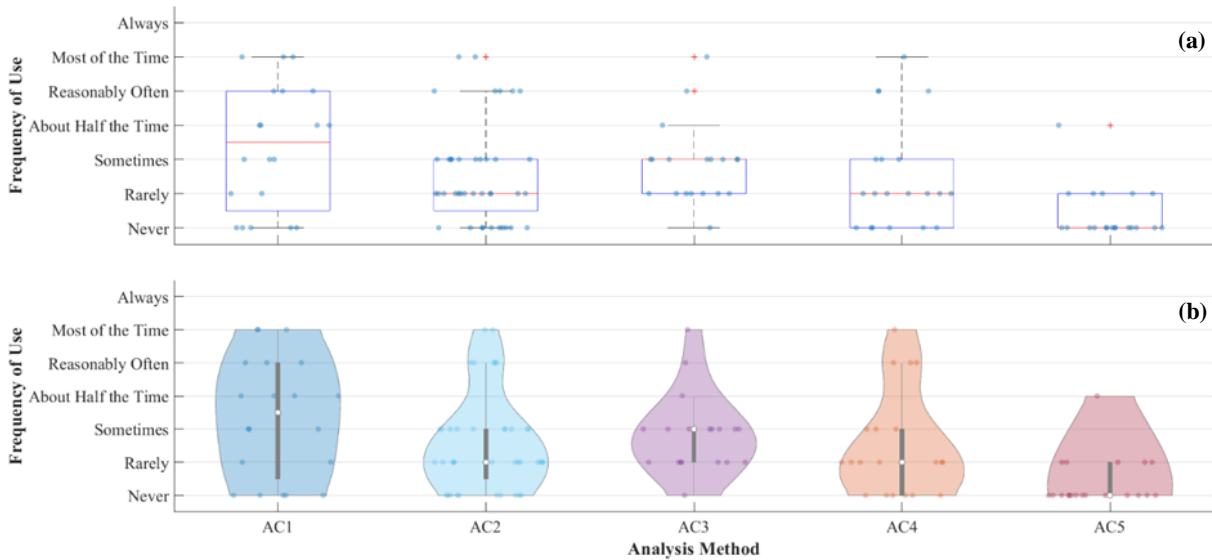


Figure 18: Analysis methods used in large sized companies (> 50 employees), (a) box plot and (b) violin plot.

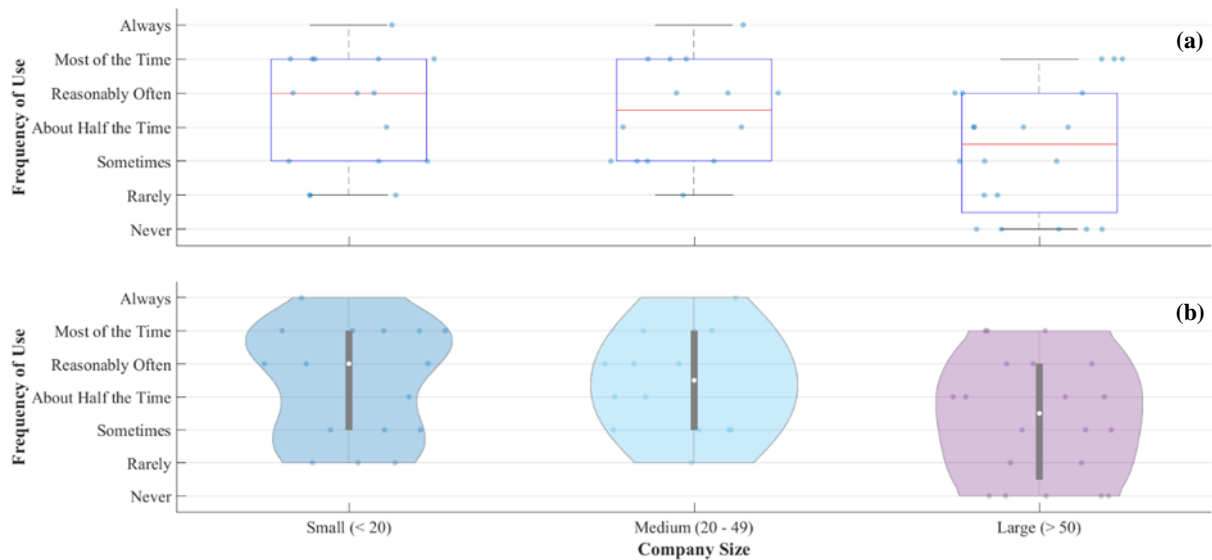


Figure 19: Variation in the use of fixed base analyses (AC1) by company size (a) box plot and (b) violin plot.

For large companies, a significant regression was found  $F(1, 165) = 12.353, p < 0.001$ , with an  $R^2$  of 0.070. Despite the poor regression model fit suggested by the  $R^2$  value, a negative trend is observed with increasing model complexity. Participants' frequency of use reduced by -0.324 points on the Likert scale for each increase in model complexity (Figure 18). The regression coefficient was comparatively lower for large companies; however, it was also observed that the use of fixed base analysis reduced with increasing company size (Figure 19). While this type of analysis is used, on average, "relatively often" in small- and medium-sized companies, it falls approximately two scales to "sometimes" in large companies. This trend was observed in both SSI analysis and modelling questions. There was no reciprocal increase in the relative frequency of higher complexity models, so while present, the reasons for the decrease in usage of fixed base analyses in large companies are not fully understood. Furthermore, no consistent trends emerged for the two SSI modelling questions with respect to the use of PBD, aside from reinforcing the already-established trend that the use of PBD is higher in larger companies.

