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Rocking foundations: geotechnical considerations

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ABSTRACT

The recent release of the draft Technical Specification TS 1170.5 (2024) includes guidance for the design of rocking foundations. Despite the potential benefits of rocking foundations in terms of reduced seismic loads transferred to the structure, the nonlinear nature of rocking foundations has made it difficult to implement in typical design practice. The simplified rocking procedure in TS 1170.5 (2024) provides a means to more easily take advantage of rocking foundations. It also creates opportunities for rocking foundations to be implemented outside of the limitations of the simplified procedure, with some additional design effort.

This paper explains the simplified rocking foundation design procedure outlined in TS 1170.5 (2024) and the limitations to adopting that procedure. The procedure is structurally focused, generally not requiring significant geotechnical input. However, this paper will explain the important geotechnical considerations that should be included in rocking foundation design through collaboration between the geotechnical and structural engineer. These geotechnical considerations include the ground profile most suited to adopting rocking foundations, implications for foundation design and building deformations, and opportunities to implement ground improvement techniques to take advantage of rocking foundation design. Geotechnical engineers have a key role to play in promoting and implementing rocking foundation design for more efficient and seismically resilient structures.

1 INTRODUCTION

The potential beneficial effects of rocking shallow foundations on seismic performance are widely understood (Gazetas, 2015). Observations after destructive earthquakes over the last century have identified tall, slender structures, such as monuments, pillars, and elevated water tanks, that have survived the strong shaking while shorter, squat structures have been destroyed. Housner (1963), in his seminal work investigating the dynamics of rocking rigid blocks, found that there was an unexpected scaling effect for taller structures that meant the dynamic stability was much greater than that inferred from static stability analysis, which could be attributed to rocking. However, due to the complexity of handling both geometric (uplift) and material (soil yielding) non-linearity, it has been difficult to implement design procedures within design codes.

The recent release of the draft Technical Specification TS 1170.5 (2024) includes guidance for the design of rocking foundations. Current provisions in NZS1170.5 acknowledge the potential energy dissipation through rocking structures but require a special study to be undertaken and it is partly the special study requirements that limit the application of rocking shallow foundations in practice. The simplified rocking procedure in TS 1170.5 (2024) provides a means to more easily take advantage of rocking foundations. The proposed simplified design procedure would mean potentially reduced foundation sizes and reduced seismic demands on the building could be implemented, provided certain limiting conditions are met and the right ground conditions are available.

This paper presents earthquake examples of where potential rocking foundations and/or nonlinear soil-structure interaction have resulted in beneficial structural performance and the geotechnical characteristics that facilitate that good performance. The simplified rocking procedure in TS 1170.5 (2024) is explained, including the role the geotechnical engineers have in that procedure, as well as the potential implementation outside of the limitations of that procedure. Lastly, the collaboration between geotechnical and structural designers is discussed as well as opportunities to implement ground improvement to take advantage of beneficial soil-structure interaction effects associated with rocking.

2 EARTHQUAKE EXAMPLES

The 1999 Izmit Earthquake in Turkey provided interesting examples where rocking and nonlinear soil-structure interaction influenced structure performance. Two mutually exclusive modes of building damage were observed in the city of Adapazarı – the first being strong shaking induced structural damage and the second being foundation bearing capacity failures (Bakir, et al., 2005), examples of which are shown in Figure 1. The second damage mode captured the attention of the geotechnical earthquake engineering community due to the large settlements, permanent tilting, and complete overturning of buildings that had sustained limited structural damage (Gazetas et al., 2003). However, the primary cause of lives lost in the city was complete structural collapse of buildings (the first damage mode), whereas even in buildings where foundation displacements exceeded tolerable limits, the damage was such that people escaped and buildings were even habitable following the earthquake. A strong foundation designed to withstand soil deformation was concluded to be required as well as a practical methodology for estimating seismically induced ultimate foundation displacements.

