Exploring the benefits of rocking shallow foundations

M.D.L. Millen

Tonkin & Taylor Ltd, Christchurch, New Zealand.

University of Canterbury, Christchurch, New Zealand

L. B. Storie

Tonkin & Taylor Ltd, Auckland, New Zealand.

ABSTRACT

Rocking foundations can offer significant benefits in terms of seismic performance, environmental outcomes and constructability. This paper explores the use of a simplified design procedure for rocking foundations and compares the design estimates to both displacement-based assessment and nonlinear time history analysis. Several simplifying assumptions were applied to the building design and modelling in this paper to isolate the role of rocking foundations. These assumptions are explicitly stated and would need to be addressed for the application on real buildings. However, this paper presents a pathway for adoption of rocking foundations in design. The simplified procedure that has been proposed for adoption in TS1170.5 is for low- to mid- rise buildings (less than 15 m to the uppermost floor or heavy roof), as well as other specific building criteria. However, by assessing both a 3-storey and 6-storey buildings, this paper shows how the procedure could be utilised for other structures provided appropriate validation is performed and constraints are assessed. The use of rocking foundations for multi-storey apartment buildings can enable more sustainable, cheaper, and easier to construct buildings and this paper provides support that the potentially higher initial design (and review) costs associated with this can be managed and justified.

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.

Millen & Hare (2024) have recently proposed updates for the New Zealand loading standard NZS1170.5 (New Zealand Standards, 2016b) to include rocking foundations for low- to mid- rise buildings, without requiring a special study. 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 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 (refer to Section **Error! Reference source not found.**)

Due to the height limit in the conditions, the proposed simplified procedure cannot be applied to a significant proportion of simple buildings, particularly apartment buildings that may benefit from rocking shallow foundations. Recent research (e.g. Loli et al. (2014), Storie (2017)) has demonstrated the beneficial rocking effects in the laboratory, which has allowed several displacement-based procedures to be developed to directly quantify these effects (e.g. Deng et al. (2014), Millen et al., (2020), Paolucci et al. (2013)). Furthermore, developments in numerical modelling allow designs to be validated with nonlinear time history analysis (NLTHA) using Winkler spring bed models (e.g. Harden & Hutchinson (2009)). This paper explores options for adopting the proposed simplified rocking foundation procedure and validating it using both displacement-based assessment and NLTHA. The paper applies these methods to both a 3-storey building (within the height limit from (Millen & Hare (2024)) and 6-storey building (exceeding the height limit).

The motivation behind analysing 3- and 6-storey buildings is the recent market interest in mid-rise apartment structures (approximately 3 to 6 storeys) and a drive for densification, particularly in Auckland. These structures often require much more substantial pile foundations or anchor systems to prevent uplift and keep the structural design approach within the bounds of simplified approaches. This has two adverse effects, first that the building is locked into the ground therefore maximising seismic energy entering the building. Secondly, the more extensive foundations can increase costs and materials for the building and can lead to projects becoming unfeasible. A rocking foundation option for these mid-rise buildings could improve seismic performance, remove the need for piles or anchors, significantly reduce shallow foundation sizes, and consequently reduce the embodied carbon in these buildings.

2 PROCEDURE

To demonstrate the credibility of rocking foundations for mid-rise structures, a 3-storey and 6-storey building have been designed to allow rocking. The buildings are artificially simplistic (see Figure 1) to demonstrate the key features of rocking, where the walls are assumed to be the only lateral resisting system. The walls are also assumed to remain elastic and the only nonlinear mechanism is rocking at the foundation level. The following sections outline the building inputs, the design process, the displacement-based assessment (DBA) process and NLTHA.

2.1 Building inputs

Building floor loads (seismic case) of 8 kPa were set assuming Z=0.4, site subsoil class=C, R=1, N=1 in accordance with NZS1170 (New Zealand Standards, 2016a). The soil was assumed to be a sandy dry soil and had a unfactored ultimate bearing capacity of 700 kPa, initial shear modulus of 25 MPa and Poisson's ratio of 0.2. Several simplifications were adopted in the development of the building, consistent with Millen & Hare (2024). Particularly that the building stiffness was set to match the initial period, T_1, where $T_1 = 0.0625h_n^{0.75}$ from NZS1170.5 (New Zealand Standards, 2016b), where h_n is the height from the base of the structure to the upper most seismic weight.