SSI Modelling Preferences for Bridge Engineers

In total, there were 16 participants who were readily identified as bridge engineers from their qualitative answers. As previously mentioned, the analyses and discussions presented thus far excluded bridge engineers, as it was evident that their use of models AC2 (pushover analyses with linear and nonlinear springs) and AC4 (dynamic analyses with nonlinear springs) were significantly higher (Figure 20) when compared to non-bridge engineers. On the other hand, bridge engineers' frequency of using fixed base analyses (AC1) was significantly lower. This is likely directly related to the use of the Bridge Manual, whereby in Section 5 displacement-based and dynamic analysis are explicitly preferred over force-based analyses [33].

This could be considered pivotal information from an industry standpoint, as it is apparent from the data that bridge engineers routinely make use of more complex models when provided with the guidance to enable such analyses. The use of SSI for buildings can be thought of in a similar light, and indeed all focus group participants collectively agreed that "training is probably one of the biggest barriers, and having a logical and

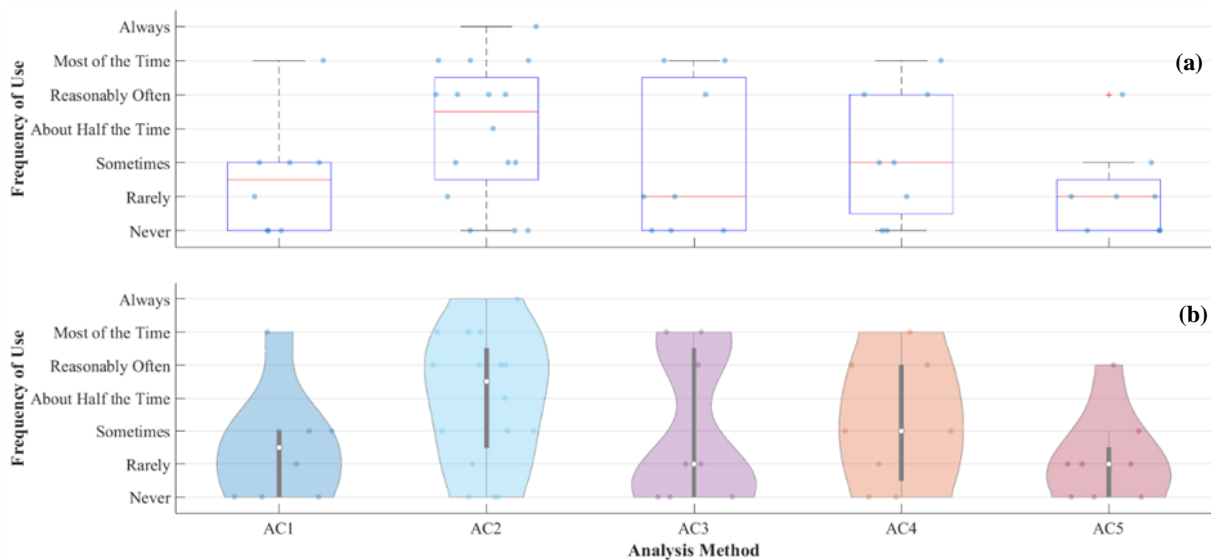


Figure 20: Analysis methods used by bridge engineering participants (a) box plot and (b) violin plot.

rational reference guide to how you might implement different strategies." It is relevant to recall Figure 10, where it was observed that if simple modelling tools were available to the engineering profession, participants reported as "very likely" to use them. This demonstrates that with clear and effective guidance, it is possible to influence the status quo in SSI analysis usage in New Zealand.

### Qualitative Data

#### Overview and Definition

The questionnaire included several open-ended questions requesting a longer text answer from the participants. The observations from these questions and the focus group sessions support the quantitative data analyses in Section 3.1 by providing further insight or context into the observed trends.

The focus group participants individually had between 10-20 years of experience in the industry. Their roles ranged from Team Leaders, Principals, and Technical Managers in structural or geotechnical engineering fields. The conversations covered a wide range of topics, with some of the common themes including lack of consistency in the industry, shortage of skills / training, and an absence of a formal SSI analysis framework for when it should / should not be considered in a New Zealand context.

#### Obstacles to Using SSI

When asked "What are some obstacles to using SSI analyses more often?", three of the top four categories, encompassing "Data Quality / Availability", "Budget Constraints", and "Time Constraints", are related to costs (Figure 21). Engineers in large companies were disproportionately affected in this regard, as 46% of those participants mentioned at least one of the above categories. This is compared to 23% and 27% mentions among participants in small and medium companies, respectively. Multiple cost-related challenges were also more common in participants from large companies than in small or medium companies.