In the 2011 Christchurch Earthquake, the 11-storey HSBC Building, which had one level of basement on a shallow raft foundation, performed particularly well (Storie, 2016). A photo of the building is provided in Figure 2 and was taken during an August 2013 survey of buildings in the CBD not demolished after the earthquake. The building has a 9 storey steel tower on top of a 2 storey reinforced concrete podium. Measurements of scuff marks the stairs made during the earthquake and comparison of the earthquake spectra with the design spectra suggested the building behaved more than 2 times stiffer than the model used to design it (Clifton, 2013). Through centrifuge experiments and numerical modelling, it was found that rather than the building behaving stiffer, the loads transferred to the structure were significantly reduced due to nonlinear soil-structure interaction (uplift/rocking and plastic soil deformation), even though the extents of these nonlinear effects were relatively small (Storie, 2016).

Figure 1: Examples of foundation bearing capacity failures in Adapazari following the Izmit Earthquake, Turkey 1999 (Bakir, et al., 2005).

Figure 2: The HSBC Building in Christchurch following the 2011 Christchurch Earthquake.

2.1 Geotechnical characteristics of rocking performance

A stiff, competent ground profile with no susceptibility to shallow liquefaction provides the ideal geotechnical characteristics for gaining the benefits of rocking foundations. The example in the 1999 Izmit

Earthquake showed that while nonlinear soil-structure interaction likely reduced the forces transmitted into the structures and avoided structural collapse of some buildings, foundation deformations were significant and resulted in damage that would require demolition and rebuild. In comparison, the HSBC Building example in the 2011 Christchurch Earthquake was founded on stiff gravel that did not liquefy so it was able to rock and the founding soils able to deform without noticeable residual settlement of the building and so that the building could be re-occupied almost immediately after the earthquake.

Geotechnical engineers and engineering geologists can identify natural ground conditions that are most suitable for rocking and where nonlinear soil-structure interaction can be taken advantage of. Some understanding of soil and structural dynamics is useful for the geotechnical engineer and close collaboration with a structural engineer familiar with dynamics is advised. There are also opportunities with different ground improvement techniques to make most sites suitable for rocking foundations, which is discussed further in Section 3.3 and Section 4.

3 ROCKING DESIGN

3.1 TS1170.5 Simplified procedure

Millen (2023) and Millen & Hare (2024) have recently proposed updates for the New Zealand loading standard NZS 1170.5 (New Zealand Standards, 2016) to include rocking foundations for low- to mid- rise buildings, without requiring a special study. Current provisions in NZS 1170.5 acknowledge the potential energy dissipation through rocking structures but require a special study to be undertaken and it is partly the special study requirements that limit the application of rocking shallow foundations in practice.

The simplified procedure in the draft TS 1170.5 (2024) allows an unrestrained shallow foundation to resist the overturning moments from the lesser of the overstrength loads and the loads from a design ductility of 2, provided that:

- The height to the uppermost floor or heavy roof is less than 15 m;
- The ratio of the height of a lateral resisting element to the in-plane length of its foundation is less than three;
- That all foundations are unrestrained (i.e. there are no lateral restraint to lateral loading such as piles or tension tie-downs);
- The difference in elevation between the underside of the foundation is less than one storey;
- The foundation elements are symmetric or restrained against out-of-plane movement;
- Lateral load redistribution is ok provided torsional resistance is not reduced;
- When estimating displacements and drifts, a pre-rocking rotation of 0.004 rad should be added at the base of the foundation elements.

The draft TS 1170.5 (2024) stipulates, though, that rocking foundations can be implemented “where foundations and foundation elements can develop a rocking mechanism…”. Geotechnical engineers play an important role determining whether a rocking mechanism can develop without implications for building performance.

3.2 Rocking design implementation

The simplified rocking design procedure provides an easy to implement method to capture the benefits of rocking for a restricted subset of buildings. If a building meets the criteria listed above and the site is suitable to develop a rocking mechanism (refer to Section 3.3 for further discussion), then significant benefits of cost, construction programme, and sustainability outcomes from a rocking foundation design can be readily realised.

