Finite Element Analyses in Geotechnical Engineering – *Part 2: An Indispensable Tool or a Mysterious Black Box?*

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This article is a continuation of the writer's contribution published in the September issue of JURUTERA Bulletin (pp. 14–18). It forms the second of three case studies that constitutes the full article.

Engineering experience and judgment as well as the fundamental knowledge and understanding of theoretical soil mechanics are important ingredients in shaping a responsible and experienced FEA user. The benchmarking of FEA analyses is good practice to avoid or reduce carelessness in design. Ong (2006) highlighted that the responses from a typical simulated geotechnical analysis can be benchmarked quantitatively and qualitatively.

Quantitative benchmarking involves
(i) software *vs.* software,
(ii) software *vs.* reliable field data and
(iii) software *vs.* reliable laboratory experimental data,

which are often used to produce closed-form and analytical solutions, while qualitative benchmarking involves software *vs.* experience and judgment.

Case Study 2: Benchmarking of a soil-structure problem (software *vs.* lab data)

As 3D geotechnical modelling can be laborious, time consuming and sometimes perceived as 'only viable in a university research environment', it is very often and normal that engineers try to analyse a 3D pile problem in a 2D FE environment where the pile is 'smeared', thus effectively analysed as a 'wall'. This simplification strategy is typically shown in Figure 1 for the case of a single pile and a pile group. The question now is whether this simplification will render the pile response less or more conservative in design, and how can we confidently answer this question?

Appreciating and modelling the problem in hand

One way to go about this problem is to compare the pile responses obtained from reliable centrifuge model tests and 2D FE analyses, details of which can be found in Ong *et al.* (2006).

Theoretically, for the case of a single pile as shown in Figure 1(a), by assuming all unit length for parameters *r*, *h*, *w* and *b* (*i.e.* all with value 1), the unit contact areas of the cylinder (2*π*r*h) and the rectangular wall (2*h*w) are 2π and 2, respectively. This shows that the contact area of a 3D cylinder is actually larger by π (=3.142) than that of a 2D rectangular wall. This value is important in the case of a single pile as it represents the extent of influence imposed by the single pile. This concept is analogous to the 'three pile diameters' rule of thumb theory for optimising pile spacing for a group of piles.

In general, the formulations used to obtain a 2D equivalent wall for the case of a single pile can be written as

- Axial rigidity: $(E_pA_p)/3d$ and
- Bending rigidity: $(E_pI_p)/3d$

where E_p, A_p, I_p and d are the Young's modulus, sectional area, second moment of area and diameter of the pile respectively. For the case of a group of piles, the 3D single pile properties are multiplied by the number of similar piles in the plane-strain direction and smeared (divided) by the pile group centre-to-centre spacing, s, in the plane-strain direction as shown in Figure 1(b).

Similarly, the formulations used to obtain a 2D equivalent wall for a group of

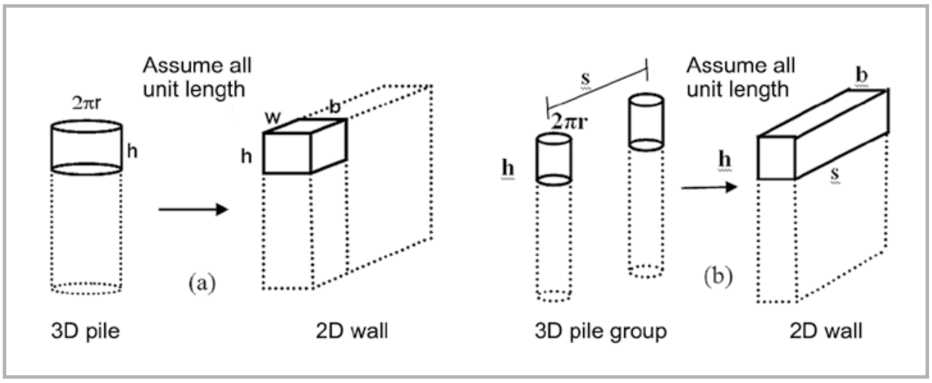

Figure 1: Method of smearing (a) single pile and (b) pile-group to an equivalent 2D wall for use in 2D FEA

Table 1: Method of converting response of equivalent wall to that of a pile for the case of a single pile

