Performance and sustainability options assessment of a building with a concrete raft foundation overlying liquefiable soil

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ABSTRACT

Communication and interaction between the project structural and geotechnical engineers are critical to obtain an efficient building solution for the site, building owner and occupants. This is particularly important at concept development phase when building form and type is being assessed. This paper provides a case study of soil-structure interaction and the holistic concept development of a four-storey apartment type building and concrete raft foundation overlying potentially liquefiable soil. It examines how a lightweight structure can have benefits from a sustainability, seismic performance, and overall cost perspective. The site comprised liquefiable soils approximately 3 m below foundation level. The Structural Engineer and Geotechnical Engineer worked together to examine the seismic and sustainability performance of a robust reinforced concrete raft foundation for three potential superstructure types: timber, reinforced concrete and steel. For simplicity, this paper presents the two maximum and minimum structural types for seismic performance and sustainability, being reinforced concrete and timber. It was established that the seismic performance of a lightweight timber structure was significantly improved compared to a conventional concrete structure. As a result, the timber structure option only required a 400 mm thick concrete raft. Whereas the conventional concrete structure option required a 900 mm thick concrete raft with poor seismic performance, and potential for additional ground improvements. It was also assessed that the timber structure option had significantly less embodied carbon compared to a conventional concrete structure. A major contribution to this was the differences in the concrete raft thickness. The improvement in foundation design, improvement in seismic performance, and reduction in embodied carbon contributed to the building owner's selection of the timber structure concept and avoided the need for expensive ground improvement.

Keywords: liquefaction, soil structure interaction, concrete raft, sustainability, embodied carbon

1 INTRODUCTION

Sustainability and seismic performance are critical aspects of building design. The best opportunities to influence these two factors are at planning and concept development phases of a project. Carbon reduction and design changes have a lower potential for implementation later in the project. This is aligned with the MacLeamy concept.

The development described in this paper comprises several stages of apartment type buildings to be constructed in Mt Maunganui. To determine a suitable building material type for the overall development, a structural and geotechnical concept assessment of a typical four storey structure (20 m by 50 m footprint) was carried out. In this paper we look at two key issues of seismic performance and sustainability and how the geotechnical conditions, structural loads and sustainability benefits link together to inform the building owner of a suitable option to proceed with. This case study also shows the significant benefit a concept assessment can have to the overall efficiency of the building design and allows the building owner to make an informed decision about the best option to proceed with.

The ground model, based on a typical cone penetration test (CPT) from the site, is summarised in Figure 1. A simplified liquefaction and cyclic softening triggering assessment was completed using Boulanger & Idriss (2007, 2014). The liquefaction and cyclic softening factor of safety is shown in Figure 1 based on the triggering assessment for an ultimate limit state (ULS) earthquake (500 year return period, PGA=0.3g, M=5.9). Liquefaction and cyclic softening were not triggered for a serviceability limit state (SLS) earthquake (25 year return period, PGA=0.065g, M=5.9).

The generalised ground profile comprised a loose to medium dense SAND of variable density to 14 m depth overlying a firm SILT layer to 18 m depth, overlying a silty SAND to 19.5 m depth, overlying SILT to 21 m depth, overlying a medium dense SAND which becomes very dense at 25 m depth. Groundwater was encountered at around 2.5 m to 3 m below the proposed foundation level based on 16 CPTs and 3 boreholes across the site.