However, buildings outside the limitations of the simplified criteria can also benefit from the procedure. Current provisions in TS 1170.5 (2024) mean that a special study still needs to be undertaken for rocking design outside the limitations of the simplified procedure but the procedure provides a good starting point for that study. Millen & Storie (2024) show that the simplified design procedure and the use of displacement-based assessment are viable options to produce a proof of concept to show it is worth pursuing more detailed analysis for taller structures (refer to Section 4).

3.3 Geotechnical considerations

In practice, by adopting a rocking design and being able to reduce the size of the foundations and/or eliminate hold down anchors or deeper pile foundations, there is potentially significant benefits in terms of cost, construction programme, and sustainability outcomes. These benefits can be realised due to less materials being used and a more standard or less complex construction methodology being adopted.

However, geotechnical considerations are important for the application of rocking foundations and gaining these benefits, even though they are not specifically mentioned in the criteria for the simplified procedure. As noted in Section 2.1, stiff, competent soil or rock sites are most appropriate for gaining the benefits of building performance from rocking foundations.

Not all sites are suitable for rocking shallow foundations. Sites with soft, weak soils or shallow soils susceptible to liquefaction, could result in significant foundation displacement, particularly differential displacement and building tilt. Particularly weak or degrading soils can also be problematic in that rocking may cause substantial deformation of the soil and permanent settlement and tilt. Some sites can be improved to mitigate against these undesirable deformations (refer to Section 4). The displacement of the building associated with the foundation displacement should also be considered, particularly if the site is constrained or the building has limited ability to displace in an earthquake. For building retrofit this is particularly relevant where overall displacement capability may be the limiting factor.

Table 1 provides a summary of geotechnical considerations for rocking foundation design depending on the ground conditions at a site. The ground conditions have been divided into three categories:

- Competent ground – dense/very dense or very stiff/hard soils or rock (refer to NZGS Field Description of Soil and Rock (2005)) near the ground surface, with no shallow liquefaction or cyclic softening. Bearing capacity factor of safety might be around 10 or above under static loading
- Marginal ground – looser/softer soils and potential for shallow liquefaction and cyclic softening but a natural raft may be present and/or the potential to do ground improvement
- Adverse ground – very loose or soft/very soft, extensive liquefaction and/or cyclic softening and potential for lateral spreading/slope displacement.

From a geotechnical perspective, rocking can be considered for sites with competent or marginal ground conditions, with consideration of whether ground improvement may be necessary. Where the building is more complex and/or the ground conditions are adverse, rocking design may not be worth pursuing. However, if the project is early enough in design development then opportunities to reduce the complexity of the building and/or improve the ground conditions with ground improvement may still make a rocking foundation design feasible.

Table 1: Geotechnical considerations for rocking foundation design.

Building type	Competent ground	Marginal ground	Adverse ground
Simple, low-rise buildings (meets TS1170.5 limitations)	Recommend rocking – *simplified method*	Recommend rocking with specific ground improvements – *simplified method*	Conventional foundation design
Tall buildings	Recommend rocking – *alternative solution*	Recommend rocking with specific ground improvements – *alternative solution*	
Complex buildings	Conventional foundation design		

3.3.1 Geotechnical elements of the TS 1170.5 simplified procedure

There are a number of elements of the simplified rocking design procedure in the draft TS 1170.5 (2024) that require geotechnical input. These are summarised below:

1. Critical foundation contact area (A_c) needs to be assessed when calculating rocking moment resistance – this is the minimum area required to support the static vertical loads after reducing the soil-bearing strength by appropriate strength reduction factors (refer to Figure 3)
2. The centroid of ground resistance is allowed to exceed the eccentricity requirement from B1/VM4 (MBIE, 2024)
3. A suitably experienced geotechnical engineer is required to determine the suitable range of possible bearing capacities, which could be between 50-200% of the expected bearing capacity (i.e. that determined using best-estimate parameters)

