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Special Contribution

Potential Damage to Steel Pipe Piles During Installation

Prof. Dr. M.F. Randolph

Fugro Chair in Geotechnics, Centre for Offshore Foundation Systems
The University of Western Australia

ABSTRACT

Steel pipe piles are widely used both onshore and offshore because of their good bending stiffness and ease of installation. They are generally vibrated, driven or jacked open-ended, although internal plates or even complete end-closures may be used to improve their bearing capacity. Large diameter, thin-walled open-ended piles are susceptible to distortion at the tip, particularly when installed into stratified sediments where the soil conditions may vary spatially, both with depth and within planes normal to the pile axis. A particular form of damage is extrusion buckling where progressive distortion of the pile occurs, starting from the tip, as it penetrates through the soil. Case histories illustrating this form of collapse are shown and possible triggers for damage discussed.

1 INTRODUCTION

Piles are vulnerable to damage during jacking or driving into strong soils or weak rock. This may often go undetected, with the only indication being a driving resistance that deviates from the expected profile. Figure 1 shows two contrasting examples from onshore pile driving. In one case tip buckling of an H-pile has occurred due to encountering unweathered basalt at a shallower depth than anticipated; in the other case a thin-walled casing has become distorted during driving, possibly due to encountering a buried object within made ground.

(a) Tip buckling of H-pile

(b) Distortion of thin-walled casing

Figure 1 Examples of damage during driving

A more general case of widespread damage in the vicinity of the pile tip, which went completely unnoticed during the original installation, is shown in Figure 2 (Broos et al. 2017). The piles, which were extracted during widening a harbour basin in Rotterdam, were 1420 mm diameter with 17 mm wall thickness in the region of the tip. They had been installed by driving at a rake of 1 in 5, bearing in medium to dense sands with cone resistance of 25 to 40 MPa. It is quite likely that the raking angle (around 11 degrees) contributed to the distortion, since the pile tip would have encountered any stronger stratum at one edge.

Figure 2 Evidence of extrusion buckling at the toe of tubular king piles extracted from the port basin in Rotterdam

The relatively large diameter to wall thickness ratio (D/t) of 84 for the piles shown in Figure 2 may be viewed in the context of the current trend in open-ended pile geometries, in particular the very large diameter monopiles now in use for European offshore windfarms. A typical monopile is shown in Figure 3. Over much of the pile length the wall thickness may be no more than 75 mm (D/t of 100), but with thicker sections in regions of high bending moment (near the seabed surface) and at the pile tip where the pile is reinforced internally with a driving shoe.

Figure 3 Photograph of 7.5 m diameter monopiles for the Gode Wind farm

The concern for piles with large D/t ratios is the potential for damage to occur during transportation and installation. Typically, construction tolerances on 'out of roundness' are for maximum deviation from a true circle of ~0.5 % of the pile radius (DNV 2010). While such tolerances may be verified immediately prior to installation, heterogeneities within the soil can trigger distortion. Indeed progressive elliptical (and beyond) distortion of pipe piles in the offshore environment, a process referred to as 'extrusion buckling' has been identified on several occasions, as indicated in Figure 4. The API guideline shown for comparison, and which is often used as the basis for choosing the pile wall thickness at the tip, targets a different form of tip damage, linked to generation of excessive axial stresses during installation by driving. It is evident that it does not provide safe guidance for gradual distortion that occurs in extrusion buckling.

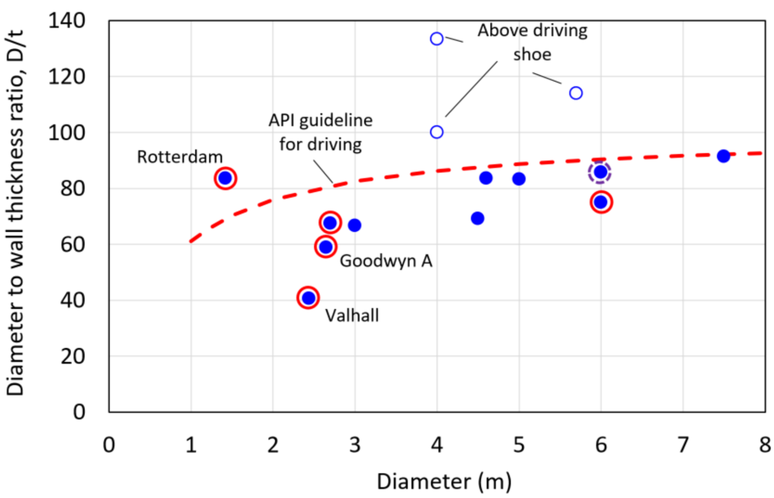


Figure 4 Trends in open-ended pile geometries. Confirmed and suspected extrusion buckling damage indicated by red and purple circles respectively

