Recent years have seen innovations in foundation construction and also innovations in techniques for solving foundation problems. However new procurement methods, especially Design & Build, have focused attention almost exclusively on cost and programme. Lack of checks on design and construction have led to declining technical standards and an increasing number of foundation failures. This paper reviews current practice and highlights some of the issues.

‘Because the success or failure of building lies buried deep with the foundations, we ignore them. But if we do, then like a child that grows up and turns round to disappoint us with their behaviour so will the foundations when we build without forethought and diligence to the ground and materials we use.’

- Karl Terzaghi

**Foundations**

Foundations are simple in principle. There are two main types:

* a spread footing connects to the structure, takes the load and spreads it out to reduce the pressure to what the soil can take.
* a piled foundation connects to structure and transfers the load to piles with solid shafts which transmit load down to a strong stratum at depth

Other alternatives are:

* vibrocompaction, where stone columns are formed to consolidate loose soil; and
* grouting, where grout is injected into the ground under pressure to fill voids.

All of these techniques are well established and have been around for many years.
**Underpinning**
This involves deepening an existing foundation or parts of foundation down to firmer ground to create even support for the structure. There are two main techniques:
* mass concrete, or
* minipiles supporting the structures via needles or a raft.
Continuous flight auger piles work like a corkscrew: first, the auger is screwed into the ground, and then slowly pulled up out of the ground, removing a plug of soil with it. The auger has a hollow stem and concrete or grout is pumped down this as it is withdrawn to fill the hole and form the pile.

There are then various types of micropiles:
* bored micropiles (e.g. Odex, Ischebeck);
* top-driven and bottom-driven micropiles.
Spread footing design:
estimate strength of ground,
estimate safe bearing capacity
calculate required foundation size

Pile design:
* calculate shaft friction
* calculate end bearing capacity
* apply appropriate safety factors to determine Safe Working Load (SWL)
The two most widely accepted pile driving formulae are the Hiley formula for top-driven piles and the BSP formula for bottom-driven steel tube piles. In the Hiley formula it is important to quantify all the coefficients and allowances as accurately as possible, as specified in CP4 (copy in metric units available at www.anbeal.co.uk). The results from these formulae can be reasonably accurate for short piles in sand or gravel but are less accurate for long piles and accuracy is poor in silt and clay. Therefore they cannot be considered a substitute for geotechnical design. However they are useful for calculating the size of hammer required and also monitoring pile driving on site.

### Testing

- **According to CIRIA report R144, standard pile integrity tests only reliably ‘see’ a pile length of about 20-30 diameters from ground level, so caution is needed with long small diameter piles.**
- **A static load test (carried out in accordance with the ICE piling specification) is expensive and inconvenient to the contractor but it is the only sure way to check pile load capacity.**
- **Indirect tests using CAPWAP and SIMBAT are useful and can be reasonably accurate for short piles but are less accurate for long piles and have limited accuracy in clay, as they do not apply sustained load.**

<table>
<thead>
<tr>
<th>Formula</th>
<th>HILEY</th>
<th>BSP (bottom-driven tubular piles)</th>
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</thead>
<tbody>
<tr>
<td>Formula</td>
<td>$Ru = Wh\eta/(S + C/2)$</td>
<td>$Ru = 0.29W(1000 + h)/(S + 12.7)$</td>
</tr>
<tr>
<td>$Ru$</td>
<td>ultimate driving resistance in kN</td>
<td>Ultimate driving resistance (kN)</td>
</tr>
<tr>
<td>$W$</td>
<td>weight of hammer (kN)</td>
<td>$W$ = Weight of hammer (kN)</td>
</tr>
<tr>
<td>$h$</td>
<td>drop of hammer (mm)</td>
<td>$h$ = Hammer drop at final set (mm)</td>
</tr>
<tr>
<td>$S$</td>
<td>final set (mm)</td>
<td>$S$ = Final set (mm per blow)</td>
</tr>
<tr>
<td>$C$</td>
<td>sum of temporary elastic compressions (mm) of pile, dolly, packings and ground</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>efficiency of blow (typically 0.4-0.7)</td>
<td></td>
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Work below ground involves many unknowns. The engineer needs adequate ground information to understand how the foundation is working and what is below it. For piles, boreholes should typically penetrate at least 10m deeper than the expected pile depth and deeper still in mining areas.

Driving piles ‘blind’ is a formula for disaster - the contractor does not know what is generating the driving resistance, or what is below the toe of the pile. In this situation, the claimed load capacity of the pile is pure guesswork.