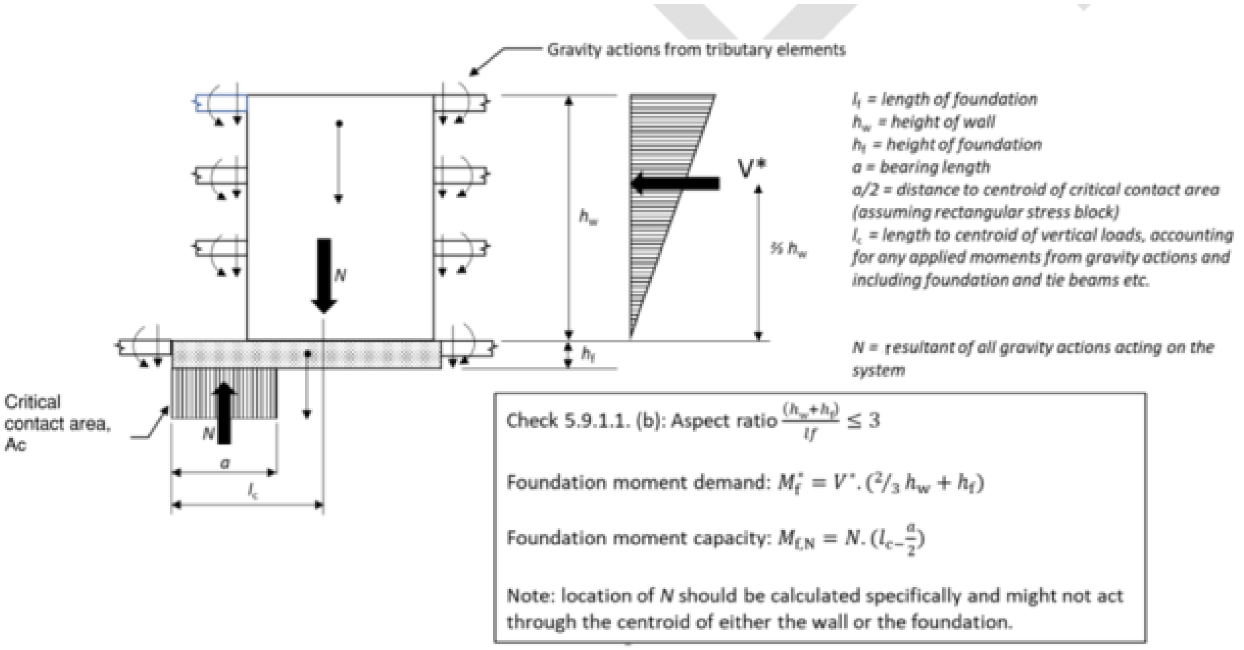

Figure 3: Calculation of rocking resistance, including critical contact area (A_c), in accordance with the draft TS 1170.5 (2024).

4. Permanent foundation deformations may need to be estimated when foundations are heavily loaded, and these can be estimated using expressions from Deng et al. (2014)
5. Sliding of the whole foundation is acceptable for ultimate limit state design, provided the building meets the rocking limitations and the foundation is well tied together, however, sliding for serviceability limit state design is explicitly not allowed.

4 GEOTECHNICAL AND STRUCTURAL COLLABORATION

Close collaboration between geotechnical and structural engineers is required to implement rocking foundations and/or allowance for nonlinear soil-structure interaction (uplift and plastic soil deformation). The simplified procedure provides a mechanism for structural engineers to more easily implement rocking foundation design, however, close input from the geotechnical engineer is advised, particularly around the suitability of the site to accommodate rocking.

Where marginal ground is present at a site, ground improvement could be considered and should be coordinated between geotechnical and structural designers. Figure 4 provides examples of ground improvement techniques that may be adopted with rocking foundations. Shallow rocking foundations can be placed on the improved site but there may be implications for the structure and the ground improvement elements that require close collaboration. Often a load transfer platform should be considered in conjunction with the ground improvement to isolate the shallow rocking response.