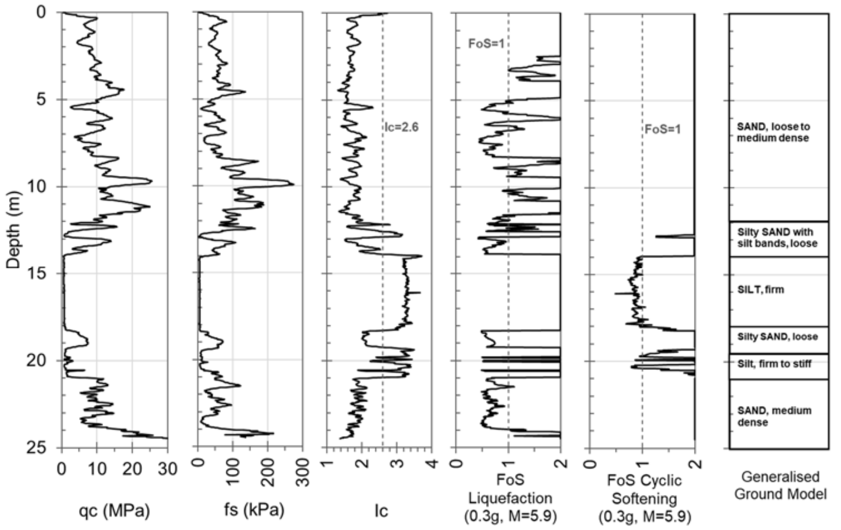

Figure 1: Summary of ground model based on typical CPT trace (CPT102)

The CPTs showed the upper sands have some level of variability in density spatially across the site and therefore there was some variation in each CPT as to the depths which were triggering liquefaction at ULS shaking intensity. However, the triggering assessment typically showed the following layers to liquefy at different earthquake intensities:

- 3 to 4 m at 500 year earthquake intensity (PGA = 0.3g, M=5.9)
- 4 to 6 m at 1,000 year earthquake intensity (PGA = 0.39g, M=5.9)
- 6 to 8 m and 12 to 14 m at 250 year earthquake intensity (PGA = 0.22g, M=5.9)

The lower firm silt layer (14 to 18 m) was also determined to trigger cyclic softening at approximately 250 year earthquake intensity (PGA = 0.22g, M=5.9). Figure 2 below also shows the development of liquefaction within different layers for three typical CPT based on shaking intensity (PGA). It shows that the predicted liquefaction triggering for the various CPT across the site is fairly consistent.

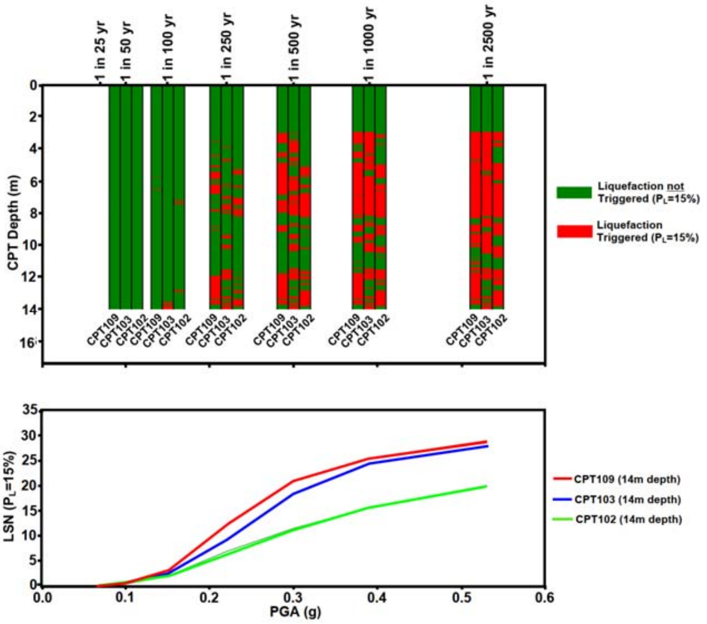

Figure 2: Liquefaction triggering plot and liquefaction severity number (LSN) based on Peak Ground Acceleration (PGA) and return period for a Mw 5.9 earthquake.

2 INITIAL OPTIONS EVALUATION

Based on review of the ground conditions at the site, liquefaction in the upper sand layer (3 to 14 m depth) was deemed the critical geotechnical issue for the site. Given the crust thickness was only 3 m and the building loads were likely to be high for a four-storey structure, conventional shallow strip foundations were considered to have unsatisfactory performance in a large earthquake resulting in excessively large settlements and potential bearing failure. Therefore, two main options were considered:

1. Conventional heavy concrete structure with a concrete raft foundation. If a concrete raft showed unsatisfactory performance, ground improvement or screw piles to the dense sand layer at 25 m depth would be necessary. Driven piles were ruled out due to noise and vibration concerns to neighbours.
2. Lightweight timber structure (cross-laminated timber, “CLT”) with a concrete raft foundation.