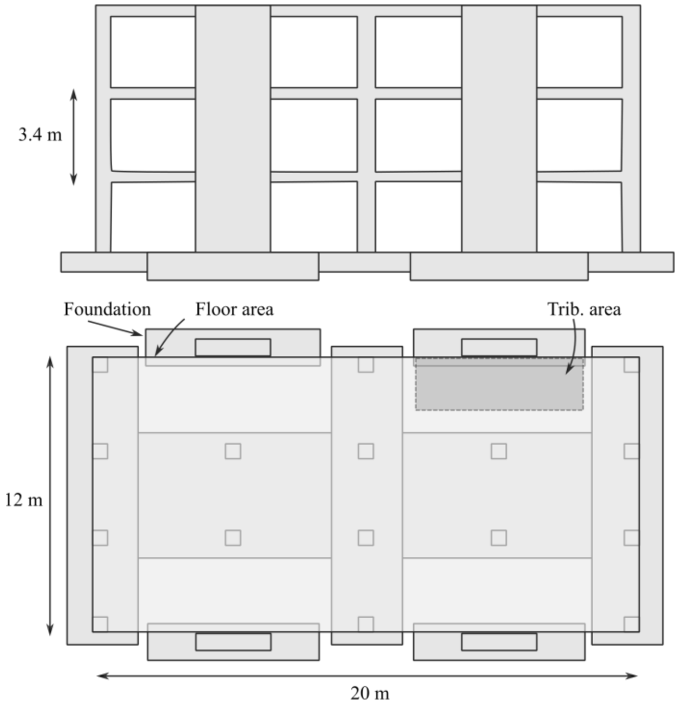

Figure 1 Case study 3-storey conceptual building

2.2 Simplified design procedure

The proposed simplified design procedure presented in Millen (2023) and Millen & Hare (2024) has been followed, except the height limit is exceeded for the 6-storey building. The design 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,
- The difference in elevation between the underside of the foundations 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 foundations for walls of the 3- and 6- storey buildings (assuming no contribution from tie-beams), would be 10.5 m and 11.8 m respectively, compared to 13.8 m and 16.2 m if nominally ductile loads were used. While these foundations are large, the design is for a high seismicity environment (Z=0.4). Potentially the foundation could be further reduced by increasing the design ductility provided there is sufficient validation. Note also that nominally ductile design would also develop the full foundation moment capacity, and according to NZS1170 (New Zealand Standards, 2002) the foundation displacements should be considered to ensure the intended mechanism develops.

2.3 Displacement-based assessment process

The assessment process is identical to that adopted in Millen & Hare (2024), as illustrated in Figure 2. The estimates of settlement and residual rotation (tilt) were obtained using both Deng et al. (2014) and Millen et al. (2020).