* Bored piles can suffer loss of section in soft or wet ground.
* The capacity of driven piles in clay can change as porewater pressures change after they are driven, so redriving may be necessary.
* The capacity of piles in groups may be reduced.
* Other possible sources of trouble could be a deep peat layers, or a layer of gravel over clay.
* Where compacted made ground has been placed over soft soil or fill, this can settle over time, so that instead of contributing to pile load resistance it applies a downdrag force to the pile shaft.

* The early years of CFA piles saw many problems, now mostly solved by precise instrumentation and monitoring of boring and concreting. However the quality of the pile base can still be unreliable. In wet and soft soil, ‘flighting’ can occur: the auger pumps soil out of the hole instead of drilling into it (like a corkscrew in a bad cork).
* Segmental Flight Augers are now used for smaller diameter and work in limited headroom. Many problems can occur with these, as many rigs are not fully instrumented and the boring and concreting processes are not continuous.
* BS8004 says that piles should be made of concrete. However small diameter piles are often formed from 1:1 or 1:2 grout. Shrinkage and alkali silica reaction (ASR) are both potentially serious problems with these mixes and their structural performance is uncertain. An enquiry to the Building Research Establishment revealed that they were unaware of any research into these issues. They were also not aware that it had become common practice to form structural columns (piles) out of sand/cement grout. Beware!

* Underpinning must be taken down to a firm stable base and it must be connected to structure - it is no use if it is not properly pinned up. If the concrete is ‘poured under a head’ instead of being pinned up, unless care is taken the underpinning may not support the structure at all.

* If clay shrinkage is the problem, piled underpinning is usually unsuitable, as it creates a two-level foundation. Unless precautions are taken, the building may be lifted off the piles when the clay swells in winter.

Grundomat minipiles - steel tubes driven by a vibrating hammer, typically 150mm diameter. On this size of pile, most of the surface area is the shaft, so most of the load capacity comes from friction and only a small amount from end bearing. When these piles bear on weak rock they can have very low capacity.
One-sided piling: the attraction of the idea is understandable but what happens if the external walls of a house are piled and internal walls are not? Differential movement could be a serious problem. Also there are technical problems:

* piles driven to refusal may have very low tension capacity unless they penetrate a long way into a firm stratum;
* a system based on raking piles will generate lateral forces - and unless the ground is good enough to resist this, movement may occur; the sharing of forces between the piles will depend on where this force acts.
The load capacity of one-sided knuckle piles is limited by the moment capacity of the pile and its head connection.

One sided screw piles: pile capacity will depend on soil conditions and also on the moment capacity of the pile and its head detail. It will also depend on the strength of the connection to the existing foundations. The load capacity when all of these are considered is likely to be very low. Where the property has cavity walls how is the inner leaf of a cavity wall supported?

Pile jacking can be a useful technique. However note that the piles should be tested to 1.5xSWL (Safe Working Load) to prove their adequacy. If the piles are in clay the load must be applied for a sustained period to be meaningful - which probably makes the technique impractical in this situation.
Although installation of the ‘Hoopsafe’ system looks like underpinning, with holes being excavated around the property and filled with steel and concrete, it is in fact very different: the concrete goes alongside the existing walls and foundations, rather than below them, and it is prestressed on completion. When considering possible use of it on a project, the engineer needs to consider how it will work with the existing structure. Is the idea to prestress the existing brick walls or to prestress the new concrete beams? What happens to the internal walls? How strong is connection between the Hoopsafe beams and the house masonry walls? How is the inner leaf of a cavity wall inner leaf supported?
The suitability of the system for a particular project will depend on the answers to these questions.

Expanding grout injected into the ground is promoted as an alternative to underpinning. One problem with grout is that it goes where you want it to, also where you don’t want it to (e.g. drains, cellars of adjacent properties). The representative for a firm selling one system at a seminar told us in all seriousness that it had a special molecular structure which expands vertically but not horizontally!

On the project illustrated above, insurers insisted on expanding grout instead of underpinning for an extension which was settling relative to the main property. Movement was monitored before and after - and it moved faster after grouting than it had before. Under their 10 year guarantee the contractor offered to pump in more grout. We decided to underpin it properly instead. As can be seen, the grout had spread horizontally as well as vertically (surprise?). The soil was fill comprising soft clay and sand and the grout had run into the sand layers but not the clay. Compressing soft clay only makes it worse, so it was no surprise that the expanding grout failed to solve the problem.
Precast concrete piles are usually connected together by costly fabricated joints but one manufacturer has a system held together by locating dowels and glue. The trouble is that each hammer blow sends a shock wave through the pile which can send the end segment flying off (like the balls in ‘Newton’s cradle’), unless the ground is very firm. ‘The house that sank’ was a new house on these piles that settled by 1 metre.

