The Use of Equivalent Circular Piles to Model the Behaviour of Rectangular Barrette Foundations

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ABSTRACT: Barrettes having rectangular cross-sections can be analysed using finite elements, but this requires a three-dimensional non-linear computation which can be time consuming. Therefore, in this paper, the use of simple means of analysis based on conventional piles of circular cross-section is examined. Equivalent dimensions are chosen for the circular piles to represent the barrette, and the behaviour of the equivalent piles is compared to finite element results for the barrettes. It is shown that for single barrettes and groups of barrettes under either vertical or lateral load, it is possible to model barrette behaviour approximately but adequately using equivalent circular piles.

KEYWORDS: Barrettes, Equivalent pile, Finite element analysis, Pile groups, Vertical load, Lateral load

1. INTRODUCTION

Barrettes (sometimes called LBEs or Load Bearing Elements) are large rectangular piles that are constructed either by use of a clamshell or a hydrofraise (a device with rotating cutter heads). The excavation for a barrette is performed under bentonite or a polymer that keeps the hole open as for a conventional drilled pile. Once the barrette is excavated and the bentonite de-sanded, a steel cage is lowered into the hole and then concrete is tremied into the base of the hole, displacing the bentonite.

Barrettes can be constructed in L, T, H or cruciform shapes in plan if so desired by cutting the rectangular hole several times to form the shape. The advantage of barrettes is that they can support large loads and can resist larger lateral loads and bending moments than a conventional circular pile having the same cross-section (Submaneewong and Teparaksa 2009).

An example of the use of barrettes is the Petronas Twin Towers in Kuala Lumpur, where barrettes of 2.8m × 1.2m in plan and from 40m to 125m deep were constructed for the foundations.

Research has been carried out through field tests for barrettes subject to vertical load. For example, (Ng et al. 2000, Ng and Lei 2003) have performed tests on barrettes or collected test data for barrettes in the residual granite soils of Hong Kong. This has enabled the skin friction on barrettes in the residual granite soils to be related to the mean SPT blow count $\overline{N}$. O-cell testing has been performed on a barrette in a tuff in the Phillipines by Fellenius et al. (1999).

Lateral loading of barrettes has been reported by Zhang (2003) for tests performed in Hong Kong. He found that cracking of the barrette contributed to the magnitude of the lateral deflection and that there was a critical depth below which deflections were small.

Analysis of barrettes has been performed by Rafa and Moussai (2018) who used the three-dimensional finite element (FE) code Plaxis-3D to model load tests on barrettes in clay with their tips in sand. They showed that they could model load test results well by using the hardening soil model for the clay and inserting interfaces along the barrette. Lei et al. (2007) have presented an analysis for barrettes with a cap that is based on the Mindlin solution. Limiting base pressure or shaft friction can be allowed for as for boundary element analysis of conventional circular piles (Poulos and Davis 1968).

To model lateral loading, Zhang (2003) used a finite element program based on p-y curves for the soil taking into account non-linear behaviour of the concrete and reinforcing in the barrette. The modelling of cracking was able to capture the observed barrette behaviour.

Although finite element analysis has been shown to be an effective tool for the analysis of barrette behaviour, it involves a good deal of effort to generate meshes and run large problems with multiple barrettes. Simpler programs that are used for analysing conventional circular (cross-section) piles and pile groups are much quicker to run and involve much less effort in setting up data. In this paper therefore, the computer program CLAP (Combined Load Analysis of Piles - Poulos 2009) is used to analyse single barrettes and groups of barrettes under either vertical or horizontal load. An equivalent circular pile is used to represent the rectangular barrette in the CLAP analysis. The results are compared with those obtained from three-dimensional finite element analyses of the rectangular barrettes, and suggestions are given for the best method of obtaining the equivalent circular pile.

2. PROBLEMS CONSIDERED

Comparisons of CLAP solutions with finite element solutions were carried out to see if the circular pile types used in CLAP could reasonably estimate the behaviour of rectangular barrettes. Two types of barrette were chosen for the comparison (i) a barrette 20m deep in a layer of clay 30m deep, and (ii) a 30m deep barrette in a 30m deep layer of clay founded on stiffer underlying soft rock.

The two types of barrette were analysed as a single barrette, and as a group of 5 × 5 barrettes (25 in all). The two types of barrette (B1 and B2) are shown in Figure 1 with the group layout shown in plan in Figure 2.

