The Repair and Enhancement of Large Diameter Caissons by Grouting

D.A. Bruce[1], M.ASCE, and R.P. Traylor[2]

Abstract

This paper illustrates how grouting techniques have been used to enhance large diameter caisson performance at different stages in construction. Attention is focused on the basic principles for the repair by grouting of the pile concrete itself – when compromised by cold joints, honeycombing or soil or slurry inclusions. A generalized repair methodology is presented, including the assessment, planning, execution, and verification steps.

Introduction

Large diameter caissons may be defined as reinforced, cast-in-place, replacement piles. The initial ground perforation is usually conducted using casing or slurry to temporarily stabilize the hole prior to placement of the reinforcing cage and the concrete although there may be occasions when the site geology permits "open hole" techniques to be used. Most caissons have diameters in the range 1.2 to 2.5 m. In many parts of the world, but especially in Western Europe and the Middle East, grouting is an increasingly common expedient to enhance pile performance and capacity. As summarized by Bruce (1986), grouting can be used at different stages of pile construction:

1. As a ground treatment prior to construction to fill voids in karstic, mined or solutioned rock masses, or to enhance the density, stiffness or strength of soils. Endo (1977) illustrates the use of chemical grouts to pre-treat founding sands and gravels (Figure 1).

[1]Principal, ECO Geosystems, Inc., P.O. Box 237, Venetia (Pittsburgh) PA 15367 phone: (724) 942-0570 fax: (724) 942-1911; email: eco111@aol.com
[2]Manager, Geotechnical Division, Structural Preservation Systems, Inc., Baltimore, MD.

