Quality assurance of bored pile foundations
By Gordon Cameron, PhD research student, Napier University and Tim Chapman, associate director, Arup Geotechnics.

Abstract
The performance of a bored foundation is affected by the construction quality of the individual piles comprising the piling system. For the purposes of quality assurance, a programme of non-destructive integrity testing (NDT) is usually implemented on a specified percentage of the working piles. Traditionally, the proportion of piles to be tested is decided upon by the foundation designer based on site-specific knowledge, engineering judgement and his prior experiences of NDT. This paper shows how the use of statistics and probability theory may help influence this decision.

Introduction
Bored cast in situ piling is regularly specified in the UK to support the ever-taller structures that are being built in urban locations. However, the high degree of contractor workmanship, experience and supervision necessary in construction coupled with the naturally variable soil and groundwater conditions on site, makes bored cast in situ piles particularly vulnerable to structural faults and variable in construction quality (Thorburn and Thorburn, 1977). The subterranean nature of their formation makes direct, visual inspection of the finished product impossible in most cases. Faced with uncertain quality, it is unknown whether the piles tested will be suitable for their intended operational function. Therefore to verify satisfactory construction and detect any defective piles that may exist, non-destructive integrity testing is usually implemented on a specified percentage of the pile population.

Blanket inspection of every pile is the most conservative yet widely adopted quality assurance (QA) strategy in the UK and internationally. However, when this is impossible, due to the number of piles or the time or cost involved, then a more detailed strategy must be adopted. This paper shows how the use of statistics and probability theory may help influence the decision about the number of piles to be tested.

Table 1
Factors that can influence the quality of piles on a particular site
- The variability of ground conditions across the site and with depth
- Knowledge of the specific ground conditions gained from a detailed site investigation
- Contractor skill and experience with a given pile type under similar operating conditions
- Supply of materials of correct quality
- Appropriateness of construction procedures for the particular soil and groundwater conditions
- Level of workmanship and site supervision during construction
- Intensity of programme pressures on the piling work
- Effects of ground movements and site traffic during construction
- Appropriate method and care in trimming pile head to final cutoff level

In general, piling contractors produce bored cast in situ piles to the best of their ability, following industry best practice to reduce the likelihood of faults. Nevertheless, faults can still occur both during and after construction in a small proportion of a pile population, with the factors in Table 1 influencing the number of piles affected on a given site.

The presence of a single pile fault does not necessarily imply that a pile cannot be used for its intended purpose. Once constructed, there must be a belief that each and every pile satisfies three general design criteria:
- Meet serviceability limit state requirements and support a proposed working load without settling by more than is permissible.
- Meet ultimate limit state requirements and carry a specified load and remain durable throughout the design life of the structure, such that the pile is not affected by time dependent activities like corrosion of the steel reinforcement or chemical attack of the concrete, which would affect its ability to continue satisfying the first two criteria.
- Some faults that occur will be more serious than others, given the site specific operating conditions of a particular foundation. However, any fault that is likely to adversely affect performance, safety or durability of a pile, in either the short or long term, should be considered a defect, with a pile containing one or more defects being classified as defective.

Incorporating defective piles into the foundation system may adversely affect its performance, safety or durability, and depending on the remedy offered by the piling layout and the robustness of the superstructure, result in failure with consequential remedial costs or even loss of life. Alternatively, implementing unnecessary inspection or remedial work on sound piles may cause defects to be inadvertently formed where there were none, or adversely affect project economy by increasing construction cost and programme of the foundation works.

Disputes about the cost of remedial works are common between clients or main contractors and their piling subcontractors when further examination shows a pile with an apparent defect to be subsequently sound.

Therefore, after implementing a QA programme of integrity testing on up to 100% of the working piles, using an integrity testing system that may be less than 10% reliable at detecting defective and non-defective piles, how confident can a foundation designer be in the construction quality of the entire piling system, and thereby the final piled foundation? Also, what is the minimum proportion of piles that should be tested on a project, under certain conditions, to achieve an acceptable level of quality assurance?