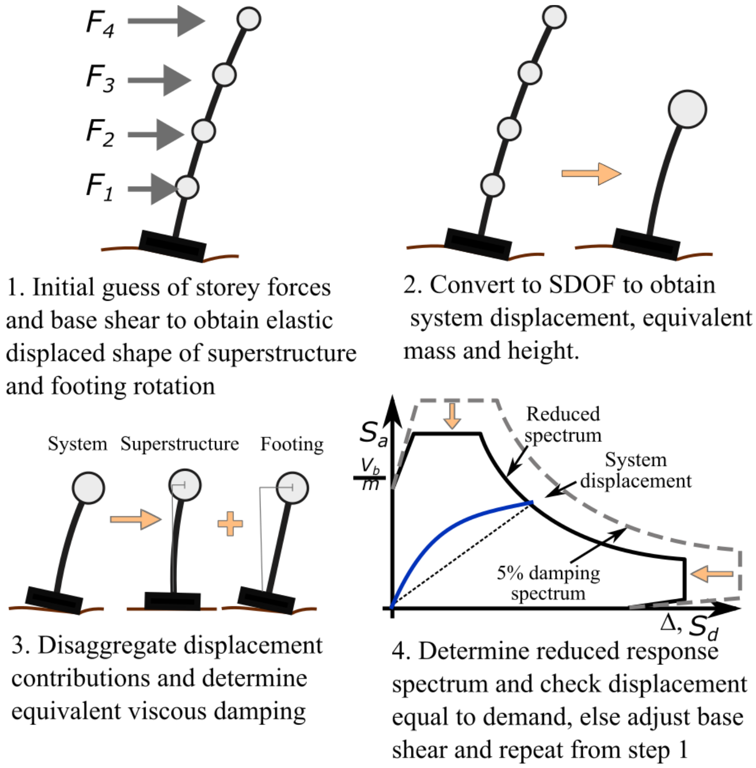

Figure 2 Key steps in displacement-based assessment procedure

The assessment procedure is a simplification of the procedures by MBIE(2017); Oliver (2023) and Sullivan, (2020) with the foundation rotation and rotational equivalent viscous damping computed using Millen et al.(2020). The following simplifications were made to the building models:

- Wall stiffness consistent with the design value,
- Nonlinearity in the wall or any lateral resistance contribution from the frame not considered,
- No torsional effects or foundation sliding were considered,
- Frame assumed to have adequate displacement capacity,
- Buildings were assessed at 100% NBS to evaluate displacements.

2.4 Time history based assessment

The time history-based assessment adopted consistent assumptions to the simplified design procedure and DBA, in that the wall stiffness was the same as the initial design stiffness, the wall remained elastic and the frame deformation was not considered. The following modelling features were adopted:

- The model was developed in OpenSeesPy with the wrapper package o3seespy
- The foundation was modelled using the beam on non-linear Winkler model for sand-type soil (Harden & Hutchinson, 2009). The damping was modelled directly with dashpots in the vertical and rotation degrees-of-freedom based on values from (Gazetas, 1991)

- Only a single wall was modelled, with shaking in one direction and no P-delta or torsional effects considered
- The wall was modelled with elastic beam elements and the storey masses were lumped at the storey nodes
- The ground motion set from (Millen et al., 2020), consisting of 40 ground motions scaled to Z=0.4 were used as input motions (refer to Figure 3), the spectrum adjustment for torsional effects from (New Zealand Standards, 2016a) was not considered
- The buildings were analysed both fixed base and with the Winkler foundation model to quantify the influence of foundation movement
- No variation in soil properties was considered, and the foundation was fixed against sliding
- Modal damping was used with 5% damping across all modes.

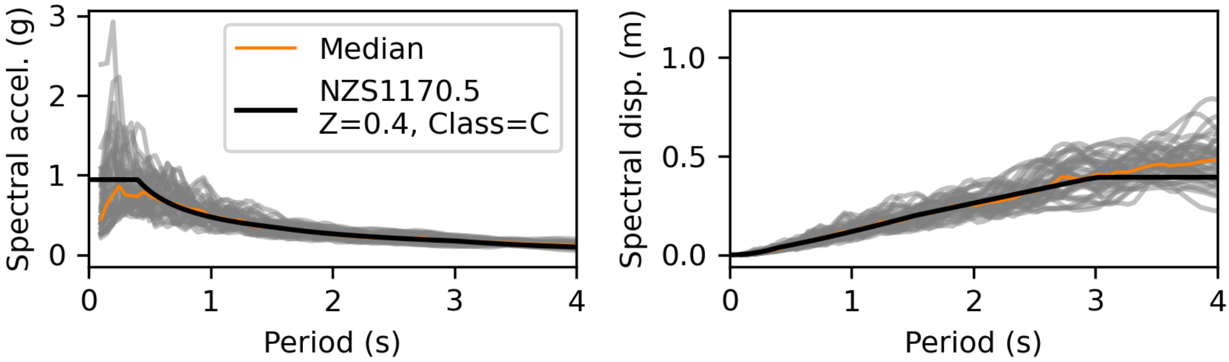

Figure 3 Scaled ground motions used for analysis

3 RESULTS

The results from the simplified design procedure, DBA and NLTHA fixed based and with the Winkler foundation model are presented in Figure 4 and Figure 5, for the 3-storey and 6-storey buildings respectively. The shear and moment demand up the building have not been addressed here.