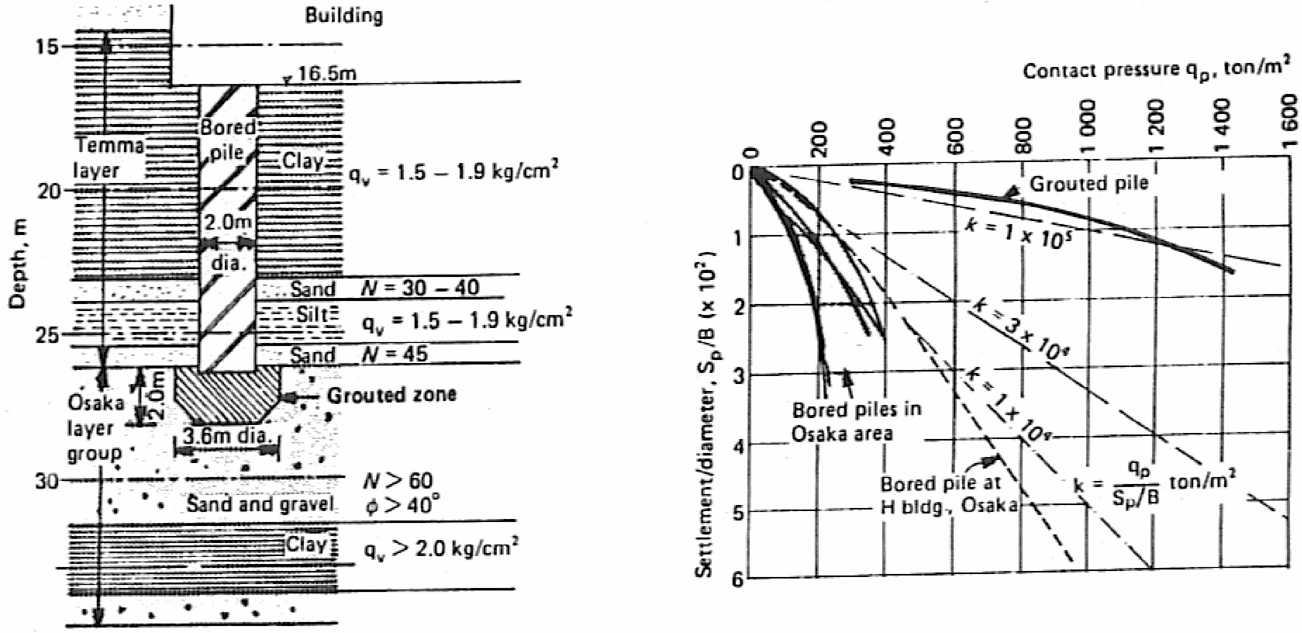
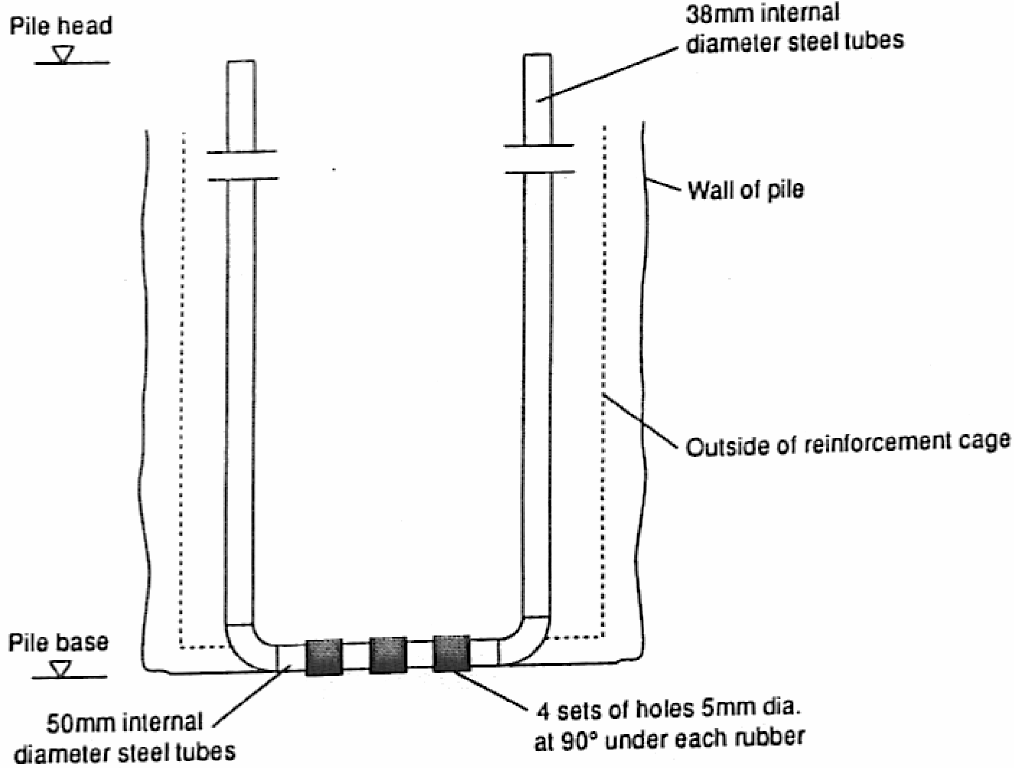
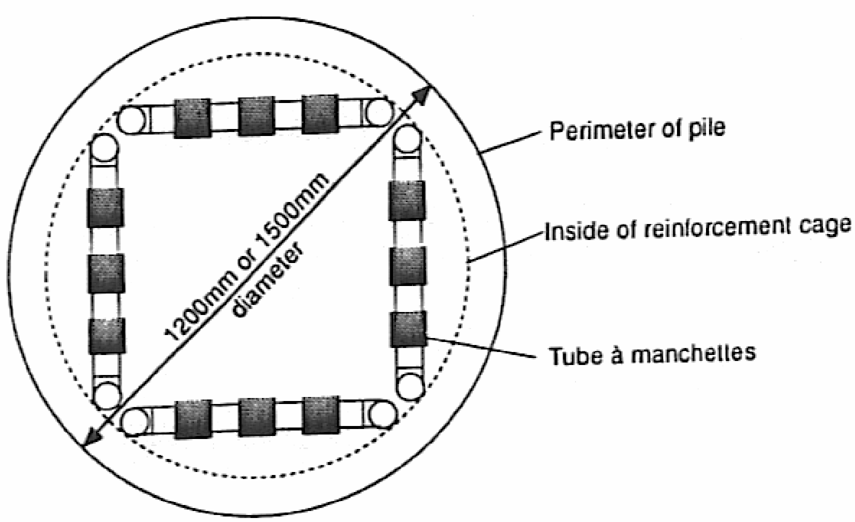


Figure 1. Details and performance of piles at Osaka founded on grouted soils (Endo, 1977).