This paper shows how the use of statistics and probability theory may help answer such questions. Through the use of a statistical approach, a foundation designer may be able to quantify their level of confidence in the foundation quality, in addition to deciding on an efficient QA programme of integrity testing. Previously developed statistical approaches have not taken into account the inaccuracy of the integrity testing process and the likelihood that a wrong diagnosis could be made regarding the true pile quality. This paper presents and discusses the results of analyses performed using a more detailed statistical sampling approach, which considers the reliability of the integrity testing system.

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- Supply of materials of correct quality
- Appropriateness of construction procedures for the particular soil and groundwater conditions
- Level of workmanship and site supervision during construction
- Intensity of programme pressures on the piling work
- Effects of ground movements and site traffic during concrete hardening
- Appropriate method and care in trimming pile head to final cutoff level
Reliability of automated algorithm for detecting whether the threshold has been breached

Tester experience with the given integrity test under similar operating conditions

Clearly redundant

Minimal effect

Non-redundant

Pile integrity: Is the pile of the correct dimensions and structural quality?

Pile capacity: Will the pile satisfactorily withstand a specified loading?

Table 2: Degree of redundancy offered by different pile cap arrangements (see Paikowsky, 2003) for 92 = 2.

<table>
<thead>
<tr>
<th>Number of piles in the structural column</th>
<th>Level of redundancy offered by the pile layout</th>
<th>Consequence of 100% loss of capacity of any one pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-redundant</td>
<td>Working load is equal to failure load</td>
<td>Extremely unsafe with potentially very large settlements</td>
</tr>
<tr>
<td>Logically non-redundant</td>
<td></td>
<td>Failure is likely</td>
</tr>
<tr>
<td>Support reduced to two piles</td>
<td></td>
<td>Failure still likely as centre of support from load</td>
</tr>
<tr>
<td>Factor of safety equals 1.0, therefore stability is marginally satisfactory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearly redundant</td>
<td>Support reduced to just two piles</td>
<td>Failure still likely as centre of support from load</td>
</tr>
<tr>
<td>Factor of safety equals 1.0, therefore stability is marginally satisfactory</td>
<td></td>
<td></td>
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</tbody>
</table>

Reliability of integrity testing

The most widely specified form of non-destructive examination in the UK are:

External: Sonic Echo (SE) and Transparent Dynamic Response (TDR)

Internal: Cross-hole Sonic Logging (CSL)

These are typically specified in design briefs as integral features of a pile from its acoustic response to the test. Wolman (1971) and 1974 and Preiss and Shapiro (1975) suggested the need for an integrity test to be associated with the pile integrity along with their attributes under different operating conditions. With these methods, the indirect nature of the integrity inference means that high degree of judgement and subjective interpretation is required when evaluating the structural quality of each pile tested.

Integrity testing reliability can be defined as the degree to which a system or component responds as anticipated in an NDT test and the interpretation of that evidence corresponds with the true state of a pile insitu. As such, any inaccurate or insufficient test data may impact integrity arising from improper test application or a lack of knowledge and experience in data interpretation. Herbin (1988) has examined the reliability of different integrity testing methods in various case histories. Furthermore, a detailed discussion of the factors influencing the accuracy of integrity testing systems has been provided by Davis (1999). Some factors influencing the reliability of testing conclusions are given in Table 3.

Table 3: Factors that can influence the reliability of integrity testing conclusions

- **As-built dimensions of the given piles and pile cap head preparations for testing**
- **Easy access to the pile head for penetrations**
- **Internally: Sonic Echo (SE) and Transparent Dynamic Response (TDR)**
- **Internal: Cross-hole Sonic Logging (CSL)**
- **As-built dimensions of the given piles and pile cap head preparations for testing**
- **Easy access to the pile head for penetrations**

- **Ability of a specific type of integrity test to detect various types of pile fault**

- **Experience with the given integrity test under similar operating conditions**

- **Volume and quality of supplementary construction and pile data used to interpret results**

- **Level of knowledge and experience in signal interpretation**

- **Determining the operational significance of pile failures in the test results**

- **The basis on which threshold values (beyond which a pile is classified defective) are determined**

- **Reliability of automated algorithm for detecting whether the threshold has been breached**
are modelled in Figure 3. Foundation quality is expressed by the number of defective piles remaining, and thus incorporated into the final piling system, after the implementation of a programme of integrity testing and subsequent repair.