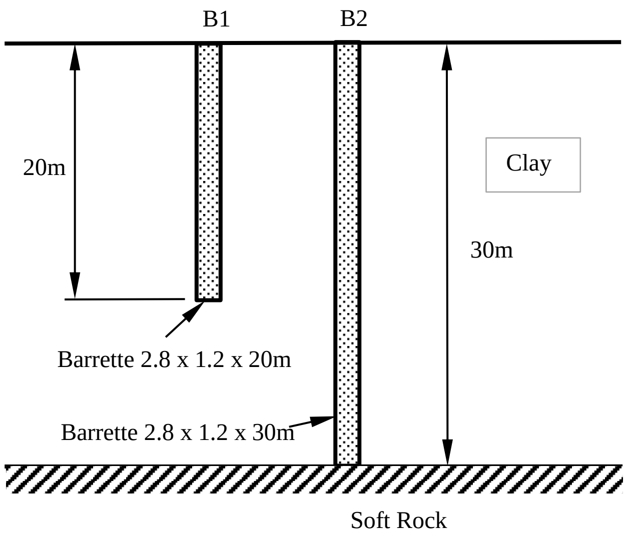

Figure 1 Soil and barrette properties

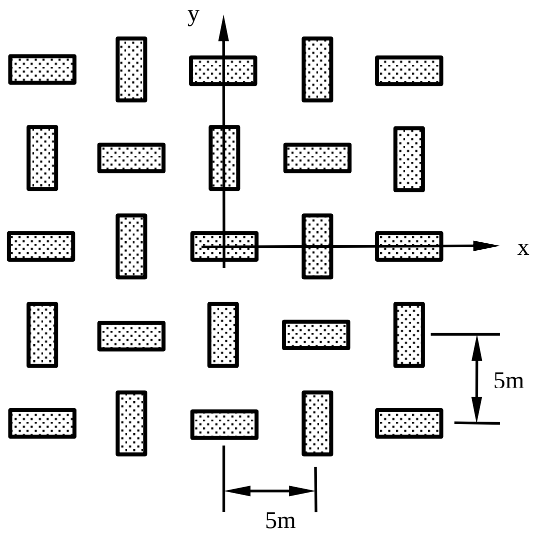

Figure 2 Plan view of 5 × 5 barrette group

The clay was considered to have an undrained shear strength s_u of 50kPa for the purposes of the finite element analysis, and so for the CLAP analysis, the skin friction on the barrettes was assumed to be 50kPa, the base resistance $9s_u$ = 450kPa and the lateral yield pressure also $9s_u$ = 450kPa. In the finite element analyses, yield of the clay under vertical and lateral loading was allowed for by using a Mohr-Coulomb yield criterion with $\varphi_u = 0$ and undrained cohesion c_u = 50kPa. All material properties used are shown in Table 1.

Table 1 Properties of materials

Finite element analysis		**CLAP analysis**	
Shear strength of clay	50kPa	Skin friction	50kPa
Undrained modulus of clay	50MPa	Maximum base pressure in clay	450kPa
Poisson's ratio of clay	0.49	Maximum base pressure in soft rock	8000kPa
Poisson's ratio of soft rock	0.3	Clay undrained modulus	50MPa
Elastic modulus of soft rock	500MPa	Elastic modulus of soft rock	500MPa
Elastic modulus of barrette	30GPa	Elastic modulus of equivalent pile	30GPa

2.1 Equivalence of pile and barrette

In order to use CLAP for the analysis of barrettes, an equivalent circular shafted pile has to be selected to represent the barrette. The properties of the equivalent single pile need to be different for vertical loading than for lateral loading, and this is examined in the following.

2.1.1 Vertical loading

For vertical loading, it seems reasonable to select a pile that has the same perimeter as the barrette, as this area will produce the same axial resistance under the same skin friction. Also, the base area of the pile can be made the same as the base area of the barrette so as to achieve the same base load. This can be done in CLAP as different pile shaft diameter and base diameter can be specified in the program.

It is assumed that the shaft friction and end bearing on a barrette are the same as those for the equivalent circular pile.

2.1.2 Lateral loading

Several schemes could be used to select an equivalent pile, such as making the pile diameter the same width as the width of the barrette, or using a higher yield pressure on the face of the barrette to account for skin friction on the sides of the barrette. These schemes were tried but without success.

It was evident however, that the bending of the barrette was highly dependent upon the second moment of area of the barrette in the direction of bending. With the narrow face of the barrette being pushed into the clay, the section has a much higher resistance to bending than if it is loaded laterally in the perpendicular direction.

It was therefore found that for lateral loading, an equivalent pile having the same moment of inertia (I_{xx} or I_{yy}) as the barrette was suitable for the analysis.