2. To enhance skin friction and/or end bearing performance via devices placed into the pile together with the reinforcing cage. Cement based grouts are used to treat the pile/soil interface via tube á manchette principles (e.g., Figure 2) or to inflate closed cells or "flatjacks" at the base, or to otherwise inject aggregate filled "baskets", also at pile bases (Figure 3). These principles are used throughout the world, as described in numerous recent piling and grouting conference proceedings (e.g., *Piling and Deep Foundations*, 1989; *Grouting in the Ground*, 1992; and *Deep Foundations on Bored and Auger Piles BAP II*, 1993).
3. As a ground treatment immediately after construction. Loosening of the soils below the pile base, prior to concreting, may occur in certain ground conditions depending on the excavation method. Littlejohn (1983) described the strengthening of sands with resin grouts for depths of 2 m under pile bases in Jeddah, Saudi Arabia. This was conducted via tubes á manchette placed into holes drilled through the pile (Figure 4), after initial load testing had confirmed unacceptable performance in end bearing.
4. As an enhancement during service. The capacity of existing piles can be threatened by new, adjacent construction, a problem often encountered in urban engineering. This is shown on Figure 5 for the case of piles in Philadelphia, Pennsylvania impacted by new subway construction. Alternatively, redevelopment of a piled structure may require that additional loads be put on existing piles to the extent that the induced end bearing stresses may exceed acceptable design limits: Bruce et al. (1995) described how microfine grouting was conducted from three peripherally located sleeve port pipes to treat sands for a depth of 4.5 m below existing belled pile bases. Axial load testing (Figure 6)



a) Section of Individual Grout Circuit



b) Plan at Pile Base

Figure 2. Base grouting assembly, London (Francescon et al., 1992).