Pile response	Quantity per linear m of wall as output by PLAXIS	Conversion to quantity per pile
Bending moment (BM)	BM in kNm/m	BM*3d to obtain kNm
Axial or shear forces (F)	F in kN/m	F*3d to obtain kN

Table 2: Method of converting response of equivalent wall to that of a pile for the case of a group of piles

Pile response	Quantity per linear m of wall as output by PLAXIS	Conversion to quantity per pile
Bending moment (BM)	BM in kNm/m	BM*[(n-1)*s]/n to obtain kNm
Axial or shear forces (F)	F in kN/m	F*[(n-1)*s]/n to obtain kN

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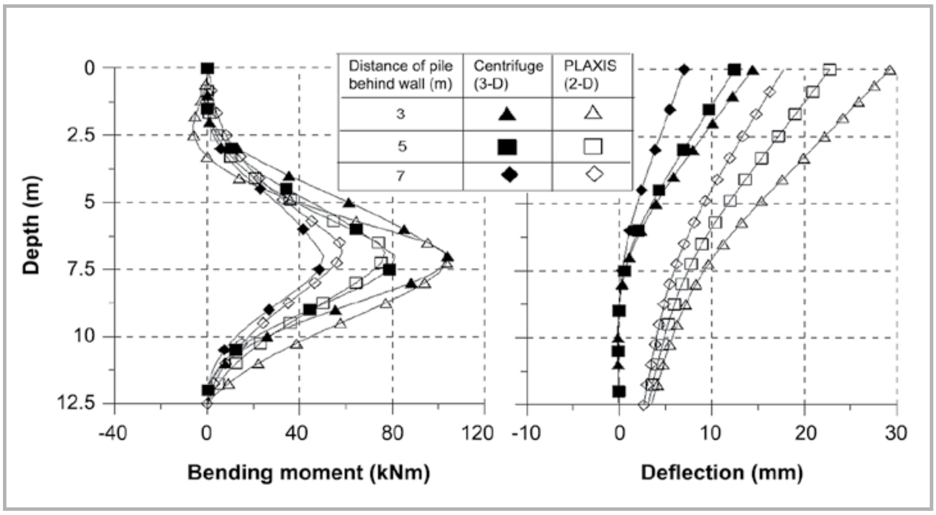

Figure 2: Measured and predicted results from centrifuge test and 2D FE modelling for the case of a single pile

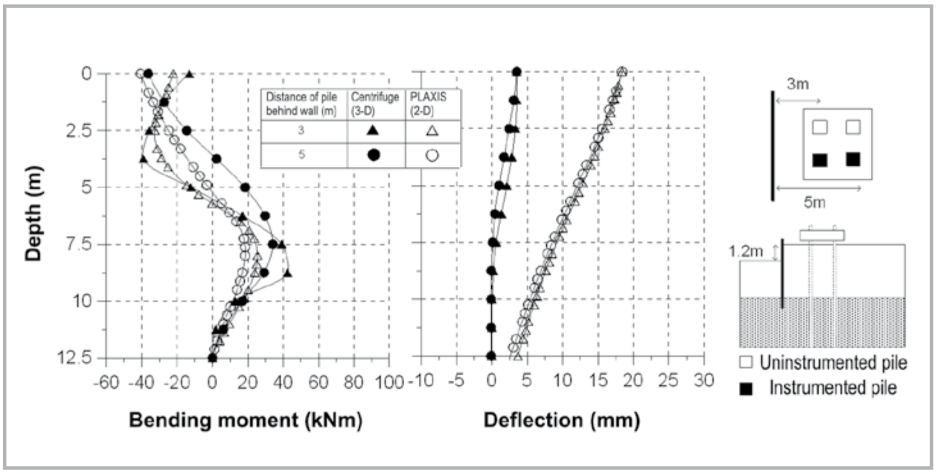

Figure 3: Measured and predicted results from centrifuge test and 2D FE modelling for the case of a four-pile group

piles in the plane-strain direction can be written as

- Axial rigidity: $n(E_pA_p)/[(n-1)(s)]$ and
- Bending rigidity: $n(E_pI_p)/[(n-1)(s)]$

where *n* is the number of piles in the plane-strain direction and s is the centre-to-centre pile spacing between two piles in the plane-strain direction. The remaining quantities remain similar as described above.

