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An Assessment of Foundation Rocking Behaviour based on Field Observations

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ABSTRACT

Controlled foundation rocking can be considered a satisfactory response to dynamic loading, as it can reduce the stress induced in the super structure, and it can reduce the required foundation size. This paper presents the results of a geotechnical assessment into the rocking behaviour of shallow foundations of a flying fox. The foundations of the flying fox were showing considerable rocking behaviour due to the dynamic loading effect when in use. This rocking behaviour was observed in the field, and the geotechnical aspects modelled using the methods set out by Pender et al. (2014). The results are then related to a more significant structure; a 550 tonne silo store. If rocking of this foundation had been allowed, then considerable material savings in the foundation construction could have been made.

Keywords: Shallow, foundation, rocking, flying fox.

1 INTRODUCTION

Shallow foundations designed in accordance with the New Zealand Building Code (NZBC) (DBH, 2011) are designed so there is no contact pressure lost between the underside of the foundation and the subgrade under an applied moment. Typically, such applied moments arise from lateral loads (usually wind and seismic) applied to the superstructure at some height above the foundation. To ensure contact between the foundation and subgrade is not lost, these foundations are designed so the following inequality is met:

$$e \leq \frac{\mathrm{B}}{6} \tag{1}$$

Where *e* is the applied eccentricity, or point of application of the resultant force on the underside of the foundation. This eccentricity is defined as the ratio of the moment to vertical force applied to the foundation. *B* is the foundation dimension perpendicular to the axis of which the moment is applied about. Should the applied eccentricity increase beyond this equality, then contact pressure will be lost on one side of the foundation, and uplift of the foundation will occur at this side. Rocking foundations are foundations in which this contact is allowed to be lost. Under a reversing lateral load (i.e. seismic), contact is lost on one side of the foundation, re-made, and then subsequently lost on the other side of the foundation as the load reverses. Thus the foundation displays rocking behaviour.

Foundations which are designed to rock have a distinct number of advantages over traditional foundation design (Gazetas, 2015). Principal among these is the forces and stresses which are applied to the superstructure are limited by the maximum overturning moment which can be applied to the foundation. Thus the structure needs only designing for these forces (Priestley et al. 1978). This limiting force mechanism means there is less chance of damage occurring in the superstructure columns during high lateral loading. The required foundation size can also be reduced, as the inequality shown in Equation 1 no longer needs to be met. This means that construction costs and constructability issues may be greatly reduced.

The benefits of rocking foundations have long been identified in the New Zealand. An investigation into the seismic response of structures on rocking foundations was undertaken by Priestley et al. (1978), who developed a simple method for predicting the maximum displacement of a rocking foundation, and undertook shake-table testing to validate the theory. Taylor and Williams (1979) presented a procedure for the design of rocking foundations in New Zealand. More recently, the work by Pender et al. (2013) to better model soil structure interaction and rocking behaviour and Storie et al. (2014) who studied the response of structures founded on shallow foundations has added to the state of the art and practice in New Zealand. Further afield, a comprehensive analysis of rocking foundations has been presented recently by Gazetas (2015).

The inspiration for this paper arose from the foundation design of two unique structures which the author was concurrently undertaking; one a flying fox located in a children's playground, the other a large silo store. Diagrams of these structures are presented in Figure 1. The two structures have similar engineering characteristics. Both consist of a centre of gravity situated at a centralised location above a square, shallow foundation. The foundation of the flying fox showed considerable rocking behaviour when in use. It was the author's brief to design a strengthening solution for the foundation to limit this rocking behaviour. The silo foundation was a new build and designed in accordance with the NZBC, so that no foundation soil contact would be lost during lateral loading of the silo.

This paper focuses on simple concepts related to foundation design and foundation rocking behaviour related to the design of the flying fox and silo foundations. The intent of this paper is not to provide a new design philosophy, theory or procedure related to rocking foundations. It is acknowledged that rocking foundations have been extensively researched both in New Zealand and overseas (Gazetas, 2015, Pender et al. 2013, Priestley et al. 1978, Storie et al. 2014 and Taylor and Williams, 1979). This case study was undertaken out of interests' sake of the benefits of rocking foundations.