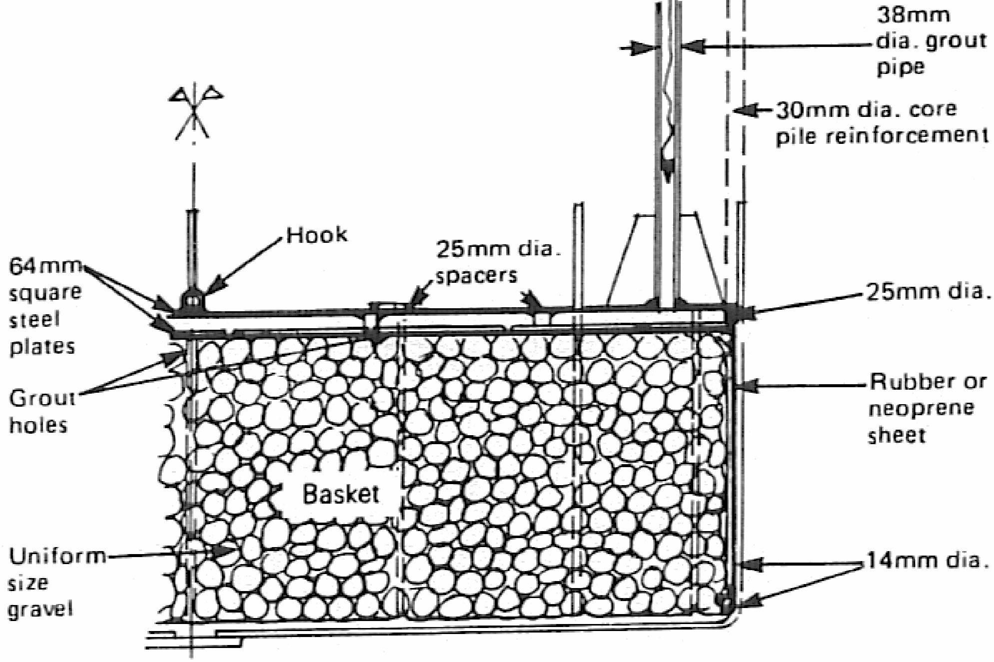
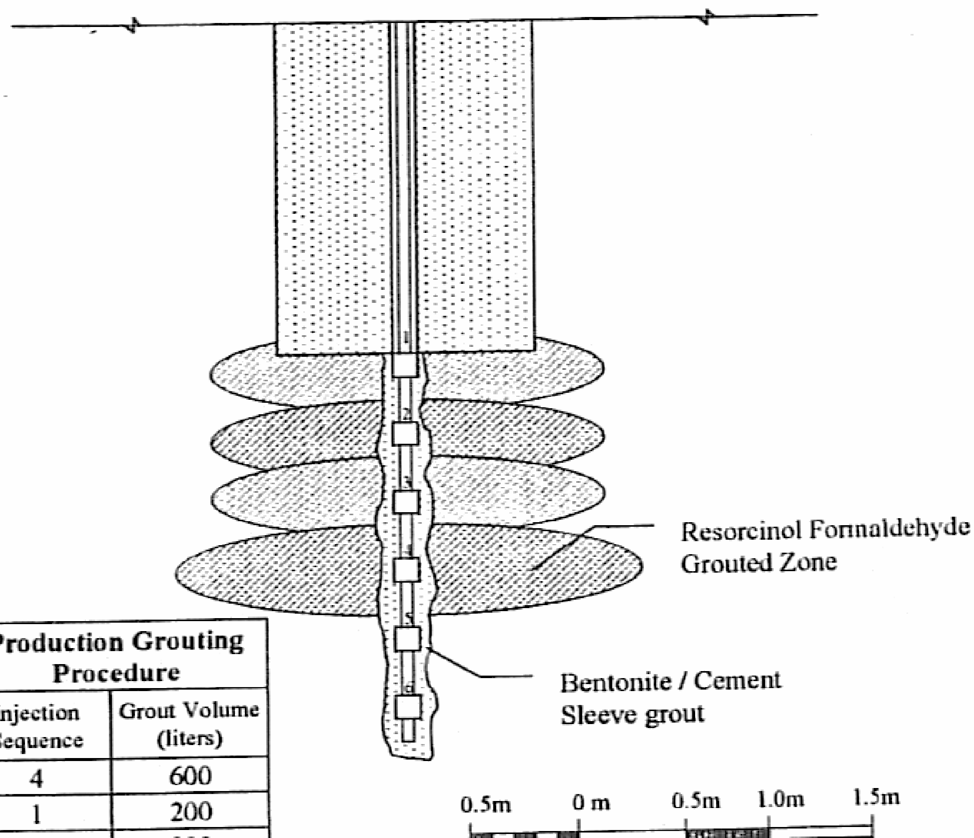


Figure 3. Details of base grouting device, Thailand (Teparaksa, 1992).



Production Grouting Procedure	
Injection Sequence	Grout Volume (liters)
4	600
1	200
2	200
3	200

Figure 4. Tube á manchette installation and production grouting procedure, Jeddah (Littlejohn, 1983).