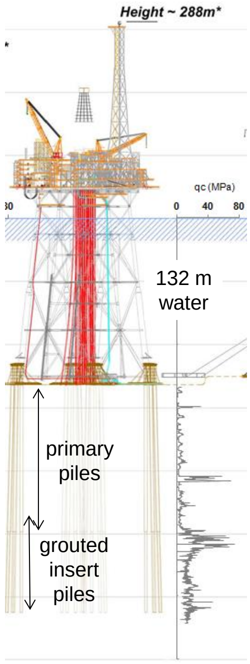
2 CASE STUDIES

Two well-studied case studies of extrusion buckling are summarised briefly below.

2.1 Case study 1: Goodwyn A, North-West Shelf of Australia

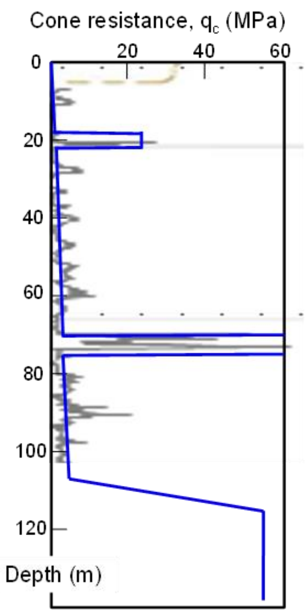
The Goodwyn A platform was installed on the North-West Shelf of Australia in the late 1980s. The seabed comprised relatively low strength calcareous silt and sand layers down to a depth of about 110 m, below which calcarenite was found. Given the low shaft capacity of driven piles in calcareous soils, the adopted foundation design consisted of primary piles driven through the uncemented sediments, below which grouted insert piles were to provide the main axial support (Figure 5). The platform included 20 piles, 5 at each corner, with diameter 2.65 m and wall thickness 45 mm (D/t = 59). However, when attempts were made to drill out the soil plug within the driven primary piles, to enable construction of the grouted insert piles, it was found that 16 of the 20 piles had undergone progressive distortion to the extent that the pile tips had become almost closed into a peanut shape. The distortion started at about the depth of a layer of cemented material (3 to 5 m thick, with cone resistance upwards of 60 MPa) embedded within the calcareous silt and sand layers (Figure 6).