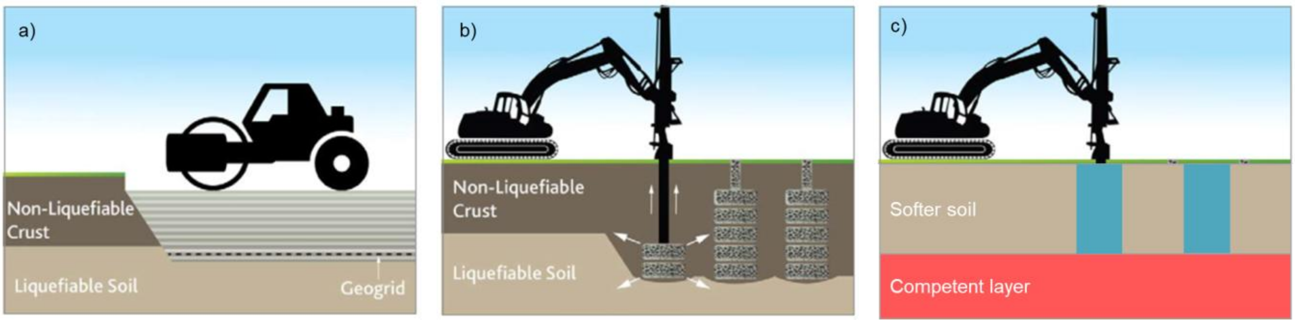

Figure 4: Examples of ground improvement options to facilitate rocking foundation design, including (a) reinforced gravel raft, (b) stone columns, (c) stiff inclusions (e.g. piles) to a competent layer (after NZGS/MBIE Module 5, 2021).

In the case of taller buildings outside the scope of the simplified procedure, the significant benefits of rocking foundations can still be realised through geotechnical and structural collaboration and an alternative design. Millen & Storie (2024) show that the simplified procedure provides a solid starting point for design and a displacement-based and/or time history-based assessment can be used to carry out the alternative solution. Geotechnical practitioners can facilitate the implementation of these assessments by providing appropriate foundation stiffness parameters, noting that a careful consideration of the range in potential foundation stiffness and capacity may be required (not just half and double as is the typical rule of thumb). Significant gains can be made through collaboration with the structural engineer on how the influence of the ground conditions is critical to the structure performance.

5 CONCLUSIONS

The potential benefits of rocking foundations in terms of reduced seismic loads transferred to the structure are well known and have been observed in historical and recent earthquakes. However, the nonlinear nature of rocking foundations has made it difficult to implement in typical design practice. A simplified rocking procedure has been developed in the draft TS 1170.5 (2024) and provides a means to more easily take advantage of rocking foundations. However, no mention of geotechnical requirements are made in the simplified procedure and this paper has provided the important geotechnical considerations for rocking foundations. The simplified procedure also creates opportunities for rocking foundation design outside of the limitations of the procedure, providing a catalyst for integrating nonlinear soil-structure interaction into regular practice.

Geotechnically, a competent ground profile provides the ideal geotechnical characteristics for gaining the benefits of rocking foundations. Sites with soft, weak soils or shallow soils susceptible to liquefaction, could result in significant foundation displacement, particularly differential displacement and building tilt if rocking is allowed for in a building design. However, ground improvement techniques can be implemented on appropriate sites to develop the ideal competent ground profile and shallow rocking foundations can be placed on the improved site, often with a load transfer platform to separate the foundation from the ground improvement. Close collaboration between the structural and geotechnical design engineers is essential for successful implementation of rocking foundations.

Geotechnical engineers should ascertain whether a site has competent, marginal, or adverse ground conditions for implementing rocking shallow foundations. Then, with the structural engineer, assess the type of building (simple low-rise, tall, or complex) and determine whether the simplified procedure available in the draft TS 1170.5 can be implemented, an alternative design can be explored, or whether standard design practices should be adopted (i.e. avoid rocking foundations). If the simplified procedure can be adopted, the geotechnical engineer should assist with bearing capacity and foundation area considerations as well as potential foundation settlement and sliding deformation. If an alternative design is pursued, the geotechnical engineer can assist with soil-foundation parameters for displacement-based or time history analysis.

In practice, by adopting a rocking design and being able to reduce the size of the foundations and/or eliminate hold down anchors or deeper pile foundations, there is potentially significant benefits in terms of cost, construction programme, and sustainability outcomes.

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