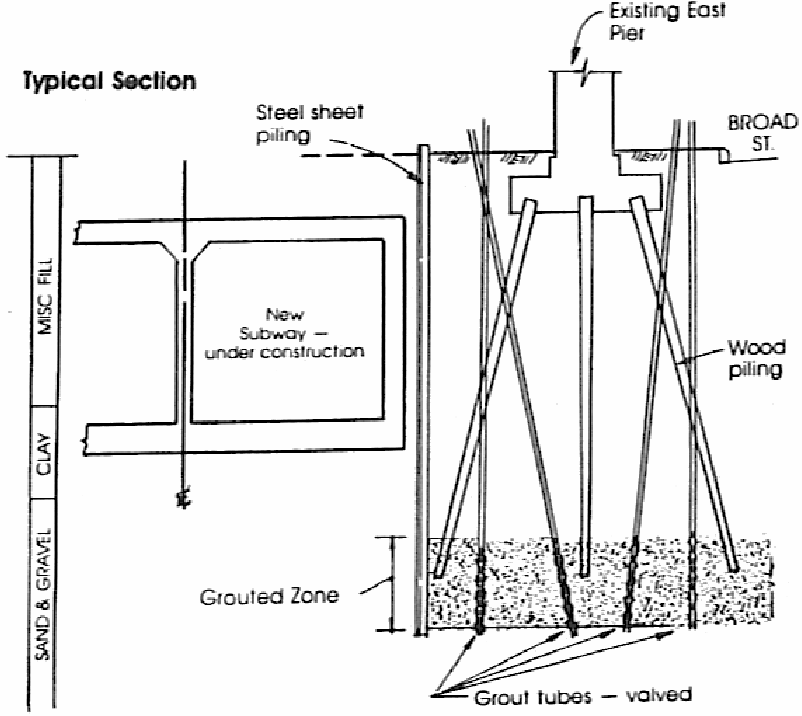


Figure 5. Grouting of sand and gravel to safeguard piles subject to external effects, Philadelphia, Pennsylvania (Karol, 1983).

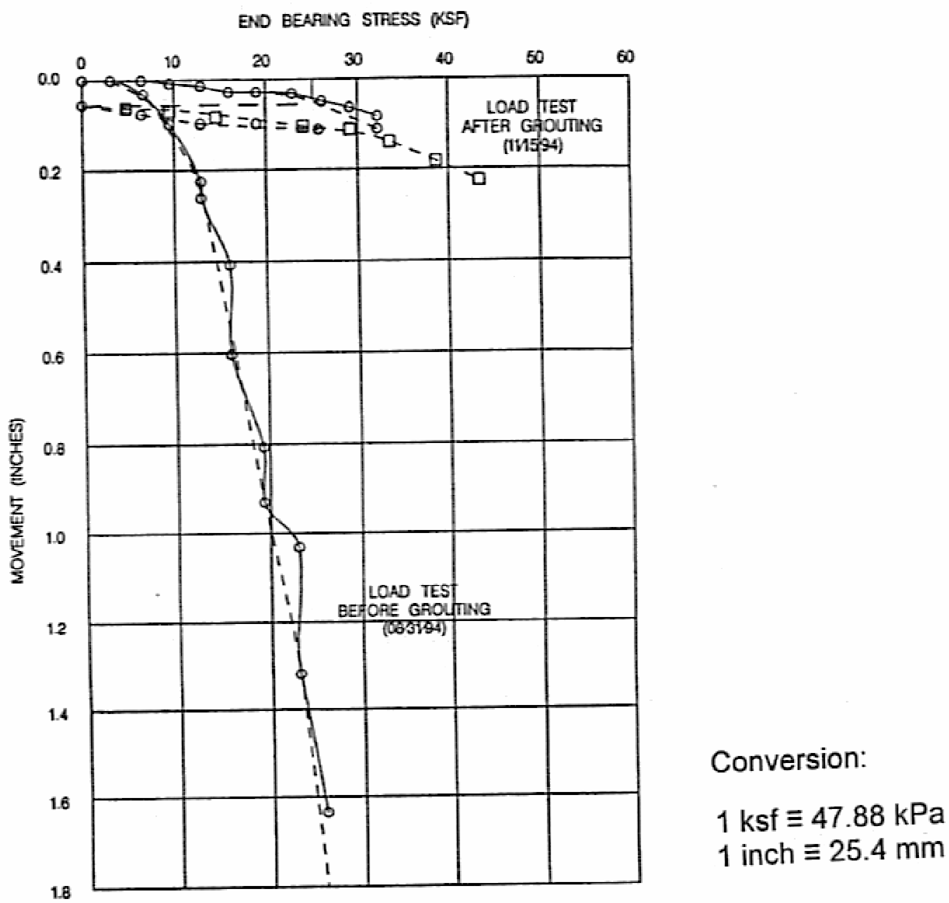


Figure 6. Movement/end bearing stress data for the test caisson, before and after grouting (Bruce et al., 1995).

clearly illustrated the degree of enhancement which was achieved in a 0.6-m diameter straight shaft test pile.

In each of these cases, the design, construction and verification of the grouting program tend to follow well established engineering criteria, supported by a wealth of published data. However, it is often the case that problems may arise with the quality and integrity of the concrete placed in the shaft, and its continuity with the ground forming its base. Construction records and post-construction tests may indicate the existence of unacceptable concrete, or the presence of soft, compressible material trapped between the pile base and the ground. Although this appears to be geographically a universal problem, there appears to be no universal approach to solving the problem: each case is treated in isolation, the wheel is reinvented, and the resultant effectiveness (and cost) is highly variable. The fact that it is not attractive to the contractors or the site construction inspectors to report on such repairs in the technical press does not help the situation.