The categories "Lack of Guidance", "Analysis Complexity", and "Lack of Skill / Knowledge" were analysed in a similar

fashion, by representing a lack of expertise in carrying out SSI analyses. There were similarities between small, medium, and large companies, with a narrow range of 27-29% mentions among all company sizes. This suggests that there is a consistent lack of expertise in carrying out SSI analyses, irrespective of company size.

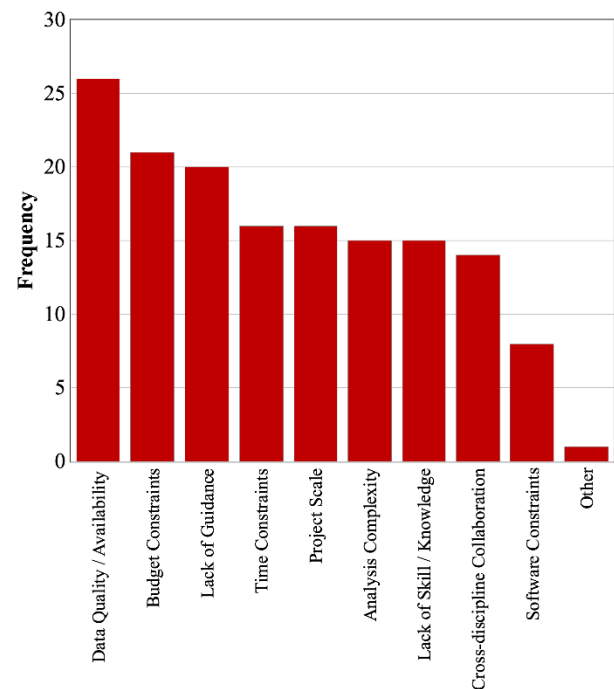


Figure 21: Obstacles to using SSI analyses among all survey participants.

#### Consideration of SSI on Projects and in Modelling

When asked "What types of projects typically demand SSI consideration?", a wide range of structural forms and situations were mentioned, as shown in Figure 22. The general perception among the survey participants was that there was a need for the project to reach a certain level of complexity before SSI would be considered.

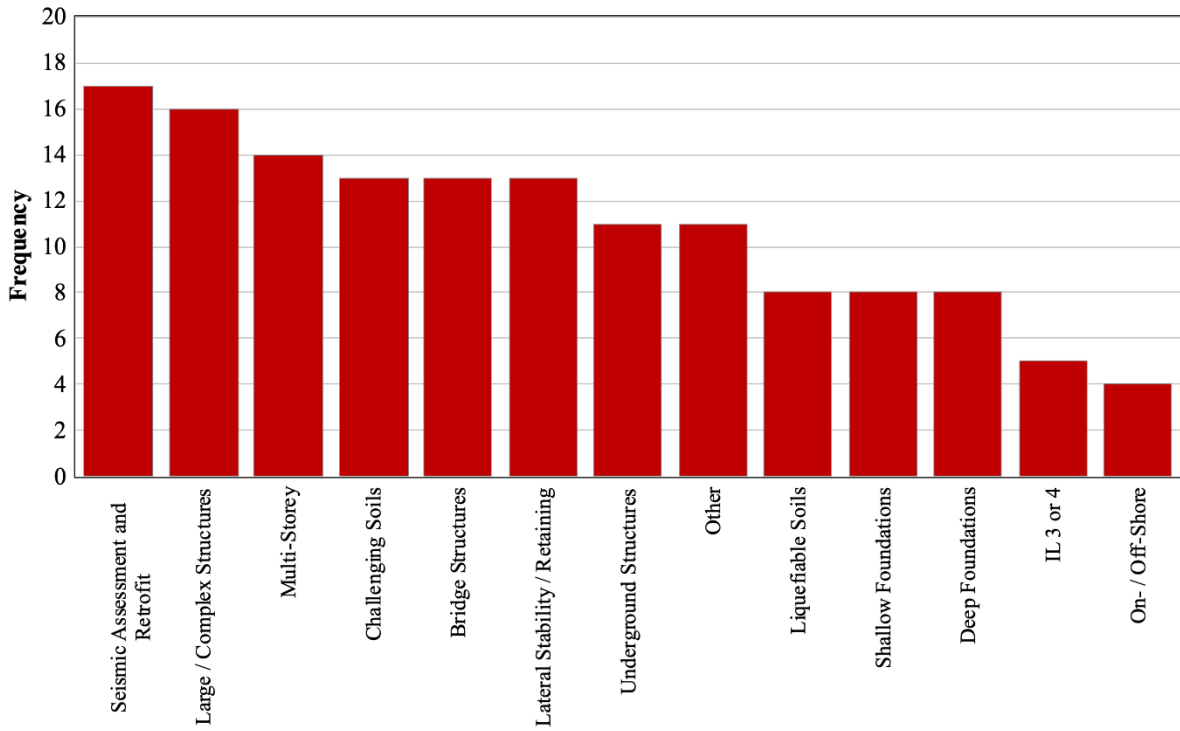


Figure 22: Reported project types that would require SSI consideration.