2 DESCRIPTION OF THE TWO STRUCTURES

The flying fox consists of a 25m long wire cable strung between two glulam timber columns. These columns are fixed to shallow foundations via a steel bracket and bolted base plate. The shallow foundations had dimensions of 1m square by 500mm deep. The wire cable is fixed to the timber columns approximately 3.8m above ground level.

The flying fox had been in use over a period of months, and worked adequately when smaller children were using it. However, when larger children (and adults) were using the flying fox, the foundations at each end showed considerable rocking behaviour. The edge of the flying fox was observed to move approximately 40mm (a rotation of approximately 5 degrees) when in use by larger children. The flying fox was a proprietary product and thus no specific engineering design was undertaken for the design of the foundation.

A cone penetrometer test (CPT) and a hand auger (HA) were undertaken to define the underlying ground conditions. The structure was constructed on a very soft Hinuera Formation organic silt layer. This organic silt was tested to have an undrained shear strength of approximately 25 kPa. This layer extended to a depth of approximately 8m; well below the zone of influence of the foundation. Underlying this material was alluvial dense sand of the Hinuera Formation. The groundwater table was measured at a depth of approximately 1m below ground surface.

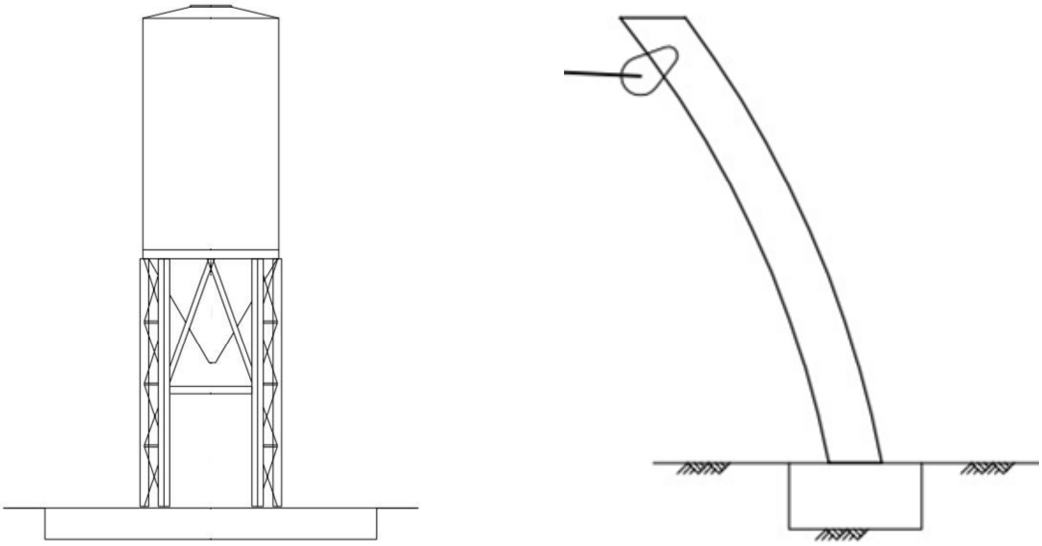

(a) (b)

Figure 1. The two structures analysed in this case study – (a) a silo store; and (b) a flying fox stand.

The second structure was a large silo store. The silo consists of a steel tank supported on steel columns which were bolted onto a shallow foundation. The tank of the silo is elevated to allow trucks to fit underneath the silo for loading purposes. The silo has a design weight of 550 tonnes. This elevation and large mass means that when full, the silo has a centre of gravity located approximately 18m above ground level. It was the author's brief to design a shallow foundation that meets the NZBC. Two CPTs and two machine drillholes (DHs) were undertaken to assess the ground conditions at the silo site. Ground conditions at the silo consisted of a firm clay, which extended to a depth of approximately 8m below ground level. This clay is part of the Taumatamaire Formation, and consists of extremely weak clasts of mudstone supported in a clay matrix. This unit overlays moderately weathered mudstone of the Taumatamaire formation. The clay was measured to have an undrained shear strength of approximately 35 to 50kPa.