The purpose of this paper is to provide simple guidelines as to how to approach the assessment, execution and verification of such repairs. As a general introductory statement, it would appear that there is no industry wide agreement on whether an anomaly – however detected – should automatically be regarded as a defect so requiring remediation. The authors would simply offer that an intelligent review and understanding of all the relevant information – technical, logistical, and economic – must form the basis of the decision to remediate or not: an anomaly need not always be a significant defect.

Generalized Repair Methodology

Awareness and Assessment of the Significance of the Problem

This can be carried out at different stages of the construction process and by different methods:

- During construction, observations on the drilling of the hole and/or the placement of the concrete may lead to the conclusion that there could be cold joints, honeycombs, or trapped soil or drill slurry.
- Post-construction non-destructive integrity testing conducted from the pile head can indicate the probability of internal defects or questionable basal conditions (*Piling: European Practice and Worldwide Trends*, 1992). Alternatively, cross hole sonic logging (CSL) can be conducted via PVC tubes attached to the inside of the rebar cage prior to installation (Branagan et al., 2000).
- Post-construction coring, possibly aided by in-hole geophysical testing, will confirm if such concerns are well founded.

- In the extreme case, static or high strain dynamic pile load tests will confirm the relevance of such defects from a system performance viewpoint.

With the benefit of such data, it must then be decided if any flaws which do exist constitute a significant departure from the Specification to the extent that the pile is genuinely flawed and/or a justification to attempt an in situ pile remediation as opposed to an outright rejection of the pile and an instruction to replace it. Alternatively it might just be decided to provisionally accept the pile as is, or to base final acceptance on a successful pile load test, if indeed it is logistically possible to conduct such a test.

Planning and Executing the Repair

This occurs in basically two steps:

Step 1 It is often the case that by this stage at least one cored hole has been drilled in the pile, usually (and nominally) at the center. The following actions may be then taken, depending on the urgency and significance of the problem:

- Verify that the hole is deep enough to investigate all the potential concerns: if not, deepen it.
- Conduct a video inspection of the entire hole length, focusing especially on any flawed areas.
- Conduct a series of packer tests on carefully selected stages in the hole to assess the internal "permeability" of the pile.
- Run an orientation survey on the hole to ensure that its trajectory, or alignment, in the pile is well defined. (This need only be conducted where the pile is relatively deep and where typical hole deviation – say up to 2% of depth – may therefore be a significant lateral deviation).
- Conduct any in-hole geophysical techniques which may be cost effective and/or technically feasible and useful. As a guideline, an anomaly will have to occupy at least 15 to 20% of the pile cross section to be detectable with fair precision with such geophysical methods.
- Depending on the position and trajectory of the hole, and its potential contribution to the subsequent repair process, pressure grout the hole in a very controlled and monitored fashion with an appropriate grout mix (as defined below) having placed any new steel reinforcement bar in the hole, as required by the Engineer's design calculations. Otherwise leave it open until Step 2 is undertaken.
- Carefully assess all available data, from cores, water testing and so on, and create a written method statement as the basis for the subsequent

repair. This document should be fully discussed and accepted by all parties prior to the repair commencing.

Step 2. This involves the execution of the new work as determined in Step 1.

- Drilling. The repair process will require at least two, and preferably three holes arranged uniformly within, around, and near the perimeter of the pile as illustrated schematically in Figure 7. The original investigatory hole (if present) can be used as one if it is appropriately located. The holes should be located to avoid (major) steel reinforcement. Holes may be drilled by coring or by down-the-hole hammer, and need not be larger than 150mm in diameter. Top drive percussion is not favored due to its tendency to deviate substantially. During drilling, careful records should be maintained of all relevant drilling parameters and observations (including loss of drill flush, interconnections, and so on). The trajectory of each hole should be measured as described above. Where a basal problem is anticipated, drilling should continue at least 1 m into the formation below the concrete, provided that the founding material is not susceptible to water disturbance, which is, of course, often the main justification for selecting a drilling slurry initially.