“Soil / Spring Stiffness” and “Settlement / Displacement” made up almost half of the total responses to the question “Which aspects of SSI do you typically consider?”, as shown in Figure 23. The “Other” category was varied; however, some of the top mentions within related to foundation flexibility, rocking, and soil shrink / swell. The qualitative questionnaire data suggests that structural engineers predominantly carry out SSI analyses, supported by data provided by geotechnical engineers. In such cases, it would be recommended for a structural engineer to establish performance-based criteria in close collaboration with a geotechnical engineer.

In the focus groups, participants agreed that “a training area that is really needed is the general method and approach to a performance design”, and that while “we do some of that with seismic design of structures, it does need to apply to every single part of the structure, including the foundations and its relationship with the soil.” Recalling that approximately 28% of participants named a lack of expertise in carrying out SSI analyses as one of the key obstacles in implementing such analyses, it follows that training and formalised guidance would be beneficial in a higher uptake of SSI in engineering practice.

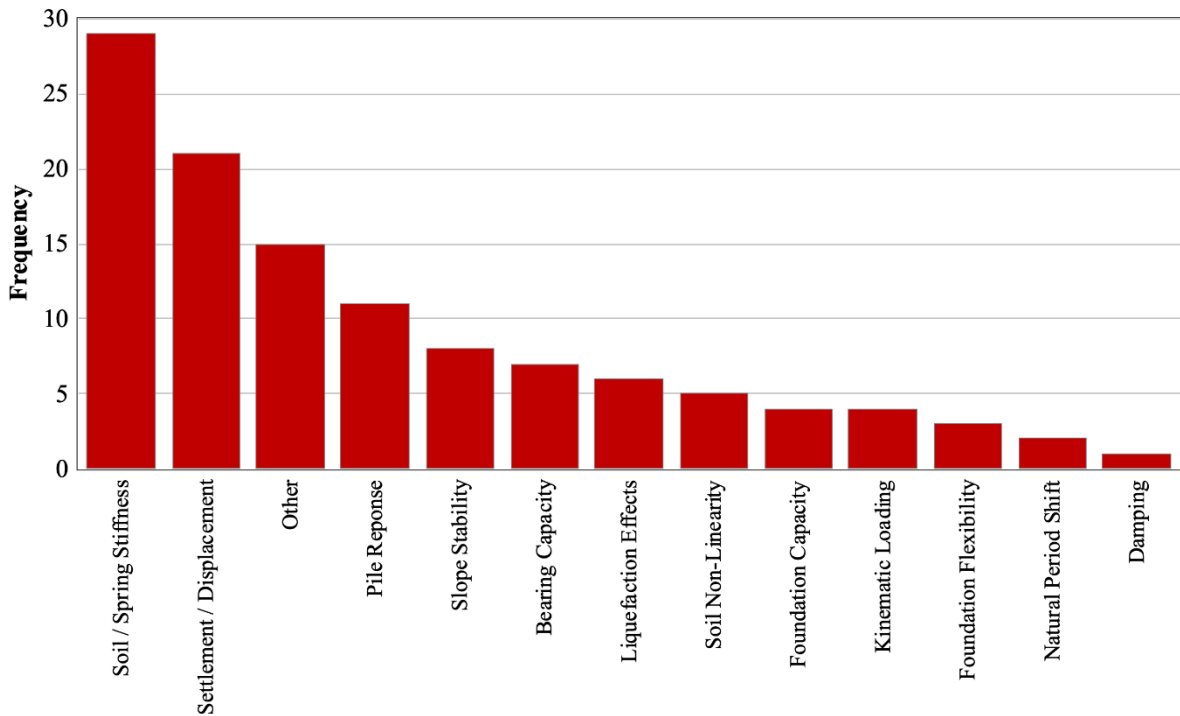


Figure 23: Aspects of SSI considered by the survey participants.