The option for the structure was closely linked to its mass and consequently the foundation or ground improvement option as a single system, so it was important at concept stage for the Structural Engineer and Geotechnical Engineer to collaborate closely to achieve an outcome that suited the site conditions and project objectives.

3 GEOTECHNICAL SEISMIC PERFORMANCE EVALUATION

3.1 Analysis methodology and determination of soil springs

The seismic performance of foundations for the two structural options (concrete and timber) were evaluated using an iterative soil structure interaction approach as summarised below:

- The Geotechnical Engineer provided preliminary soil spring stiffnesses (“soil springs”) to the Structural Engineer.
- Bearing pressure distributions were obtained by the Structural Engineer using ETABS software and provided to the Geotechnical Engineer.
- The Geotechnical Engineer assessed settlement and stability of the raft by inputting the bearing pressures into the Plaxis 2D soil model. Soil springs were then calculated from the Plaxis model results, updated and provided to the Structural Engineer.
- The Structural Engineer updated the bearing pressures and the process above was repeated until convergence was established.

For this assessment, once the Structural Engineer used the second set of soil springs based on the Plaxis 2D model, the updated bearing pressures were within 5% of the original bearing pressures provided, and therefore convergence was achieved with a single iteration. Static SLS springs of 2000 kPa/m were determined and for the post ULS liquefied case an elastic-perfectly plastic spring was provided with a stiffness of 500 kPa/m and a pressure limit of around 80 kPa. The springs were quite “soft” due to the size of the concrete raft (50 m by 20 m) and the liquefaction issues at the site. The Structural Engineer completed a sensitivity analysis with springs that were half and double of those provided above and established that the pressure distribution and actions within the concrete raft had a low level of sensitivity to the soil spring stiffness.

3.2 Analysis cases

The Plaxis 2D analysis was completed using an elastoplastic constitutive soil model with Mohr Coulomb soil parameters. Three load and soil strength combinations were assessed for different purposes as summarised below:

1. SLS Static loading (working loads) with non-liquefied soil strength and stiffness parameters to understand the likely static settlement and global bearing capacity.
2. Seismic loading with liquefied and cyclic softened soil parameters to understand global bearing capacity (factor of safety (FoS)). Settlement was not assessed in this case as the liquefaction triggering is likely to occur toward the end of the earthquake and the loads provided by the structural engineer are transitory (occur for a short duration).
3. SLS Static loading with liquefied and softened soil parameters to understand settlements following the earthquake (primarily ULS and above).

Static strength and stiffness parameters were developed based on CPT correlations from Lunne, Robertson and Powell (1997). Liquefied soil strengths were determined using Idriss and Boulanger (2008). The CPT shaft friction was used to represent the residual cyclic softened strength at depth. The liquefied and cyclic softened stiffness was taken as 10% of the static (non-liquefied) stiffness.

3.3 Comparison of seismic performance

Figure 3 shows the global FoS for bearing/punching failure and post liquefaction settlement determined from Item 2 and 3 above using Plaxis 2D.