(a) View from the air

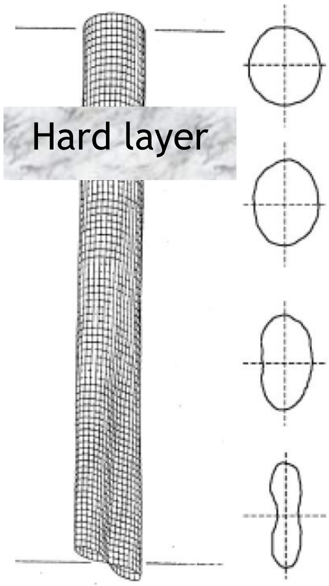


(b) Elevation of platform and foundations

Figure 5 Overview of Goodwyn A platform on North-West Shelf of Australia



←(a) Profile of cone resistance



←(b) Progressive pile distortion below hard layer

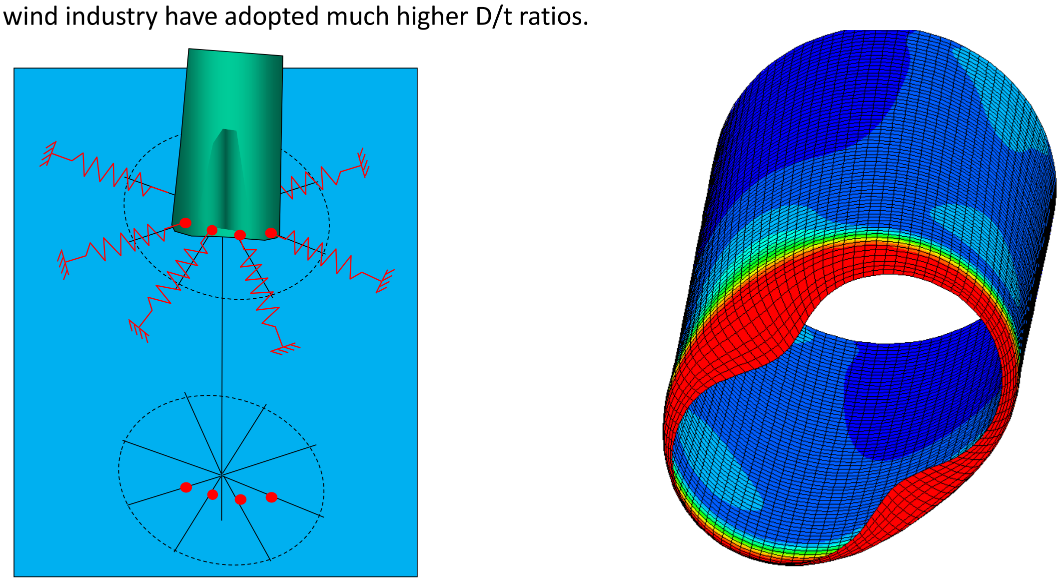
Figure 6 Soil strength profile and measured growth in pile distortion

In order to understand the process of extrusion buckling, a numerical technique (BASIL) was developed within ABAQUS (Barbour & Erbrich 1995, Erbrich et al. 2010). The pile-soil interaction is represented by layers of 'hair' springs distributed around (and along the length of) the embedded section of the pile (Figure 7a). The zero force and displacement for each spring is taken from the point where the pile tip 'cuts' the hair spring. As the pile advances further, any forced radial movement of the spring (for example, if the pile wall is not parallel to the direction of advance) will invoke a force acting on the pile wall.

The analysis typically starts with the pile pre-embedded to some depth, and with the pile tip distorted according to the shape of a radial buckle (mode 1), with the maximum out of roundness adjusted in a parametric fashion, but typically 0.5 to 2 % of the pile radius. The pile is then advanced through the sets of soil springs, each of which has been pre-assigned an appropriate non-linear load-displacement response curve.

An example outcome from a BASIL simulation of extrusion buckling of a Goodwyn A pile is shown in Figure 8 (see also Erbrich et al. 2010). In order to achieve the progressive distortion, an initial out of roundness of 25 mm (1.9 % of the pile radius) was needed, which is somewhat outside the specified tolerance (Figure 7b). Notwithstanding potential limitations of the numerical analysis, the need to apply a more significant initial distortion indicates that some external factor might have contributed to initial damage of the pile tip prior to installation, either a structural collision during stabbing of the pile or lateral heterogeneity of the cemented sediment layer.

At the time of the Goodwyn A platform installation, the pile D/t ratio of 59 was somewhat greater than in routine practice in the offshore oil and gas industry. However, as discussed above, many of the very large diameter monopiles used in the offshore wind industry have adopted much higher D/t ratios.



(a) Soil represented as 'hair' springs (b) Initial imperfection (exaggerated)