The equivalent single pile properties are given in Table 2.

Table 2 Properties of equivalent piles

Property	**Barrette**	**Equivalent single pile**	**Comment**
Perimeter	8m	Diam = 2.546m	Pile perimeter = 8m
Cross-sectional area	3.36m^2	Diam = 2.068m	Pile area = 3.36m^2
Vertical loading			
Pile shaft diameter		Diam = 2.546m	Same perimeter as barrette
Pile base diameter		Diam = 2.068m	Same base area as barette
Lateral loading			
Pile shaft diameter		Diam = 2.068m	If loaded with narrow face forward
Moment of inertia (in long direction)	2.1952m^4	2.1952m^4	If loaded with narrow face forward
Pile shaft diameter		Diam = 2.546m	If loaded with wide face forward
Moment of inertia (in short direction)	0.4032m^4	0.4032m^4	If loaded with wide face forward

2.2 Finite element analysis

The finite element analysis GENFE (Small 2017) was used to obtain solutions to compare with CLAP solutions, and was based on a 20 noded isoparametric three-dimensional element. The barrettes were modelled as solid three-dimensional inclusions in the finite element mesh. The edges of the mesh were attached to infinite elements so that the distant boundaries could be modelled without the use of a large number of elements.

For vertical loading, no interface elements were used between the barrette and soil, although for the lateral loading case, breakaway was allowed at the back of the barrette. For vertical loading, symmetry could be used, and just one quarter of the barrette (or group of barrettes) needed to be analysed. For lateral loading, half of the problem was analysed as the breakaway at the back of the barrette meant that the problem only had two-way symmetry.

The finite element mesh used for a laterally loaded barrette 20m deep with breakaway at the back is shown in Figure 3.

2.3 Single barrette loading

The first loading case considered was for a barrette 20m deep as shown in Figure 1 (Case B1), where the loading was vertical.

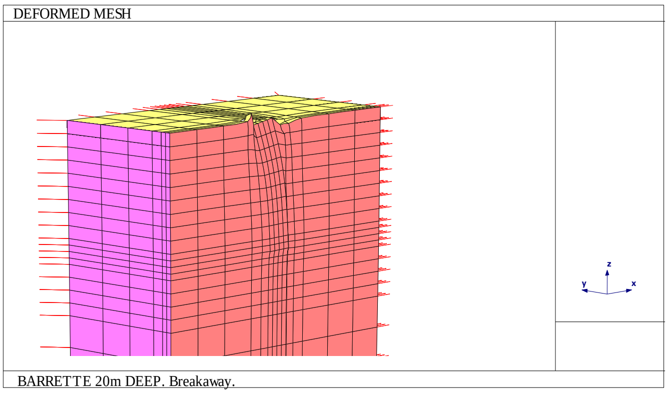

Figure 3 Three-dimensional finite element mesh used for lateral loading of barrette (half mesh shown).

The load-deflection curve from the finite element analysis and the CLAP analysis is shown in Figure 4. The figure shows that the initial stiffness of the barrette and the collapse load are well modelled by CLAP, but the overall shape of the curve is different. The finite element solution shows a more rapid failure of the barrette after a fairly linear initial portion of the load-deflection curve, while the CLAP solution shows a more gradual failure. The shape of the CLAP load-deflection curve is determined by a hyperbolic equation where

$$K_{vt} = K_{v0}\left(1 - R_f \frac{P}{P_u}\right)^2 \qquad (1)$$

and K_{vt} is the tangent stiffness of the pile, K_{v0} is the initial vertical pile stiffness, P is the load on the pile, R_f is a hyperbolic parameter, and P_u is the ultimate pile load.

Figure 3 Three-dimensional finite element mesh used for lateral loading of barrette (half mesh shown).

The effect of R_f on the shape of the curve can be seen in Figure 4 where a value of 0.8 gives a flatter curve and 0.4 gives a steeper curve, with little yield evident before failure. The effect of having no interface elements can be seen also in Figure 4, where a solution obtained using the commercial code Plaxis 3D (Plaxis 2018) is shown compared to the GENFE result. The two solutions are close, showing that it is not necessary to use interface elements in this case.