By converting 3D piles to equivalent 2D wall, the magnitudes of bending moment and forces (axial or shear) will be output as kNm/m and kN/m respectively. In order to obtain the 'actual' pile bending moment and forces, multiplication of smeared dimensions is necessary. Tables 1 and 2 show the methods of converting the response of equivalent wall to that of a pile for a single pile and group of piles respectively. Nevertheless, the resulted deflections and rotations remain similar.

Results, interpretation and discussion

Figure 2 shows the measured and predicted results from FEA and centrifuge modelling for the case of a single pile respectively. It is noted that the bending moment profiles show a particularly good match compared to the deflection profiles, which are over predicted by about 2.2 times of the measured values. The measured and predicted pile response from FE and centrifuge modelling for the case of a 2x2 pile group is shown in Figure 3. It is also noted that the bending moment profiles show a reasonable good match but the same cannot be said of the deflection profile, which is about five times over predicted.

The smearing of pile properties is a common method used in practice to model an actual pile as an equivalent wall in 2D

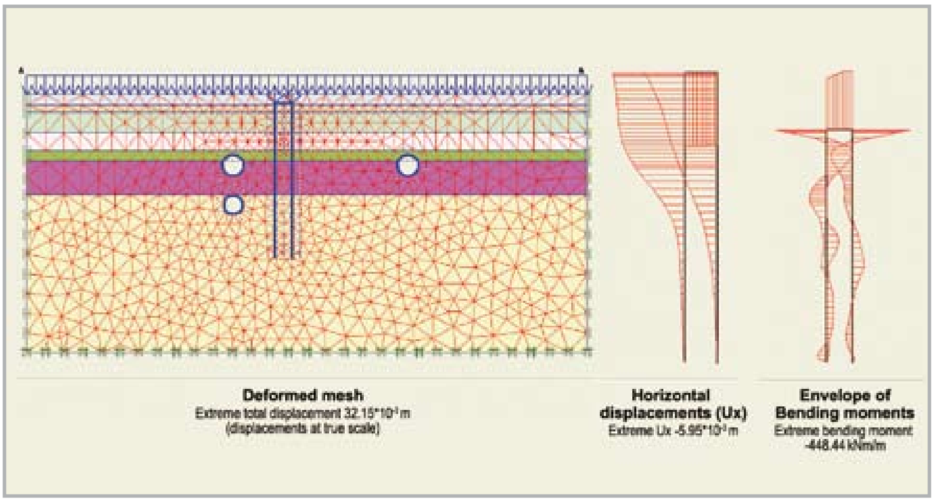

Figure 4: Finite element modelling is used to analyse complex soil-tunnel-pile

FE analysis. Otherwise, 3D FE analysis, which is more complicated, expensive and time consuming, may be necessary. From the present benchmarking study, it can be surmised that 2D FE analyses produce more compatible bending moment, but err on the conservative side for deflection as compared to values obtained from the well-documented centrifuge tests, which perhaps are the closest simulations possible to a realistic real-life soil-structure interaction problem.

Based on this benchmarking study, the concept of 2D pile smearing can be confidently used to model an actual 3D single pile or a group of piles as it has been established that this method would yield conservative deflection thus erring on the conservative side of design. Subsequently, more complex analysis, *e.g.* soil-tunnel-pile interaction, as shown in Figure 4, can be assessed with confidence knowing that the 2D pile response will be conservative.

Concluding remarks for Case Study 2

The implication of modelling a 3D pile in a 2D environment as an 'equivalent wall' is that the resulting soil movements are prohibited from flowing in between and around the piles as they are effectively screened off by the wall.

Soil flow phenomenon in large strain deformation and its associated limiting pressures have been studied and explained in detail by Ong *et al.* (2006). It has been found that despite not being able to capture the actual soil flow phenomenon associated to large strain deformation, it is worthwhile to note that the modelling of 3D piles in 2D environment will err on the conservative side in design for pile deflection while the bending moment prediction can be reasonably well predicted if calibrated soil and pile properties are used in the FEA.

Furthermore, codes used in practice for design purposes do not utilise residual soil strength parameters associated to large strain deformation and near soil failure condition, thus rendering the results of 2D FEA for modelling a 3D pile problem appropriate for use in routine geotechnical engineering design. ■

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