As shown in Table 2, it may be possible for a foundation to tolerate a number of defective piles without being significantly adversely affected, due to the redundancy offered by the piling layout. Therefore, to assure foundation quality through a programme of non-destructive testing, at least all but a tolerable number of defective piles must be detected. The degree of confidence in satisfying this QA criterion (level of quality assurance achieved) can be quantified through the use of a statistical procedure. Referring to Figure 3, the statistical analysis answers the question:

- What is the probability of detecting at least all but a tolerable number of defective piles amongst the (ND) apparently defective piles detected and subsequently repaired within a sample of (n) piles tested at random using an integrity test with a defective and non-defective detection reliability of 1-(0.8) and 1-(0.9) respectively, given that a total of 5% defective piles are assumed to initially exist within a population of 100 piles prior to the programme of inspection and repair?

This degree of confidence is given symbolically as: Pr[(ND – TD) ≥ (ND – nD)]

**Discussion of results**

The results of statistical analyses, for a range of likely practical values, are given in Figure 4. Each graph shows the number of piles tested versus degree of confidence, within a population of 100 piles for a given number of defective piles in the population, testing reliability and tolerable number of defective piles.

Assume that the pile population contains 5% defective. The foundation can tolerate up to four defective piles (TD = 4) and the integrity testing system used is 100% reliable at detecting defective piles, then a totally competent testing specialist would be 96% confident in detecting at least one defective by testing 37 piles. However if the test is only 60% reliable then the same testing specialist would be only 71% confident. Furthermore, to achieve the same 96% level of confidence, with a 60% reliable test, 62 piles should be inspected. Thus, to achieve the same level of quality assurance with the less reliable integrity test, almost twice as many piles should be tested. Therefore, the results show that:

- For a given number of piles tested, a greater degree of quality assurance will be achieved with a more reliable integrity testing system used;
- A more reliable integrity testing system requires a smaller sample of piles to be tested to achieve a predetermined level of quality assurance.

A programme of integrity testing is effective if the QA criteria are satisfied with an acceptable level of confidence and efficient if those objectives are accomplished with as little effort as possible.

If it is assumed that the cost and time required to test a pile is the same for each type of integrity test, then to achieve a predetermined level of quality assurance, the more reliable the test is the more effective and efficient the testing programme due to the smaller sample of piles to be tested.

However, in reality, the cost and time to test a pile varies with the different NDST methods. For example, testing a pile using a SE or TDR method may only take a few minutes (30 to 20) piles tested per hour with a good access (PFS, 1996) and cost typically £1 to £2 per pile in addition to a site mobilisation fee and minimum testing charge, while a CSL test may take up to an hour per pile and cost hundreds of pounds depending on the length of the piles and the number of pre-installed access tubes.

As such, in achieving a predetermined level of quality assurance, increasing the reliability of the integrity testing system improves the testing effectiveness, as a smaller sample of piles must be tested. However, the testing efficiency does not necessarily improve due to the increased time and cost of testing each pile with a more reliable test method.

Many foundation designers like to believe that they are achieving high levels of confidence during integrity testing. However, even when a NDST programme is carried out on an entire pile population, a foundation designer can rarely guarantee that there will be absolutely no defective piles incorporated into the final foundation.

In fact, the results show that even if blanket inspection of every pile is performed, in the hope of achieving total quality (UD = 0), the inaccuracies in the integrity testing system only allows for low levels of confidence to be achieved. For example, assume that the population contains 5% defective and the integrity testing system used is 60% reliable. If a programme of 100% inspection is carried out under those conditions, the likelihood of detecting all the defective piles in the tested sample is only 32%. Thus, on the basis of these data, foundation designers need to allow for either accepting:

- Lower levels of confidence in ensuring total quality of the foundation;
- That the piled foundation should tolerate a number of undetected defective piles.