3 ANALYSIS OF THE FLYING FOX

The author was briefed to re-design the foundations of the flying fox so that they would not rock when in use. To do this, the foundation was enlarged to meet the requirements of the NZBC. The foundation was increased in size to 3m by 1.5m. The embedment remained the same (500mm). This increase in foundation size proved to prevent the foundation from showing any signs of rocking when in use. However, the steel base plates showed signs of overstressing (cracking and fracturing) after the foundations had been strengthened (albeit at opposite ends of the flying fox). These steel base plates thus had to be also strengthened by thickening the steel plates (Figure 2).

Figure 2. The steel base plates required thickening following the strengthening of the foundation (at alternative ends of the flying fox). The large weld on the base plate is the results of this thickening.

This example explicitly shows the benefits of a rocking foundation. Prior to the enlargement of the foundation, the moment transferred through the baseplate by the cable forces was limited by the overturning moment capacity of the foundation. When subsequently enlarged, the overturning moment capacity of the foundation was increased, and thus the stresses induced in the baseplate became larger. This eventually caused overstressing and damage to the base plate.

This rocking behaviour has been analysed using the methodology as set out by Pender et al. (2013). The vertical force, horizontal force and moment applied to the underside of the foundation at the destination end as a passenger moves along the flying fox are presented in Figure 3. These forces were derived using simplified assumptions regarding the cable behaviour. Typically this graph could be reversed if plotted for the origin end foundation of the flying fox; however in this case study the origin end foundation and destination end foundation were different sizes. As observed, the horizontal moment applied to the foundation is reasonably consistent throughout the journey, only decreasing as the passenger reaches the very end of the journey.

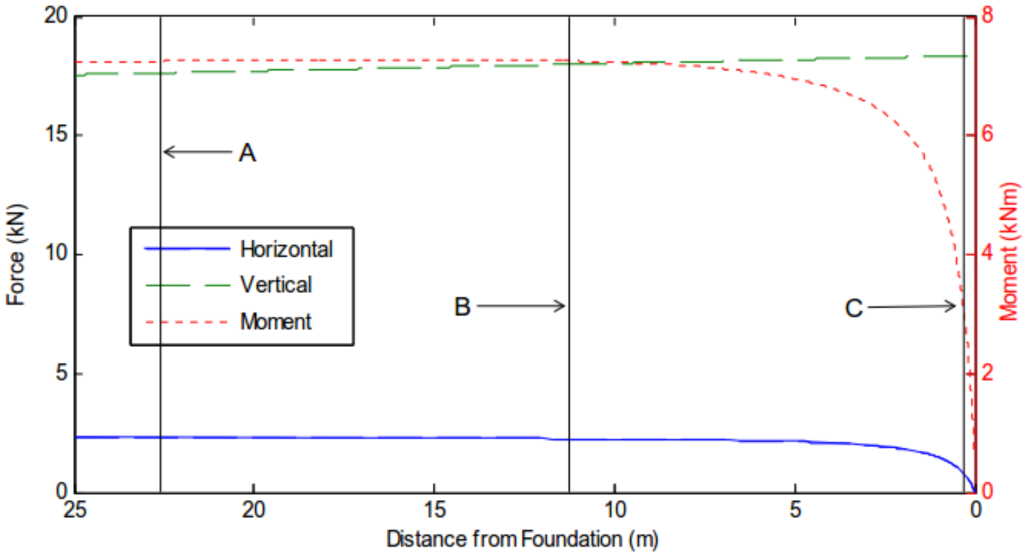
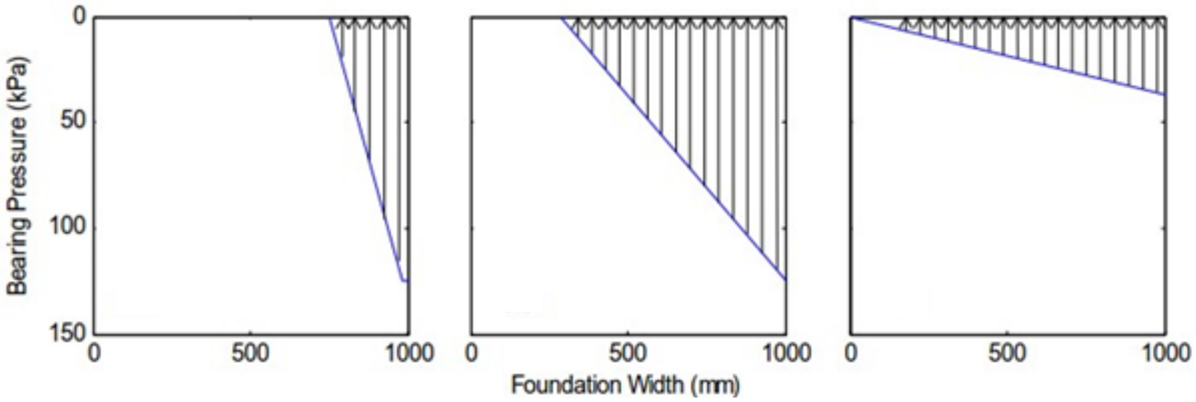