On a recent project a major national contractor used SFA piles. He did the integrity testing himself but several piles failed. The specified SWL was 310kN and a static load test to 1.5SWL. The contractor argued noisily against static load testing, saying that it cost too much and ‘nobody does this any more’. The first test passed 1.0 SWL successfully but at 1.25SWL it settled 26mm - failure. A second pile settled 22mm at 1.5SWL and kept moving, so it failed too. There were no more arguments about static load tests. Integrity tests by an independent testing contractor found twice as many defective piles as the piling contractor’s own testing. The whole job had to be re-piled.

As noted earlier, the BSP and Hiley formulae have limited accuracy is limited but are fairly respectable.

A typical formula for Grundomat piles predicts infinite load capacity at refusal! I have seen failures of Grundomat piles driven to rock. Geotechnical calculations show end-bearing capacity is small and pile loads should be modest.

The Engineering News formula dates from 1882 and uses a safety factor of 6. In the 1960s Terzaghi and Peck said it should no longer be used.

SCI publication P156 includes the EN formula, saying it is used in the USA. However it fails to mention that it needs a safety factor of 6 and is hopelessly inaccurate - and it gets the formula wrong.
Some anecdotes about real problems

(i) A national piling contractor who believed driven piles are ‘self testing’ calculated the set for each pile depending on its load and drove long piles in clay with layers of peat on this basis. When some failed to achieve their designed set, he calculated a revised capacity based on the actual set and added more piles. What he did not realise was that (a) the Hiley formula is not accurate for long piles in clay and (b) the failure to achieve a set was sign of a soft layer (peat) at depth. The piles failed.

(ii) On a job in Cheshire a contractor proposed 200mm bottom driven piles with SWL = 200kN. Based on geotechnical calculations, the estimated pile length was 13-14m. The piling contractor said this was very conservative and the piles would achieve refusal well before this. I asked him what weight of hammer he used - he said 250kg, with a 1.7m drop. With this the BSP formula predicted a refusal load $R_u = 154kN$, so no wonder the piles couldn’t be driven to 13-14m - they were never going to achieve the specified SWL of 200kN. Because the piling contractor did not know about the BSP piling formula, he had bought too light a hammer.

(iii) On another job a contractor proposed 220 diameter driven piles for 320kN SWL. Instead of using a standard formula, their engineer relied on a formula his old boss had devised which predicted over 1500kN ultimate capacity. The standard BSP formula predicted less than half this. The contractor promised that the piles would be OK. He was confident they would easily carry the load and argued that a load test was expensive and unnecessary. However on site the piles struggled to achieve the design set. The load test failed at about 175kN i.e. 50% of the specified SWL. There were no more arguments about load testing - the job had to be re-piled.

(iv) On an underpinning job in Scotland, with fill overlying clay and rock, we told the contractors that bored piles were probably appropriate but one contractor proposed:

(i) Grundomat piles bearing on rock, which were rejected, then

(ii) pile jacking to 1.0SWL, which was rejected, then

(iii) pile jacking to 1.5SWL but no sustained proof load, which was rejected because of the clay, then

(iv) driven piles with a predicted 300kN SWL for 220mm piles driven with a 0.5t hammer. The contractor used the SCI P156 Bearing Piles formula (see earlier), which predicted $R_u = 785kN$ and SWL = 314kN with a safety factor of 2.5. However the standard BSP formula predicted $R_u = 161kN$ and SWL 64kN, so this proposal was rejected.

The contractor then gave up suggesting different ideas and accepted that bored piles would have to be used.

I could go on ....

It is clear that design to BS8004 is the exception rather than rule. Many piling contractors are simply guessing load capacity, driving piles to near refusal and hoping for the best. ‘Who Dares Wins’ - the piling contractor who uses fewest piles bids the lowest cost and wins the contract.

It is important to remember that, when a consulting engineer is appointed to design foundations for a building, it is not enough to simply state that the piles should be designed by a specialist contractor to carry the stated loads. In a recent case in Northern Ireland, the judge (rightly) ruled that in this situation the consulting engineer still had a duty to his client for the adequacy of the foundations. Although the engineer could not be expected to carry out the full detailed design of the piles, he had a duty to carry out approximate checks to satisfy himself that the design was ‘in the right ballpark’.

When foundations fail, the costs to the project are out of all proportion to the money saved by skimping on the design and construction. ‘Leaving the design to the contractor’ can be a formula for disaster. For their own good and also the good of their clients, engineers need to assert their authority more on projects, carry out simple checks on designs submitted by piling contractors - and reject those which are not good enough.

For details of pile driving formulae and other engineering issues, see my website www.anbeal.co.uk

Alasdair Beal March 2012