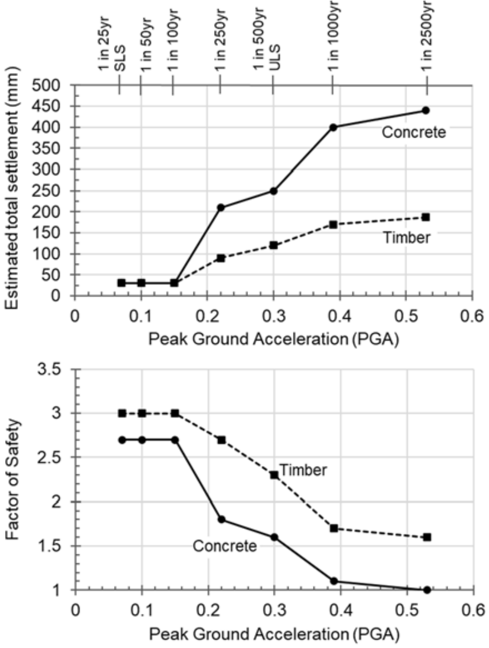

Figure 3: Estimated foundation settlement and global bearing/punching FoS at different levels of Peak Ground Acceleration (PGA) and earthquake return period. PGA is a measure of shaking intensity.

The concrete structure option shows a significant increase in total settlement, with a sharp step change at PGA of 0.15g to 0.22g (100 year to 250 year return period). This settlement continues to rise steeply at larger levels of shaking. The reduction in FoS also shows a similar sharp reduction at 0.15g, with it approaching 1 at 0.39g (1,000 year return period). Given the uncertainties relating to liquefaction and seismic shaking, the FoS near 1 means that the estimated displacement would have a high level of uncertainty. These observations show that a concrete structure with a concrete raft foundation is likely to provide poor seismic performance. The seismic performance for the concrete structure could only be improved through ground improvement or piling which would provide a stiffer response (reduced settlement) and improve the factor of safety.

The timber structure option shows a more gradual increase in total settlement and a gradual reduction in FoS with increasing PGA (shaking intensity). This indicated significantly improved performance compared to the concrete option. Ground improvement would also have provided further improvement to performance but was considered unnecessary for the timber option based on discussions between the Structural and Geotechnical Engineer. Therefore, from a seismic performance perspective the timber structure was preferred and avoided the need for ground improvement or screw piling, which would add cost, carbon emissions, time, and disruption to the project.

4 BUILDING SUSTAINABILITY COMPARISON

An embodied carbon assessment was completed by Calibre Group using the concept structural and geotechnical design information. The purpose of the assessment was to compare the structural options and identify embodied carbon “hotspots” and opportunities for reduction. Three options were assessed. However, for simplicity, only the comparison of concrete and timber are shown here.

The assessment was completed in general accordance with the MBIE document 'Whole-of life Embodied Carbon Assessment: Technical Methodology' (February 2022) using typical New Zealand-specific carbon factors for the different materials based on data published by BRANZ and specific environmental product declarations (EPDs). The carbon factors are simply multiplied by the material quantity used. Transportation carbon emissions are built into the carbon factors for each material and based on the distance from 'factory' to site. For this concept design, when this isn't known accurately, it was based on three categories of transport distance: local source (same city/town), national source, international source. The scope of this analysis covered the lifecycle stages from procurement (raw material and manufacturing) to end of construction, or modules A1-A5 in the terminology of lifecycle analysis (LCA). This is often referred to as 'up-front embodied carbon'.

Figure 4 below shows the comparison of the two options based on tonnes of embodied carbon (tCO_2e) to supply and build the structure and foundations, which can typically represent up to 60% of a building's embodied carbon. On the right side of Figure 4 the emissions are also normalised to gross internal floor area (GIA, $kgCO_2e/m^2$) using a GIA of 4,200 m^2 for comparison with other similar buildings. The concrete structure option shows the concrete raft contributes approximately 50% of the total embodied carbon. The concrete raft foundation was required to be larger (900 mm thick) due to the higher loads applied to the foundation (heavier structure). The timber structure option shows 40% less embodied carbon compared to concrete. A significant portion of this is from the reduction in concrete raft thickness to 400 mm, and the modification of building frame to timber from concrete.