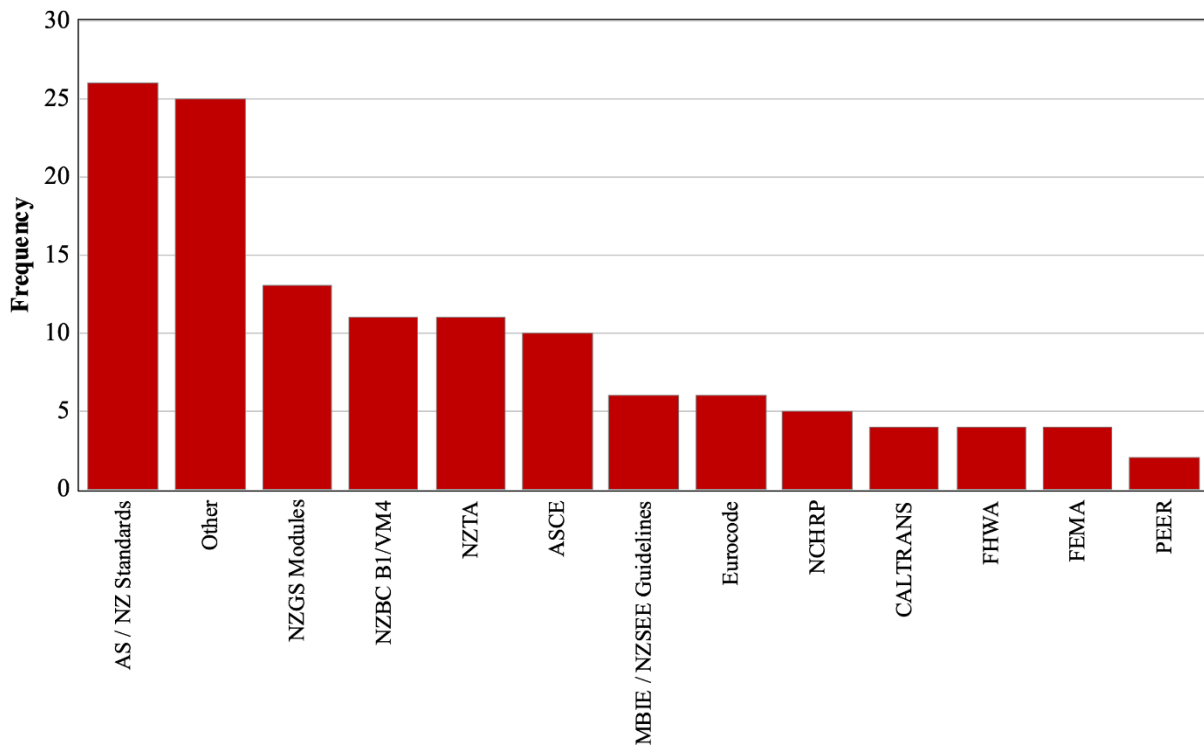


Figure 24: Codes and/or guidelines followed by survey participants.

#### Use of Codes and Guidelines

There was a notable lack of consistency among survey participants as to which guidelines were typically utilised for SSI analyses. When asked “What codes and/or guidelines do you follow?”, the top categories were “Other” and “AS / NZ Standards” (Figure 24). The AS/NZS1170 series featured heavily within the latter category. The top two categories, when combined, accounted for approximately half of the total mentions. The AS/NZS1070 series do not offer any SSI guidance [34], and the “Other” category typically featured one-off supplementary research papers and guidelines which did not otherwise fall into any of the more populous groupings, in addition to reported use of “first principles”. Not all participants cited specific manuals, however among these the following were indicated: ASCE 41-17, NIST GCR 12-917-21, ASCE 61-14, NZTA Bridge Manual and Research Report 553.

This current state of practice in the SSI space is likely due to a lack of New Zealand-specific resources or guidelines. There was general agreement in the focus groups that “the framework we have is very limited” and that “there should be at least some guideline, how to set up [a] model, what are the minimum test you need to carry out before you start a project”. These comments were also tempered by the sense that any “standard should not be so prescriptive - how to do it, but not what to do” and certainly not a “cookbook”, a fond reference used by New Zealand engineers to describe National Standards

#### Use of Software and Testing Methods

Similarly to the large number of software solutions, there was a wide variety of software reported for the question “What programs do you utilise to carry out or inform SSI analyses?”, as shown in Figure 25. “ETABS” and “SAP2000” proved to be particularly popular, as well as Strand7, Robot Structural Analysis and in-house programs / spreadsheets which featured heavily within the “Other” category. Similarly, focus group participants reported that “many structural engineers will choose to do ETABS.” For geotechnical engineers particularly, PLAXIS [35], LPile [36], and WALLAP [37] proved to be the most popular.

It was evident from the qualitative data and focus group discussions that either structural engineers are in control of the entire model when SSI is implemented, or a separate geotechnical model is analysed in parallel with a structural model. In one such scenario describing the latter, the project geotechnical engineer would “run their full analysis model in PLAXIS or FLAC and give us the lateral spreading displacement without considering the structural effect there. For our model, it is [a] purely structural model, and there is no component of soil.” When asked for a typical design scenario which incorporated SSI, a participant in one of the largest engineering firm in New Zealand reported that “[geotechnical engineers] gave us all the ground displacements and P-Y springs, which we applied in our structure. And that is how far we went. We didn’t consider in our analysis, no additional damping effect and they didn’t consider also the effect of [the] pile preventing that kind of high displacement. Yeah, that is more on the less the standard so far.” From the quantitative data, current SSI analyses were only thought to reflect real-world performance “moderately well”.

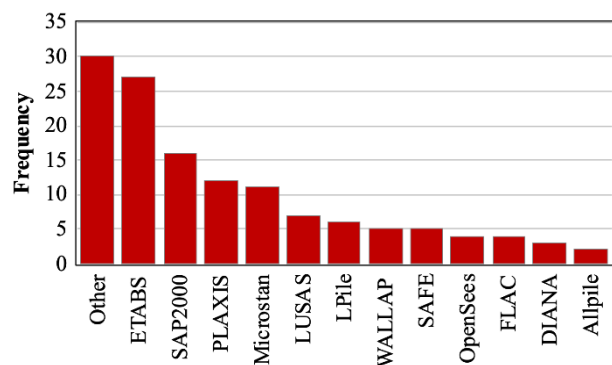


Figure 25: Computer programs used to carry out or inform SSI analyses.