Figure 3. Forces applied to the flying fox foundation as a passenger moves towards the foundation at the destination end of the flying fox.

The applied moment is a function of this horizontal load, and thus follows a similar path. The vertical load increases linearly along the journey. This is the total load acting on the foundation, including foundation weight. The self-weight of the foundation and glulam timber column dominates the vertical foundation load. This structure is unique in that it is self-regulating with respect to overturning. As the applied horizontal load causes rotation of the foundation, the tension in the cable reduces due to rotation of the timber column. This reduces the horizontal load (the load acts more vertically) and thus the moment load applied to the foundation. At the start of the journey, the moment applied to the foundation at the destination end is largest while the vertical load is smallest, thus the eccentricity is at its largest. As the passenger moves towards the foundation, and the moment reduces while vertical load increases, the applied eccentricity decreases. Thus as a passenger gets closer to the destination end foundation, the foundation can withstand more moment capacity before the inequality requirement shown in Equation 1 is not met. The effect of this on the foundation resistance is depicted in Figure 4. These graphs were produced assuming a linear soil response until a yield limit is reached, as set out by Taylor and Williams (1979).



(A) (B) (C)

Figure 4. The soil reaction as a passenger moves along the flying fox. Graphs (A), (B) and (C) corresponding to the same points along the journey as depicted in Figure 3.

Near the start of the journey (point A), the soil is at its yielding point under one edge of the foundation. This is depicted by the flat line of the soil pressure curve. Uplift has occurred at the other side of the foundation. If further moment is applied, then the zone of soil yielding (the flat part of the curve) will increase. At point B, The soil is only just at its yielding point under one edge of the foundation. For a square shallow foundation, this occurs when the eccentricity applied to the foundation is as shown in Equation 2. At point A, the eccentricity of the foundation is equal to B/6 (Equation 1 is just satisfied), and thus no loss of contact has occurred at the edge of the foundation.