Furthermore, for a given level of confidence, the more defective piles that can be tolerated, the less integrity testing is required. Thus, the amount of in situ redundancy offered by the piling system (tolerable proportion defective) may influence the decision as to how many piles should be integrity tested.

It is the general recommendation of many (Turner, 1997; Paikowsky, 2001) that every pile on a given site should be post construction tested for defects. However, in practice it is often difficult to test 100% of the working piles due to a number of factors including cost, time and access. As foundation construction is usually on a project’s critical path, any delays that may occur during pile testing can adversely affect the progress of all follow on activities, the direct cost of which may exceed the value of the entire piling contract (Chapman and Marvettone, 2003).
As such, there is a significant advantage in terms of cost and programme if some piles could be omitted from testing. Consider a programme of inspection carried out on a population of 100 piles, assumed to contain 5% defectives, using an integrity test that is 80% reliable. Under these conditions, Figure 5 shows the increase in confidence (quality assurance) gained for every additional 10 piles tested. It is shown that where the foundation can tolerate up to four defective piles, most benefit comes from the initial piles tested. However, where the foundation cannot tolerate any defective piles with, in most, benefit comes from testing the final piles. Therefore, the greater the reliance on each individual pile in a population, the more important it is to check the integrity of every single pile, even when performing 100% testing may be disruptive to the construction programme.

Figure 5 shows that in some cases the added value gained by the last piles tested could be judged by the foundation designer not to be worth the time and money involved in the testing. This is particularly true on large projects with a rapid construction programme, where the construction manager wants the groundwork contractor to follow on directly as the piling contractor leaves site.

Often on these projects, there is immense pressure not to integrity test the final say 20% of the piles to allow an earlier package handover. The analysis shows that such an omission may be possible only if the tolerable proportion of defective pile is high. Hence, there could be programme advantages in selecting a more redundant foundation system.

Conclusion

Many engineers like to perform 100% inspection in the hope of detecting all the defective piles that may exist on a site. However, the results of statistical analyses have shown that even if every pile is tested, the accuracy of the integrity testing system used does not allow for high levels of confidence to be achieved. Furthermore, in some cases testing slightly less than 100% of the piles may be a viable option, with little reduction in the level of quality assurance occurring but with potential benefit in terms of cost and programme savings. Nevertheless, it must be highlighted that the only way that this can happen is by selecting a more redundant foundation design.

Hence, the redundancy offered by supporting columns on a layout of pile groups, as opposed to single large diameter piles, may serve as a major reason for a decrease in the amount of integrity testing necessary for quality assurance of a bored pile foundation.

As in any modelling activity, assumptions and simplifications have been made to the real life pile construction and integrity testing sequence to model the problem in a statistical manner. Notwithstanding, the use of these statistical results, supplementing experience and sound engineering judgement, may provide a more rational basis for deciding on a suitable level of integrity testing, thereby helping to improve foundation construction efficiency.

The paper highlights the folly of absolute reliance on the results of integrity testing as the sole arbiter of quality in bored pile foundations. While integrity tests have a valuable role to play in the detection of defects, statistical analysis accounting for inaccuracies in the techniques, indicates that a high level of dependence should not be attributed to the results of integrity tests alone. Moreover, the best approach in ensuring quality of piled foundations is to follow the basic principles laid out by Chapman and Marcellutti (2003):

- good site investigation properly gathered together
- careful design appropriate for the particular ground conditions as part of a coherent design process
- appropriate choice of acceptable piling methods
- clear specification and fair procurement of the piling contract
- experienced contractor who has considered all the risks
- independent supervision to verify that standards are maintained.

Adopting this doctrine should reduce the likelihood of defects occurring and maximise the likelihood that suspected piles will have already been identified prior to integrity testing. The findings of this paper reinforce these well-accepted principles.

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References


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Figure 5: Marginal benefit of testing each additional 10% of the pile population.

![Figure 5](image-url)

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