Related to the modelling software used are the inputs required to produce a quality model. When asked “What testing methods do you predominantly use to identify key parameters for use in SSI analyses?”, 55% of the structural engineers answering this

question reported that they would defer the choice to a geotechnical engineer, as shown in Figure 26. CPTs were the most popular ground test according to both the qualitative data analysis and the Focus Groups, however “for something smaller [projects], then just Scala penetrometers and hand augers” are reportedly used. A potential area for concern in these responses relate to the type of information provided by geotechnical engineers. It was apparent from the qualitative and focus group data that structural engineers typically carry out and are responsible for the building model which incorporates SSI. However, there was significant evidence that the parameters provided for vertical springs related to the subgrade reaction moduli. These are used for the determination of the static stiffness, rather than dynamic stiffness, which may under- or over-predict the dynamic response of a structure depending on the correlations used [38].

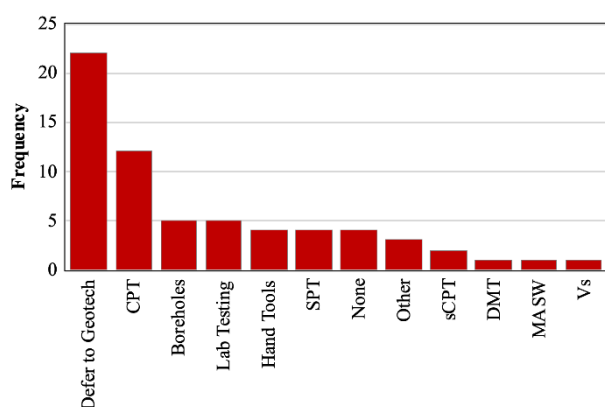


Figure 26: Testing methods reported to identify key parameters for use in SSI analyses.

Within the group discussions, there was a perception that “we don’t test enough in New Zealand overall, that a lot is left to interpretation” and that clients “often don’t see the value of any investigation and ... they think we can do miracles”. It is evident that there is often insufficient data from testing for engineers to then proceed with modelling, particularly the type of information that would be required to inform an SSI analysis. “Data Quality / Availability” was the highest-mentioned category for obstacles in implementing SSI analyses, therefore if such analyses are to be carried out this would need to be identified and budgeted for prior to the preliminary design stage.

#### Industry Communication Challenges

Finally, the effectiveness of communication between engineering fields was queried. Participants were asked “In projects involving a mix of disciplines, can you describe the level of communication and interaction between the different fields?”. As shown in Figure 27, “Collaborative” and “Comprehensive” were considered as positive forms of communication and interaction categories and combined accounted for half of the total responses. The other half was comprised of the neutral and negative groupings “Siloed”, “Mixed”, “Minimal” and “Negative”. Overall, communication effectiveness was split evenly between positive and negative categories. These trends call into question the quality of the communication between structural and geotechnical engineers, perhaps due to a “lack of people with broad knowledge, who have a good understanding of both”, which is also reflected in the large number of “Siloed” mentions.

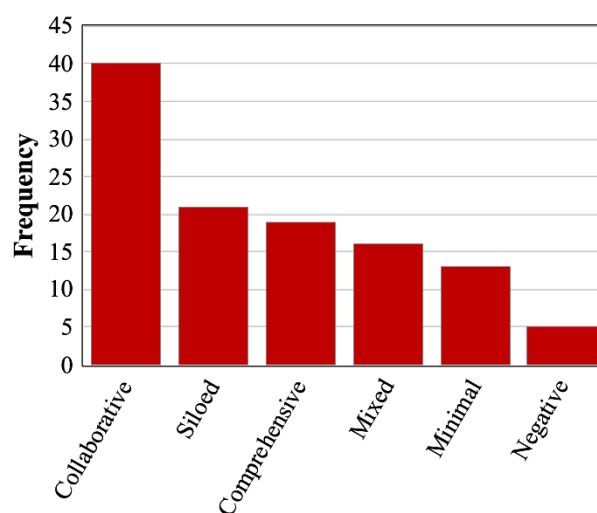


Figure 27: Communication and interaction tendencies between different engineering fields.

## CONCLUSIONS AND RECOMMENDATIONS

An industry questionnaire using a mixed methods, sequential explanatory research design was carried out to investigate the current state of practice in SSI modelling within the New Zealand engineering profession. The quantitative and qualitative data gathered showed several statistically significant relationships for SSI modelling approaches between different engineering fields, company sizes, and years of experience. These trends were further reinforced when incorporating the focus group data.

Overall, the key observations from this study include:

1. There is no consensus on the best SSI analysis methods, modelling strategies, or guidelines to be used. Overall, fixed base analysis remains the most popular method across all company sizes and years of industry experience. The use of fixed base models was found to be significantly lower with increasing company size, however remained the overall most popular analysis method.
2. Engineers from large companies reported higher consideration for SSI modelling and use of PBD for design projects. This perhaps reflects larger or more complex types of projects carried out in those companies. In small companies, technical expertise or resourcing constraints may contribute to SSI and PBD being considered less.
3. When SSI is considered, analyses are typically limited to nonlinear vertical springs under the foundation as part of a dynamic analysis.
4. The quality of communication and interaction between structural and geotechnical engineers is questionable. A lack of training was noted in both the qualitative data set and focus group discussions. This encompassed both SSI-specific guidance on when it should be considered, and broader training to ensure that structural and geotechnical engineers fundamentally understand the requirements and input/output needs of each role.
5. Use of SSI for buildings is typically limited to seismic assessments and complex or otherwise high importance structures.
6. Bridge engineers routinely used pushover analyses with linear and nonlinear springs (AC2) and dynamic analyses with nonlinear springs (AC4), in contrast with the rest of the industry. This is likely directly related to the use of the Bridge Manual, as displacement-based and dynamic analysis are preferred over force-based analyses [33].