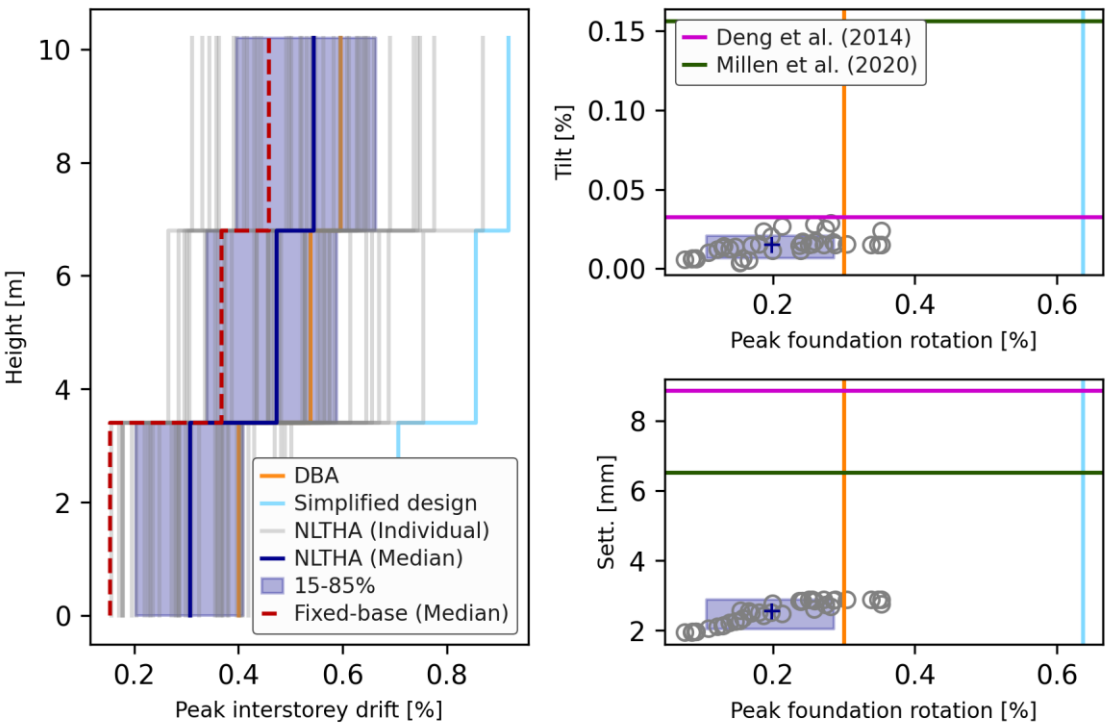

Figure 4 Key results from 3-storey building

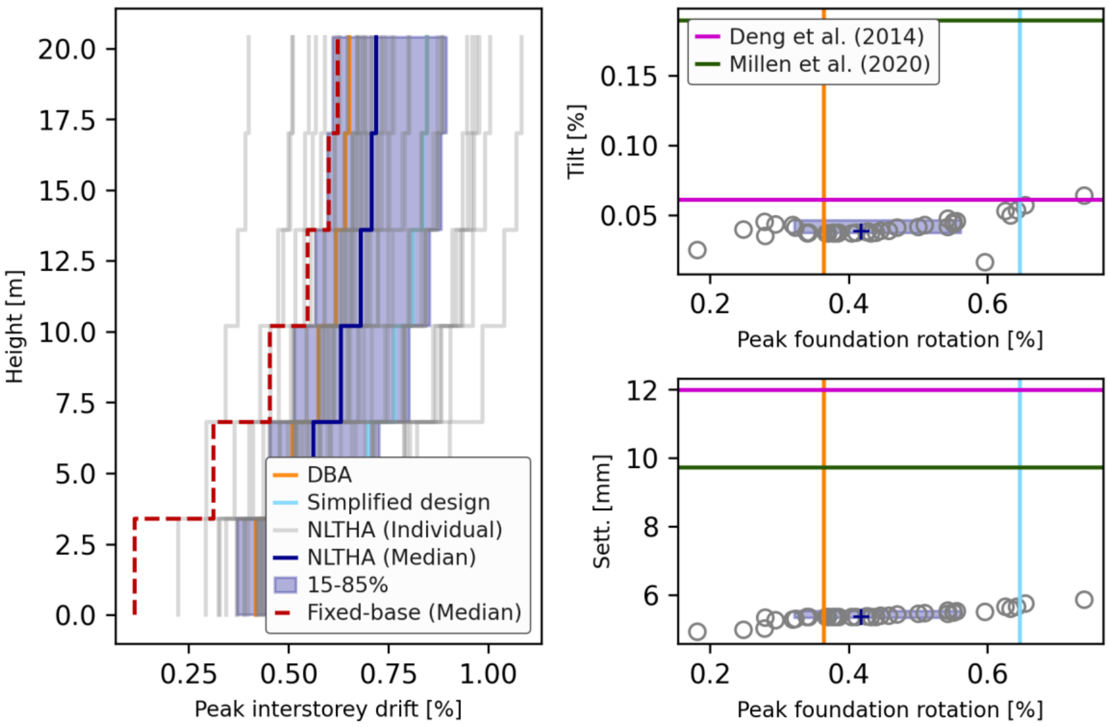

Figure 5 Key results from 6-storey building

4 DISCUSSION

From Figure 4Figure 5 it can be seen that the simplified design procedure has higher drifts than both DBA and the median of NLTHA, for both buildings. The higher design drifts are discussed in (Millen & Hare, 2024) and are linked to the implicit conservatism in the equivalent static procedure, in that the entire seismic weight is considered to contribute. While some of this conservatism is reduced when adopting a k_d less than one to reduce displacements, the commentary of NZS1170.5 (New Zealand Standards, 2016b) states that the k_d factors are intended to remain on the conservative side compared to the modal response spectrum method.

The match in interstorey drifts between DBA and NLTHA is quite remarkable given the original foundation deformation equations are based on a macro-element compared to the Winkler model adopted here. Interestingly, the interstorey drifts near the top of the building are similar to the fixed-base analysis, except for the first storey. The rocking mode contributes more drift to the first storey compared to the 'beam flexure' deformed shaped of the wall in the fixed base analysis.

The foundation deformations in terms of peak rotation from NLTHA were fairly similar to the DBA estimate and smaller than the simplified design estimates. The residual rotation and settlement were both considerably lower than the simplified estimates from DBA. This may be due to a limitation of the Winkler spring model or some conservatism in the simplified estimates. Importantly, the simplified procedure seems to provide a conservative estimate of foundation rotation for the taller 6-storey building, capturing the larger displacements in the suite of NLTHA.

Of note is that both the 3-storey and 6-storey building have similar levels of interstorey drift in both the design and assessment, which is encouraging in terms of applying the simplified procedure to taller buildings.

5 CONSIDERATIONS FOR DESIGN

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, it may be difficult at the design stage to highlight these benefits due to the additional design effort required.