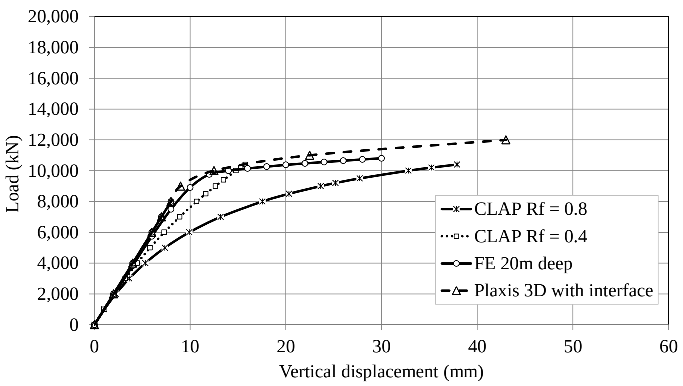

Figure 4 Load-deflection curve for 20m deep barrette under vertical load

For vertical loading of the 30m deep barrette that is founded on the soft rock, the CLAP load-deflection curve and the finite element curve both show a gradual onset of failure, and good agreement can be obtained between the two methods of analysis (see Figure 5). This is probably due to failure progressing more slowly when the barrette is supported by the soft rock at its toe.

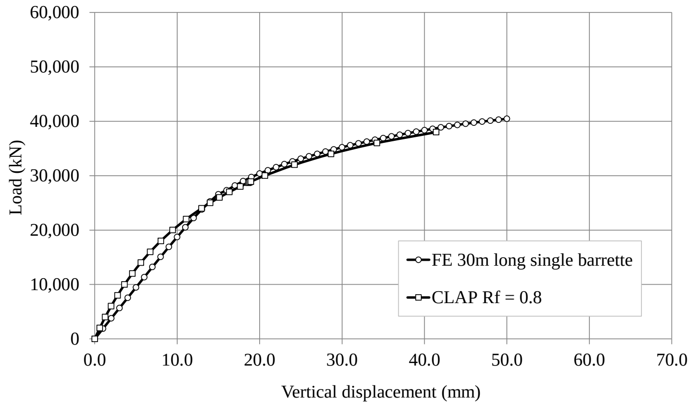

Figure 5 Load-deflection curve for 30m deep barrette under vertical load

When the loading is lateral, the load-deflection curve depends on the direction of loading. As can be seen from Figure 6, when the barrette is loaded with the narrow face forward, it is predicted to carry more load and have a stiffer response than when the wide face is forward. This is due to the higher bending resistance of the barrette (with the narrow face forward). For the CLAP curves shown in Figure 6, $R_f = 0.8$.

The curves for the 30m deep barrette in Figure 6 are almost identical to those for the 20m deep barrette (not shown), as the bending only takes place over the upper part of the barrette.

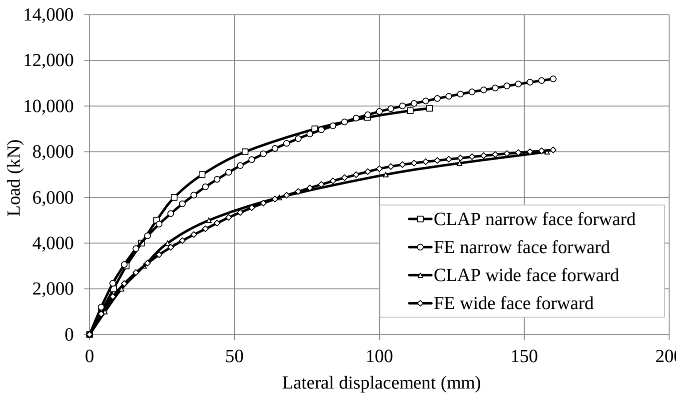

Figure 6 Lateral displacement for 20m deep barrette

2.4 Groups of barrettes

The groups of barrettes were analysed by using the same equivalent pile properties as for the single piles. For lateral loading this meant using two types of equivalent pile (see Table 2) as the barrettes are orientated in two different directions within the pile group.

2.4.1 Vertical loading

For vertical loading of the 5 × 5 group of barrettes, it was assumed that the barrettes were joined by a rigid cap so that all barrettes displaced downward an equal amount vertically. For the finite element analysis this was achieved by placing plate elements in the location of the cap. This cap was made thick (4m thick) so that bending of the cap was small.

The load-deflection curves for the 5 × 5 group of barrettes loaded vertically are shown in Figure 7 where it may be seen that the CLAP and finite element curves are in good agreement for both the 20m deep and 30m deep barrettes. For this analysis it was assumed in the CLAP analysis that the cap had a bearing capacity of $5s_u$ or 250kPa.