Comparing the above findings to the NEHRP study [14], points 1 – 4 were also reported. While interesting, it also highlights that the use of SSI in New Zealand engineering practice is at a level equivalent to that in the US at least a decade ago, noting that the authors do not have any comparative data on US progress in SSI usage or implementation. As measured in the case of bridge engineers, a significant uptake in the state of practice in SSI can be achieved through clear and effective industry guidelines.

Given the key observations, it is anticipated that the results of this study can be used to raise the bar and encourage use of more appropriate SSI models in practice. The results may also be used to inform regulatory bodies such as the MBIE to guide future updates of the assessment guidelines.

## REFERENCES

- FEMA P-750 (2009). “NEHRP Recommended Seismic Provisions for New Buildings and Other Structures”. Building Seismic Safety Council of the National Institute of Building Sciences, Washington, DC. <https://www.fema.gov/node/nehrp-recommended-seismic-provisions-new-buildings-and-other-structures>
- Jennings PC and Bielak J (1973). “Dynamics of building-soil interaction”. *Bulletin of Seismological Society of America*, **63**(1): 9-48. <http://dx.doi.org/10.1785/BSSA0630010009>
- Veletsos AS and Meek JW (1974). “Dynamic behaviour of building-foundation systems”. *Earthquake Engineering and Structural Dynamics*, **3**: 121-138. <http://dx.doi.org/10.1002/eqe.4290030203>
- Riddell R (1979). “Statistical Analysis of the Response of Nonlinear Systems Subjected to Earthquakes”. University of Illinois at Urbana-Champaign. <https://core.ac.uk/download/pdf/4823105.pdf>
- Ciampoli M and Pinto PE (1995). “Effects of soil-structure interaction on inelastic seismic response of bridge piers”. *ASCE Journal of Structural Engineering*, **121**(5): 806-814. [http://dx.doi.org/10.1061/\(ASCE\)0733-9445\(1995\)121:5\(806\)](http://dx.doi.org/10.1061/(ASCE)0733-9445(1995)121:5(806))
- Stewart JP, Kim S, Bielak J, Dobry R and Power MS (2003). “Revisions to soil-structure interaction procedures in NEHRP design provisions”. *Earthquake Spectra*, **19**(3): 677-696. <http://dx.doi.org/10.1193/1.1596213>
- NEHRP and BSSC (2001). “NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures”. Building Seismic Safety Council, Washington, D.C. [https://www.fema.gov/sites/default/files/2020-10/fema\\_2020-nehrp-provisions\\_part-1-and-part-2.pdf](https://www.fema.gov/sites/default/files/2020-10/fema_2020-nehrp-provisions_part-1-and-part-2.pdf)
- Applied Technology Council (2005). “Improvement of Nonlinear Static Seismic Analysis Procedures”. FEMA Region II. <https://nehrpsearch.nist.gov/static/files/FEMA/PB2008108249.pdf>
- McManus KJ (2011). “Foundation Design Reliability Issues”. NZ Zealand. [https://canterbury.royalcommission.govt.nz/documents-by-key/20111018.469/\\$file/GEO.MCM.0001.SUB.pdf](https://canterbury.royalcommission.govt.nz/documents-by-key/20111018.469/$file/GEO.MCM.0001.SUB.pdf)
- MBIE (2020). “Acceptable Solutions and Verification Methods for New Zealand Building Code Clause B1 Structure, B1/VM1/AS1/VM4”. Wellington, NZ. <https://www.building.govt.nz/building-code-compliance/b1-stability/b1-structure/b1-acceptable-solutions-and-verification-methods/>
- Cubrinovski M and McCahon I (2011). “Foundations on Deep Alluvial Soils”. University of Canterbury, Christchurch, NZ. [https://canterbury.royalcommission.govt.nz/documents-by-key/2011-09-2354/\\$file/SEI.UOC.0002.Final.pdf](https://canterbury.royalcommission.govt.nz/documents-by-key/2011-09-2354/$file/SEI.UOC.0002.Final.pdf)
- Anderson H, Hare J and Wentz R (2017). “Investigation into the Performance of Statistics House in the 14 November 2016 Kaikōura Earthquake”. <https://apo.org.au/node/75122>
- Gazetas G and Mylonakis G (2001). “Soil-structure interaction effects on elastic and inelastic structures”. *Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics. Symposium in Honor of Professor WD Liam Finn*. San Diego, California, USA. <https://core.ac.uk/reader/229085730>
- National Earthquake Hazards Reduction Program (NEHRP) Consultants Joint Venture (2012). “NIST GCR 12-917-21: Soil Structure Interaction for Building Structures”. <https://www.nist.gov/publications/soil-structure-interaction-building-structures>
- Ivankova NV, Creswell JW and Stick SL (2006). “Using mixed-methods sequential explanatory design: From theory to practice”. *Field Methods*, **18**(1): 3-20. <http://dx.doi.org/10.1177/1525822X05282260>
- Tashakkori A and Teddlie C (2003). “The past and future of mixed methods research: From data triangulation to mixed model designs”. In *Handbook of Mixed Methods in Social and Behavioral Research*, pp 671-701. Sage Publications, Thousand Oaks, United States, 912 pages.
- Onwuegbuzie AJ and Leech NL (2004). “Enhancing the interpretation of “significant” findings: The role of mixed methods research”. *The Qualitative Report*, **9**(4): 770-792. <http://dx.doi.org/10.46743/2160-3715/2004.1913>
- Creswell JW, Plano Clark VL, Gutmann ML and Hanson WE (2003). “Advanced mixed methods research designs”. In *Handbook of Mixed Methods in Social and Behavioral Research*, pp 209-240. ISBN-13: 978-1412972666. Sage Publications, Thousand Oaks, United States, 912 pages.
- Creswell JW (2009). *Research Design: Qualitative and Mixed Methods Approaches*. Sage Publications, Thousand Oaks, United States, 273 pages.
- Johnson B and Turner LA (2003). “Data collection strategies in mixed methods research”. In *Handbook of Mixed Methods in Social and Behavioral Research*, pp 297-319. ISBN-13: 978-1412972666. Sage Publications, Thousand Oaks, United States, 912 pages.
- Clason DL and Dormody TJ (1994). “Analyzing data measured by individual Likert-type items”. *Journal of Agricultural Education*, **35**(4): 4. <http://dx.doi.org/10.5032/jae.1994.04031>
- Chatham House Rule (2022). <https://www.chathamhouse.org/about-us/chatham-house-rule>
- Zhang Z and Sun J (2010). “Interval censoring”. *Statistical Methods in Medical Research*, **19**(1): 53-70. <http://dx.doi.org/10.1177/0962280209105023>
- Gómez G, Calle ML, Oller R and Langohr K (2009). “Tutorial on methods for interval-censored data and their implementation in R”. *Statistical Modelling*, **9**(4): 259-297. <http://dx.doi.org/10.1177/1471082X0900900402>
- Cohen RJ, Swerdlik ME and Phillips SM (1996). *Psychological Testing and Assessment: An Introduction to Tests and Measurement*. Mayfield Publishing Co. <https://psycnet.apa.org/record/1996-97180-000>
- Botsch R (2011). “Chapter 12: Significance and measures of association”. In *Scopes and Methods of Political Science*. <http://polisci.usca.edu/apls301/>