This paper has explored the adoption of a simplified approach to foundation rocking and provided initial validation on a simplistic building using both DBA and NLTHA. In practice, validation using NLTHA requires specialist skills, takes extra design time, and requires specialist peer review. However, this should be balanced against the potential benefits discussed above and communicated to the client. Furthermore, the application of the simplified design procedure and the use of DBA are viable options to produce a proof of concept to show it is worth pursuing more detailed analysis.

It should be noted that not all sites are suitable for rocking shallow foundations. Sites with soft soils or shallow soils susceptible to liquefaction, could result in significant foundation displacement, particularly differential displacement and building tilt. Some sites can be improved to mitigate against these undesirable deformations. 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 capacity may be the limiting factor.

6 CONCLUSIONS

This paper explores the use of a simplified design procedure for rocking foundations. The design values are compared against both displacement-based assessment (DBA) and nonlinear time history analysis (NLTHA). The simplified design procedure was applied to two simplistic wall buildings (3-storey and 6-storey) where the walls were assumed to remain elastic. The simplified design produced reasonable design drift values for both buildings which were higher than the values obtained from both DBA and median response of NLTHA. The NLTHA also showed only a moderate increase in interstorey drift when comparing fixed base analysis to a model that captured foundation deformation with a nonlinear Winkler beam model, particularly in the first storey. The benefits of rocking design were explored in the context of practicalities of design, including reduced cost, reduced construction programme, and positive sustainability outcomes. A number of simplifying assumptions were applied to isolate the role of rocking foundations which would need to be addressed for the application on real buildings.

7 ACKNOWLEDGEMENTS

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