Figure 7 Numerical modelling approach to investigate extrusion buckling

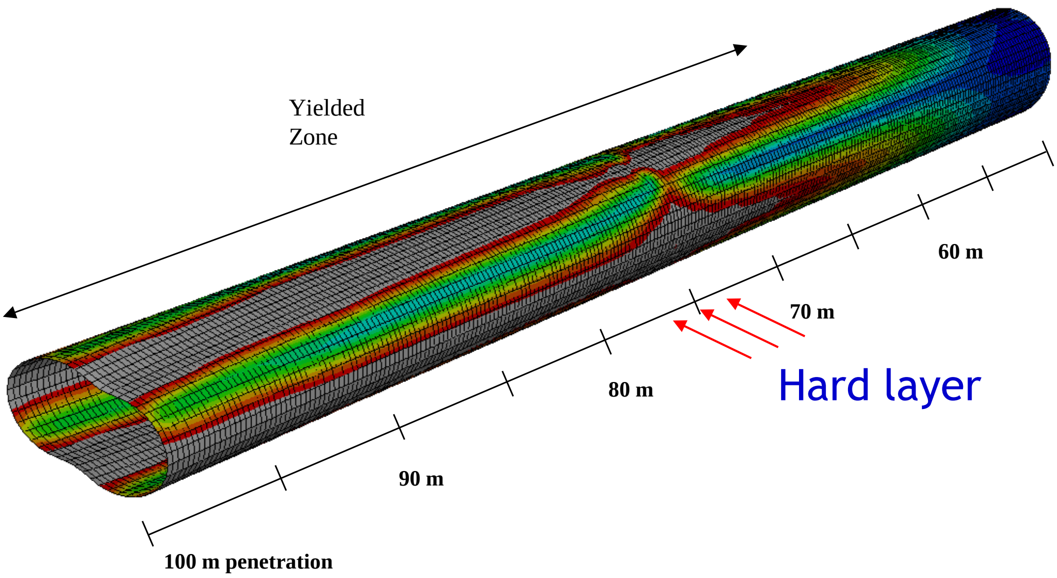
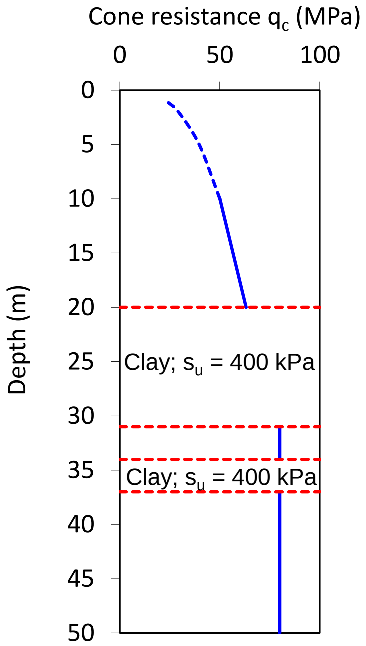


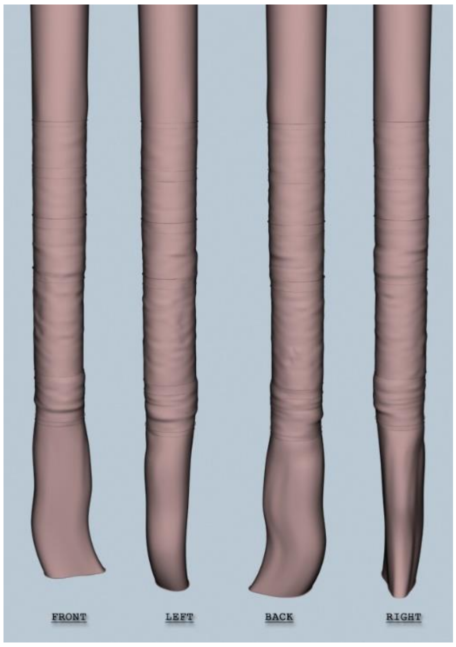
Figure 8 Example pattern of plastic strains for a pile pushed 25 m beyond the hard layer

2.2 Case study 2: Valhall, North Sea

The Valhall water injection platform was installed in the North Sea in 2002, but encountered problems when 5 of the 8 piles reached refusal at penetrations between 45 and 55 m, compared with the target penetration of around 70 m (Alm et al. 2004). The premature refusal meant that external weld beads, and the profiled variations in pile wall thickness, were then not at their anticipated design depths relative to the jacket structure. Investigations revealed that the piles that met refusal had undergone extrusion buckling to the extent that the tips were almost closed (Figure 9). The soil stratigraphy below about 37 m comprised very dense sands, with cone resistances estimated as about 80 MPa. The piles were 2.44 m in diameter, with a wall thickness of 60 mm (so D/t of 40), hence consistent with routine practice.
During investigations into the cause of the pile distortion, attention focused on what might seem a relatively minor design detail, in the form of an external chamfer that was applied to the pile tips (Figure 10). In the context of the 2.44 m pile diameter, it is perhaps surprising that this detail could have such ramifications for pile installation. However, analysis suggests that the chamfer may indeed give rise to significantly greater external radial stresses acting on the pile wall, hence triggering distortion.