- 27 Khamis H (2008). "Measures of association: How to choose?". *Journal of Diagnostic Medical Sonography*, **24**(3): 155-162. <http://dx.doi.org/10.1177/8756479308317006>
- 28 Giorgini S, Pampanin S and Cubrinovski M (2014). "Towards performance-based seismic design of integrated foundation-structure systems considering soil-foundation interface nonlinearity". *NZSEE Conference*, Auckland, NZ. [https://www.nzsee.org.nz/db/2014/oral/16\\_Giorgini.pdf](https://www.nzsee.org.nz/db/2014/oral/16_Giorgini.pdf)
- 29 New Zealand Small Business Council (2019). *Defining Small Business*. ISBN: 978-1-99-000409-4. <https://www.mbie.govt.nz/assets/defining-small-business.pdf>
- 30 Structural Engineers Association of California (1995). "Performance-based Seismic Engineering of Buildings, Vision 2000 Report". Structural Engineers Association of California (SEAOC), USA.
- 31 Kalton G and Schuman H (1982). "The effect of the question on survey responses: A review". *Journal of the Royal Statistical Society: Series A (General)*, **145**(1): 42-57. <http://dx.doi.org/10.2307/2981421>
- 32 Lewis-Beck MS and Skalaban A (1990). "The R-squared: Some straight talk". *Political Analysis*, **2**: 153-171. <http://dx.doi.org/10.1093/pan/2.1.153>
- 33 NZTA (2018). *Bridge Manual (SM061)*. New Zealand Transport Agency, Wellington, NZ <https://www.nzta.govt.nz/resources/bridge-manual/bridge-manual.html>
- 34 Standards New Zealand (2004). "NZS 1170.5:2004 Structural Design Actions Part 5: Earthquake Actions". Standards New Zealand, Wellington, NZ. <https://www.standards.govt.nz/shop/nzs-1170-52004/>
- 35 PLAXIS CONNECT Edition V20.1. Available from: <https://www.bentley.com/software/plaxis-3d/>
- 36 LPILE Version 2022.12.6. Available from: <https://www.ensoftinc.com/products/lpile/>
- 37 WALLAP Version 6. Available from: <http://www.geosolve.co.uk/wallap1.htm>
- 38 Wichtmann T and Triantafyllidis T (2009). "On the correlation of "static" and "dynamic" stiffness moduli of non-cohesive soils". *Bautechnik*, **86**(S1): 28-39. <http://dx.doi.org/10.1002/bate.200910039>