- Investigation. Water pressure testing and any geophysical testing (including cross hole seismic) that may be useful, are then conducted. Stage lengths for water testing should be chosen with respect to the location and extent of the pile "flaw", but should not be greater than 6 m in length. Testing in multipressure sequence (Houlsby, 1990) via a double packer (Figure 8), from the bottom of the hole upwards is recommended to maximize the usefulness of the data obtained since the precise location and hydraulic characteristics of each flaw can be identified.

- Washing. At this stage it may be useful to attempt to wash the flawed zone to remove any fine grained trapped material which would otherwise reduce the pile's amenability to grout. Various methods can be used, but most feature the use of a small diameter drill rod with a laterally oriented jet through which water and/or air can be ejected at elevated (but safe) pressures. If the goal is to remove clay or silt, especially in a subbasal inclusion, then a suitable chemical dispersant should be used.

  Interconnections between holes should be noted (and encouraged), and the process continued until no further debris is being eroded. The investigation tools and processes can then be reapplied to verify the effect of this washing phase.

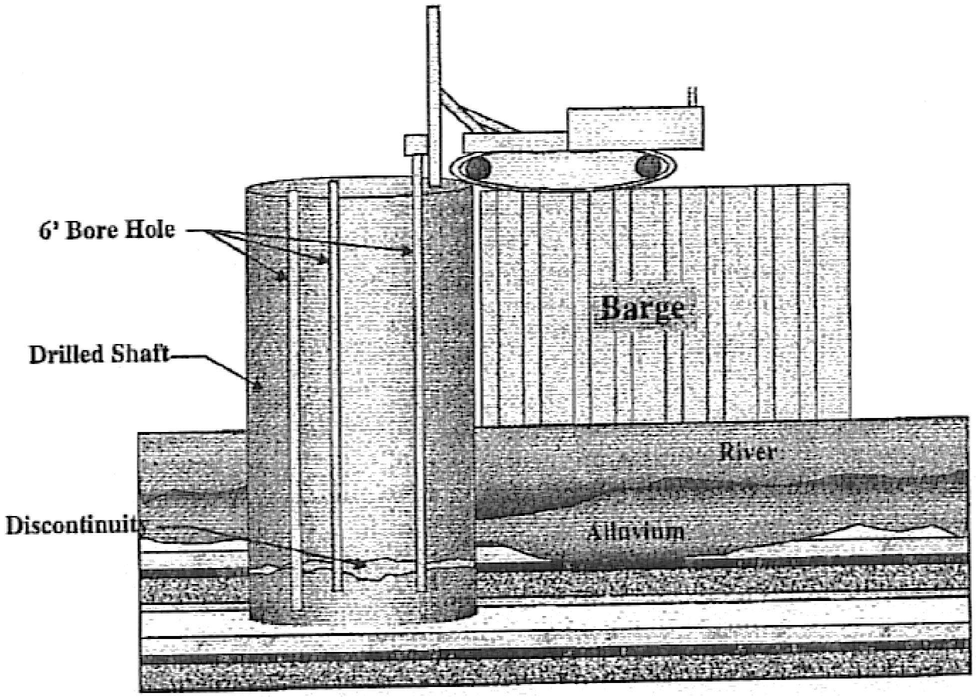


Figure 7. Schematic representation of drilling into a shaft containing a discontinuity.