(a) Simplified cone profile



(b) Typical distortion of lower part of pile

Figure 9 Soil profile and surveyed pile distortion for Valhall

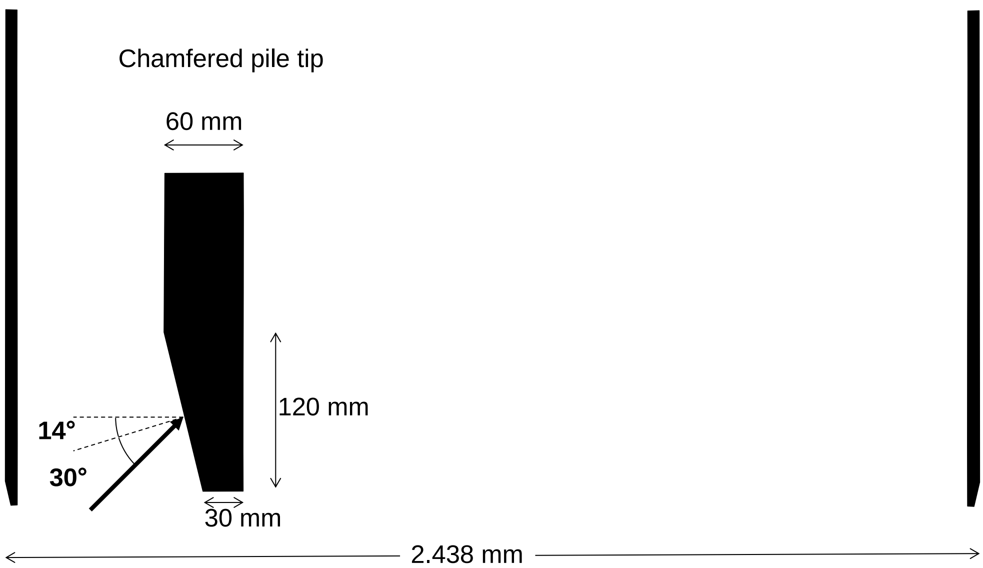


Figure 10 Detail of chamfered pile tip

Analyses using BASIL were carried out to explore conditions for triggering extrusion buckling, allowing for the radial stress enhancement of the chamfered tip. Figure 11 (Erbrich, private communication) shows example output for an initial out of roundness of 0.8 % of the pile radius. The pile was pre-embedded to 10 m and then pushed to a penetration of 50 m. Although full collapse was not achieved, significant outward (in one plane) and inward (in a perpendicular plane) movements occurred, hence initiating extrusion buckling.

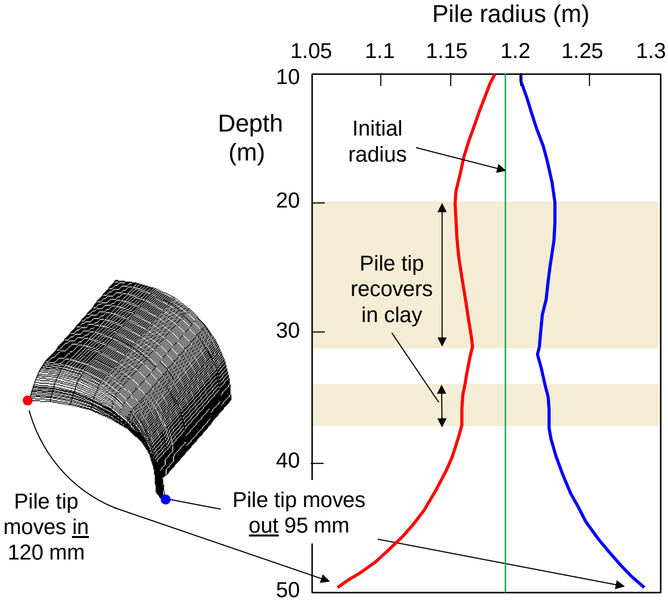


Figure 11 Soil profile and surveyed pile distortion for Valhall

3 INITIATION AND PROPAGATION OF EXTRUSION BUCKLING

Extrusion buckling can be initiated during driving of pipe piles by a variety of conditions that include:

(1) initial out of roundness of the pile cross-section with non-verticality of the pile wall;
(2) high differential internal and external stresses acting on the pile wall from the soil;
(3) heterogeneous soil conditions.