$$e = \frac{B}{2} - \frac{2V}{3L \cdot q_{ult}} \tag{2}$$

where B and L are the interchangeable plan dimensions of the foundation, V is the vertical load applied to the foundation, and qult is the ultimate bearing pressure of the soil. The foundation behaviour of the flying fox can be further expanded using the method set out by Pender et al. (2013). The moment – rotation relationship of the foundation obtained using this method is shown in Figure 5. Points (A), (B) and C shown on Figure 5 correspond to points (A), (B) and (C) in Figures 3 and 4. As observed, point (C), where no uplift has occurred, is located near the end of the initial linear part of the curve. Point (A) is located at the vertex of the curve. After this point, any extra moment applied to the foundation results in foundation rotation. Point (B) is located in between the two. The rotation of the foundation at point C is approximately 4 degrees, which agrees generally well with site observations. To stop the rocking behaviour of the foundation, the foundation was enlarged considerably. This results in a new moment – rotation relationship as depicted by the solid line in Figure 5. As observed, point (C) on the new foundation is now located on the linear part of the curve. Thus more moment can be applied to the foundation before rocking behaviour initiates, and thus more stress is induced in the superstructure under lateral loading.

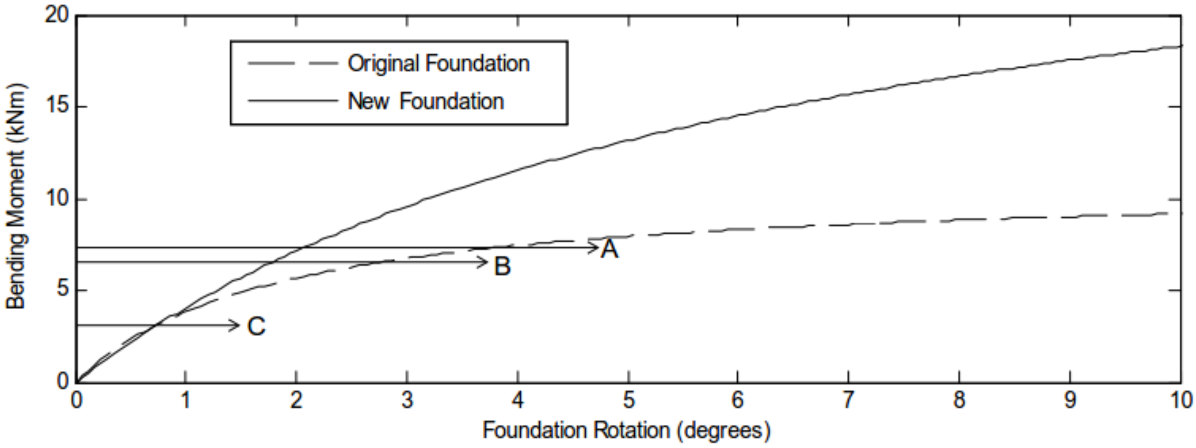


Figure 5. Moment – Rotation curve for the foundation of the flying fox.

4 IMPLICATIONS FOR THE SILO DESIGN

Due to the large mass, height of the centre of gravity and geographical location of the silo, the design moment and eccentricity acting on the foundation under ultimate limit state (ULS) earthquake loadings was large. This governed design of the foundation. The shallow foundation was designed in accordance with the NZBC. To meet static loading requirements, the foundation size was in the order of 12m x 12m by 1m deep. However, to satisfy Equation 1 during seismic events, the foundation was enlarged to 14m by 14m by 1.5m deep.

The moment-rotation curve obtained using the method described by Pender et al. (2013) for the 12m x 12m foundation is presented in Figure 6. The NZ Transport Agency (2013) defined serviceability limit state (SLS; 0.07g) and ULS (0.27g) earthquake induced moment are plotted on the curve. As observed, the SLS moment is located on the linear portion of the curve, implying that uplift of the foundation is unlikely during SLS events. The ULS induced moment plots below the vertex of the curve, which indicates that excessive foundation displacement wouldn't occur during ULS events. The estimated foundation rotation under ULS loading is in the order of 6 degrees. This is a crude estimation as it ignores the response spectra of the structure. Such rotation would not result in overturning of the structure, as the centre of mass is still located inside the foundation footprint; however it is noted that this amount of tilt is beyond reliable analysis. The soil pressure underneath the foundation (insert in Figure 6) indicates the soil pressure has not yet reached its ultimate bearing pressure underneath one side of the foundation (i.e. the eccentricity has not yet reached the limiting value as set out in equation 2). This indicates by allowing some rocking behaviour in the foundation, the amount of concrete required for the foundation would have halved. It is likely that additional savings could have been made in the superstructure if the limiting forces in the superstructure due to the foundation rocking behaviour were analysed and accounted for.