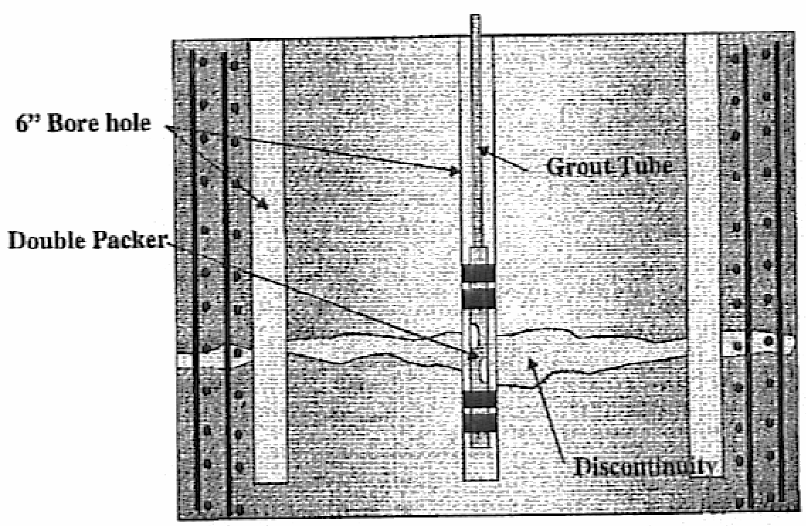


Figure 8. Schematic illustration of use of a double packer to investigate internal flaws.

- Grouting. The interpretation of the investigation data will determine the nature of the grouting operation, and in particular the characteristics of the grout mix design. As a general statement, if the permeability of the flaw is very low (say less than 1 Lugeon), then it is unnecessary and futile to attempt to pressure grout, bearing in mind that only particulate based grouts are acceptable. (Solution grouts typically have low strength, questionable durability, and high cost.) The particulate grout mix (regular or microfine based) must have low cohesion, excellent pressure filtration resistance, high strength (at least that of the pile concrete) and high durability (Gause and Bruce, 1997). This implies that it must be a carefully balanced and controlled blend of materials of low water/cement ratio, but including perhaps several additives: neat water-cement grouts will not meet the required rheological and stability criteria, despite the fact that they have been widely used in repair practice to date. Such grouts must be accurately batched, and mixed in high speed, high shear colloidal mill mixers.

  The grout volumes required will typically be small, and so the use of sophisticated computer-aided grouting analytical and control instrumentation will likely be cost-prohibitive. Nevertheless it is essential to monitor accurately the key grout injection parameters (pressure, rate, specific gravity, and marsh cone) in order to efficiently bring each successive grouting stage to proper refusal.

  Grouting is conducted in each hole in turn – or simultaneously, depending on the plan of operation – from the bottom up via a single packer. Interconnections between holes should be carefully looked for and recorded. If these do occur, the interconnecting hole should be "packered off" to prevent easy escape of grout, or, alternatively, injected simultaneously.

  During grouting it is prudent to observe structurally the pile for signs of cracking, movement, or peripheral grout escape. Any one of these phenomena should lead to immediate cessation of grouting activities and reassessment of the situation.

  After all the holes have been grouted to refusal, steel reinforcements may be placed in them if required by the pile structural design, and the holes then backfilled with an appropriate stable neat cement grout of adequate strength. (This may require the grout hole to be first washed or reamed clean of already set pressure grout.)

- Verification. Various levels of verification can be applied, depending on the situation and the requirements of the various parties. In increasing order of cost implication, these are:

  - Analyze the grouting data: this analysis will reflect on the quality of the execution of the grouting, as a grouting operation.
  - Drill and test through additional core hole(s): this will demonstrate the effectiveness of the grouting in terms of its reaching and filling any flaws.
  - Conduct some form of geophysical testing in the core holes, such as gamma-gamma logging or cross hole seismics. This will illustrate the continued presence of any significant flaws.
  - Conduct a full-scale axial load test if logistically feasible: this will prove the structural acceptability of the repaired pile.

Clearly, it is the intention that the remedial work will be successful to the extent that the caisson in question can be accepted by the Engineer as in all likelihood satisfying the specified design requirement. However, remediation is no guarantee of success: if the remediated caisson does not prove acceptable, then the options available are obvious: further attempts can be made to repair it, it can be accepted at a de-rated capacity, or it can be rejected and required to be replaced.

Final Remarks

Although it is of course true that all structural problems associated with the concrete of large diameter caissons are not the same, it is possible to design a relatively common approach to their solution. The methodology summarized in this paper is designed for piles with internal concrete flaws, or with unacceptable basal concrete/rock contacts. The methodology has been tried and proven on numerous sites throughout the world. However, where the problem involves large pockets or seams of clay or silts, which cannot be removed effectively, and which are not amenable to penetration by even microfine grouts, then other grouting options may have to be considered: in this context, the use of jet grouting may be dictated.

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