In each case, it is necessary for the soil to be sufficiently stiff to overcome the elastic hoop stiffness of the steel, and also – in the case of (2) and (3) – to generate differential radial stresses of sufficient magnitude. Conditions (1) and (2) are considered the most likely primary causes of the pile distortion discussed above in case studies 1 and 2. Clearly any plastic distortion of the circularity of the pile section near the tip would be expected to propagate further during driving through strong soils. Equally, if the differential stresses across the pile wall exceed the radial buckling pressure (the Bresse pressure, HSE 2001), then potential instability of the pile circularity can be initiated.

The effect of heterogeneous soil conditions is illustrated in Figure 12. An eccentric zone of stronger soil, a layer dipping relative to the horizontal, or a raking pile encountering a stronger horizontal layer, will tend to apply localised pressure in one region of the cross-section. For high D/t ratios the hoop stiffness of the pile is significantly lower than the corresponding soil stiffness, hence the soil will distort the pile rather than the other way round.

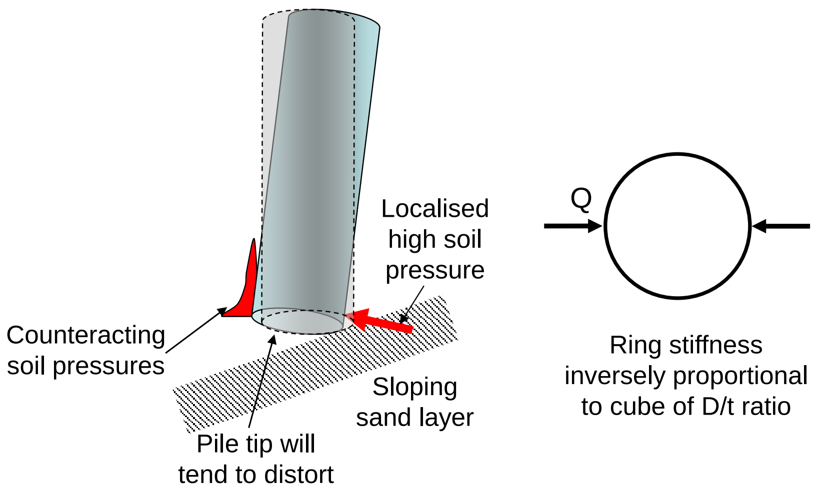


Figure 12 Initiation of pile tip distortion in heterogeneous soil

The hoop stiffness and critical radial buckling pressure are given by

$$\text{Hoop stiffnes (Figure 12):} \quad \frac{Q}{\delta E_{steel}} \sim \frac{10}{(D/t)^3}$$

$$\text{Critical Bresse pressure:} \quad \frac{p_e}{E_{steel}} = \frac{2}{(D/t)^3} \tag{1}$$

Both quantities are inversely proportional to the cube of the diameter to wall thickness ratio (D/t). Thus, for a D/t ratio of 80, the hoop stiffness and critical Bresse pressures would be about 4 MPa and 0.8 MPa respectively. The latter figure is of the same order of magnitude as the external radial stresses expected in relatively uniform layers of dense sand with cone resistance in excess of 50 MPa, but the low hoop stiffness is the more critical factor in initiation of pile tip distortion. The hoop stiffness may be compared with the initial gradient of a load transfer curve for lateral pile response. This would exceed the pile hoop stiffness for soil with shear modulus greater than about 1 MPa – so easily satisfied in all but quite soft soils. This is consistent with a similar assessment, although for somewhat thicker walled piles, by Aldridge et al. (2005).