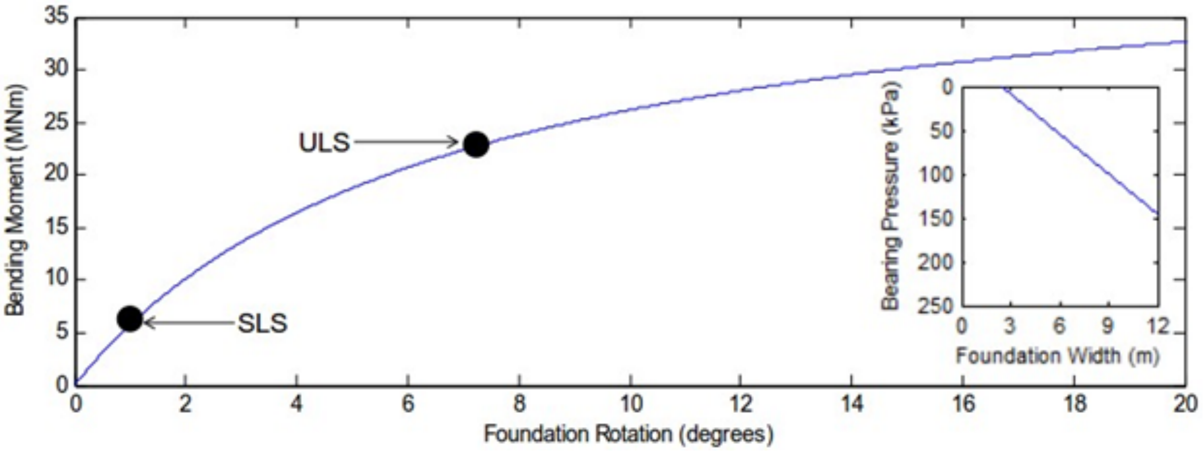


Figure 6. Moment – rotation curve for the silo foundation which satisfies static bearing capacity. The insert shows the bearing pressure reaction underneath the silo foundation under ULS seismic loading.

5 LIMITATIONS OF ROCKING FOUNDATIONS

Rocking foundations have limitations which should be factored in to the consideration of their use. Primarily, they will reduce the factor of safety against bearing capacity during static conditions, simply because of the smaller foundation size employed in rocking foundations. Also, careful analysis of the soil behaviour as it approaches its yield limit is required; strain softening behaviour may be induced and loose sand filling the void made as contact is lost can cause the foundation to 'walk out of the ground'. Also, the relationship between foundation shape and loading direction needs to be considered. Unless the foundation is circular, it will behaviour differently when loaded in different directions (orthogonal and diagonal).

6 CONCLUSION

The benefits of rocking foundations are presented here using two structures of which the author was involved in the foundation design of as examples. The first structure, a flying fox, initially displayed rocking behaviour when in use. When the foundation was subsequently enlarged to prevent this rocking behaviour, additional stresses were induced in the columns of the structure which potentially caused the base plate to fracture. The moment-rotation curve for the foundation, obtained using the method set out by Pender et al. (2013), matched well with field observations made of the flying fox. The second structure was a large silo store. The foundation for the silo was designed so that no loss of contact pressure of the foundation and the subgrade would occur during ULS seismic events. If the foundation was designed to static bearing capacity only, then the moment induced by SLS and ULS events would have been unlikely to lead to excessive foundation displacement. Thus by allowing the foundation to rock, significant material savings could have been made in the foundation construction.

7 ACKNOWLEDGEMENTS

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