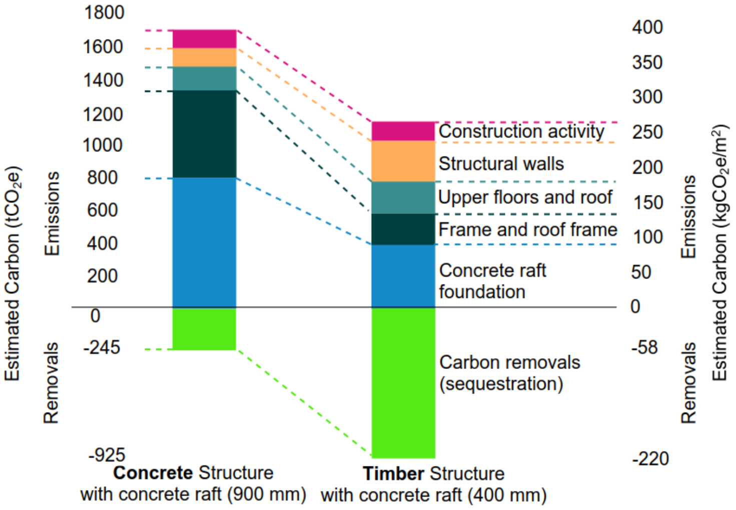

Figure 4: Estimated embodied carbon in the structure and foundations of a four-storey building (GIA=4,200 m^2) in tCO_2e and $kgCO_2e/m^2$, Modules A1-A5, Raw material to end of construction (Courtesy of Calibre, graph reproduced for visual purposes)

The timber option was estimated to contribute approximately 270 $kgCO_2e/m^2$ up to end of construction, whereas concrete was approximately 405 $kgCO_2e/m^2$. A proposed UK structural carbon benchmarking scheme (SCORS, Arnold et al. 2020) has benchmarks from A++ to G in terms of embodied carbon. This scheme would rate the concrete option as a G (high carbon intensity) and the timber option would be rated as a D (moderate carbon intensity). An A++ rating is proposed as less than 100 $kgCO_2e/m^2$. LETI (2021) has an equivalent 2020 and 2030 target of around 500 $kgCO_2e/m^2$ and 300 $kgCO_2e/m^2$ respectively, although these figures are for all building elements, not just the structure. A widely accepted carbon benchmarking scheme is yet to be established for buildings in New Zealand.

Although not included in these numbers, the timber option also has the added benefit that atmospheric carbon has been stored in the timber during the life of the tree (removals). The benefit of these removals is represented below the axis of the graph in Figure 4. The carbon emissions and removals are listed separately as there is not common agreement within the industry regarding how atmospheric carbon stored in natural materials (biogenic carbon) should be assessed in lifecycle analysis. This method allows a true comparison to be made between options, whilst still acknowledging the potential added benefit of the stored carbon in the timber.

5 CONCLUSION AND OVERALL OPTIONS EVALUATION

In conclusion, interaction between Structural and Geotechnical Engineers is critical at concept development phase to determine the most suitable building material type, foundation concept and understand the advantages and disadvantages associated with different options. This allows a more efficient building solution that is well suited to the site conditions.

For this case, Table 1 below summarises the two key considerations for the decision between a concrete and timber structure along with other considerations for this project. The main benefits were the improvement in foundation design, improvement in seismic performance, avoidance of ground improvement and reduction in embodied carbon. The builder owner also identified a programme saving with timber (approximately 1 to 2 months). These factors contributed to the building owner's selection of the timber structure option for future buildings across the site. The timber structure was therefore taken forward for development at detailed design.

Table 1: Overall options evaluation

	Concrete structure with 900 mm thick concrete raft foundation	**Timber structure with 400 mm thick concrete raft foundation**
Foundation seismic performance	Poor – Large settlements and low FoS. Additional ground improvement or piling required to improve performance.	Significantly improved – Low settlements and high FoS. Ground improvement not required.
Carbon emissions	High ~ 405 $kgCO_2/m^2$	Low ~ 270 $kgCO_2/m^2$
Other considerations for this project	Larger impact on site and neighbours during construction. High durability. Low maintenance. Effective sound proofing. Higher thermal mass.	Faster construction (reduced programme). Less impact on site and neighbours during construction (less noise, dust). Sound proofing needs to be considered (i.e. between floors/walls). Typically more offsite manufactured components which reduces site impact.

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