For heterogeneous or dipping soil layers such as shown in Figure 12, localized increased soil stresses across the relevant vertical plane will initiate distortion of the pile tip, provided the soil stiffness is sufficiently high. Extrusion buckling is then likely to proceed, since minor distortion exacerbates the increased external stresses in that plane, while increased internal stresses will be generated across the perpendicular plane. The process is illustrated in Figure 13, considering a situation where the originally circular pile section has been distorted into an elliptical shape. If the pile wall at any given location around the tip attempts to advance vertically (parallel to the pile axis) as the pile penetrates further, the external stresses will be increased further across the minor axis of the ellipse, while the internal stresses will be increased across the major axis of the ellipse. This provides a feedback loop, which will instead encourage the pile wall to advance parallel to its current direction in each vertical plane (see dashed arrows in Figure 13).

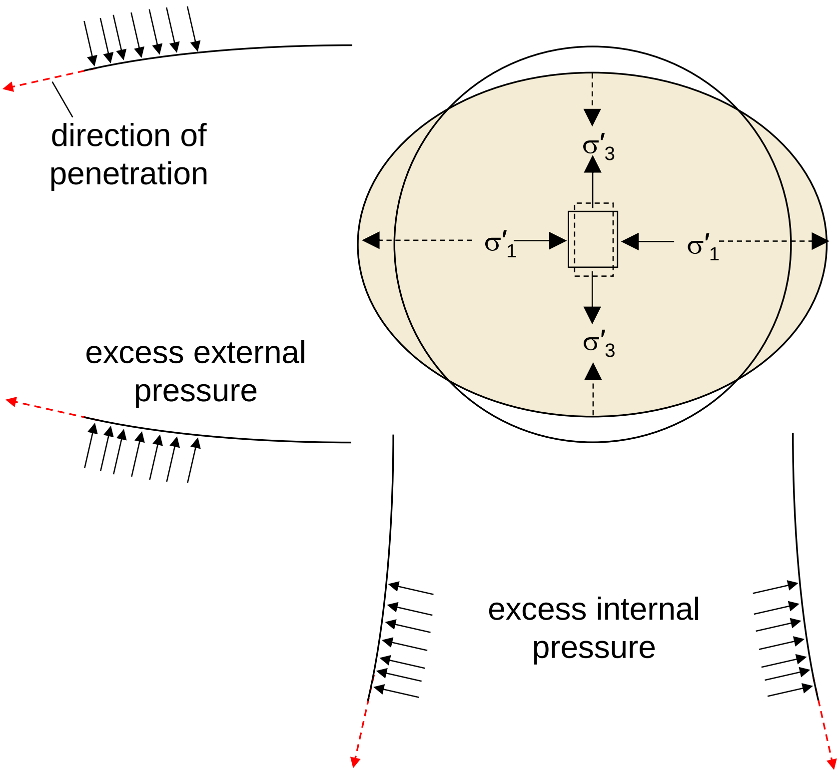


Figure 13 Schematic of extrusion buckling kinematics

4 CONCLUSIONS

The offshore oil and gas and renewable energy industries have provided incentive towards ever increasing diameters of open-ended steel piles to support jacket structures and offshore wind turbines. Fabrication techniques have developed in parallel, now enabling piles with diameters of 8 m or more to be constructed to tight tolerances. However, one aspect that has received less attention than it deserves is the construction risk associated with installing large diameter piles with very high ratios of diameter to wall thickness.

This paper has provided some background information illustrating a process of gradual tip distortion referred to as extrusion buckling. Although the process may be simulated using numerical analysis, this is more commonly undertaken retrospectively, after a problem has arisen, rather than during the design phase. The mechanism is well understood, but the analysis is relatively complex and at present there are only very limited guidelines to guard against situations where extrusion buckling may occur.

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A Brief CV of Professor Mark Randolph

Mark Randolph holds the Fugro Chair in Geotechnics in the Centre for Offshore Foundation Systems at the University of Western Australia. His two main research interests are piled foundations and offshore geotechnics, co-authoring books in each area, Piling Engineering, now in its third edition, and Offshore Geotechnical Engineering, as well as over 250 journal articles. Professor Randolph interacts closely with industry, both in research and through his role as Technical Authority within Fugro AG. He is a Fellow of several learned academies, including the Royal Society and the Australian Academy of Science. He is a former Scientist of the Year in Western Australia and holds an honorary doctorate from ETH Zurich.