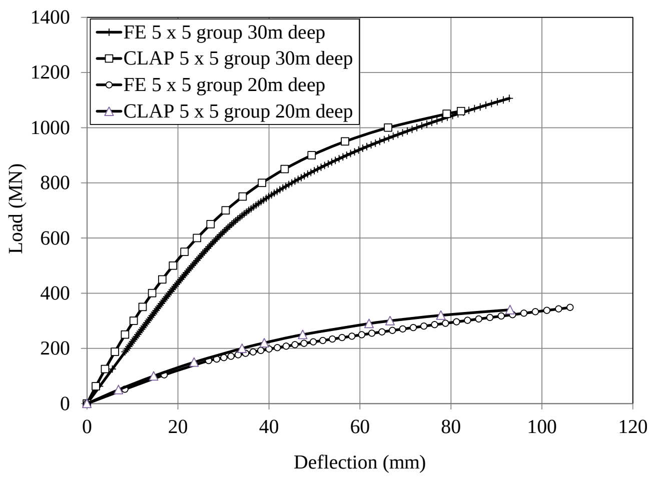

Figure 7 Load-deflection curves for vertically loaded 5 × 5 barrette groups

2.4.2 Lateral loading

For lateral loading of the group of barrettes, a rigid cap was again assumed for the group. The results of the finite element and CLAP analyses are shown in Figure 8. Here the agreement between the CLAP and finite element analyses is not close except over the initial part of the load-deflection curve. The reason may be that the group of barrettes behave as a block, and the CLAP analysis assumes individual pile behavior, despite taking pile-pile interactions into account. Nevertheless, as a means of providing a check for finite element analyses, the equivalent pile analysis using CLAP appears to be adequate from a practical viewpoint.

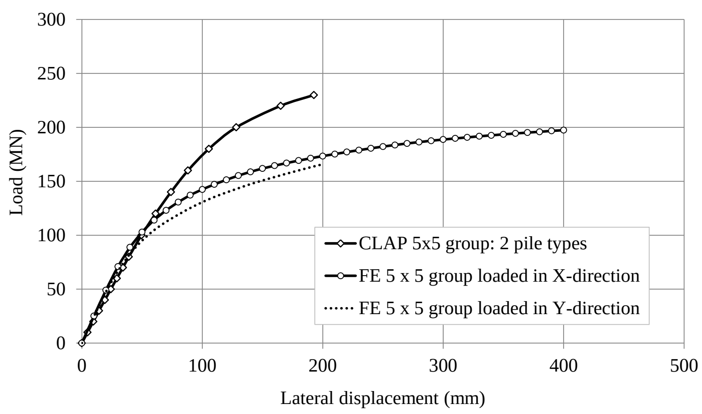

Figure 8 Load-deflection curve for lateral loading of a 20m deep 5 × 5 group of barrettes

3. CONCLUSIONS

The use of an equivalent pile of circular cross-section to model a rectangular barrette has been examined, and it has been found that:

(i) For a single barrette under vertical load, an equivalent pile with the same circumference and the same base area as the barrette could be used. For a floating barrette (i.e. not founded on bedrock), the equivalent pile had the same initial stiffness and the same maximum load, but the overall load-deflection curve was not the same as that of the barrette. The barrette showed a more sudden increase in displacement just before its ultimate load than the equivalent pile.

For a barrette that was founded on a stiffer soft rock foundation, the pile with the same circumference and the same base area, gave a good approximation to the load-deflection curve of the barrette.

(ii) For a vertically loaded group of barrettes (a 5 × 5 group was examined here), the behaviour of the group of barrettes could be modelled adequately with a group of equivalent piles having the same circumference and same base area as the barrettes. This was true for both the end bearing barrettes and the floating barrettes.

(iii) For a single barrette subjected to lateral loading, the flexural stiffness of the equivalent pile is of importance. It was found that an equivalent pile having the same second moment of area as the barrette (in the direction of loading) and the same circumference as the barrette, had a very similar load-deflection curve. This was true of both the floating barrette and one founded on bedrock, as only the upper part of the barrette deflects under lateral load, and there is little horizontal deflection below a critical depth.

(iv) For the 5 × 5 group of barrettes subjected to lateral loading, the barrettes have a different bending stiffness depending on their orientation. Therefore the group was modelled using two different equivalent piles having the appropriate second moment of area (as for the single barrette modelling). However, it was found that the overall shape of the load-deflection curve for the group was in less satisfactory agreement with the finite element result than for the vertical loading case, although the initial group stiffness was very similar. This lower level of agreement could be due to the fact that the CLAP analysis was not able to model the block behaviour of the barrettes under lateral loading. Nevertheless, the use of the equivalent circular piles to model the behaviour of a barrette foundation provides a useful and generally adequate means of checking the results of more complex finite element analyses.

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