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The Construction of Bored Piles in Weathered Sedimentary Rock

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SUMMARY The conventional methods of constructing bored piles socketed into rock are critically examined. Rock socket designs normally involve construction-related assumptions regarding (i) socket dimensions, (ii) expected rock materials, (iii) rock disturbance caused by construction, (iv) base cleanliness, (v) wall surface conditions, and (vi) concrete integrity. Often these assumptions are not valid in practice, so that better construction equipment and methods are needed.

1 INTRODUCTION

The designer of the foundations for a structure usually makes several construction-related assumptions, often implicitly. The opportunity arose during the construction of the elevated section of the West Gate Freeway to study whether certain design assumptions were being invalidated by construction practice.

The twin structures of the 1.8 km elevated section of the West Gate Freeway through South Melbourne are founded on 420 vertical, bored, cast-in-place piles socketed into variably-weathered Silurian sedimentary rock or Tertiary basalt rock. The 72 basalt-founded piles generally had stable rock sockets that were dewatered and inspected, so that many of the construction-related assumptions made in their design could be verified (Evans, McDonald and Worotnicki, 1984, in this conference).

1.1 Geology of Site

The Silurian sedimentary rock consisted mainly of mudstones with the minor occurrence of sandstones ranging from thin laminations to relatively thick beds. The mudstones were deeply and erratically weathered with major folding and occasional faulting. The fault zones often contained highly to extremely jointed material with slickensided surfaces, which were the major cause of unstable sockets. Over most of the site, the Silurian bed-rock was overlain by 30 to 40 m of Quaternary deposits, which ranged from very dense sands and gravels that lie on the rock to very soft silty clays near the surface. The water table was relatively close to the ground surface, in many places being less than 1 m below it.

1.2 Design of Bored Piles

The steel-cased, reinforced concrete piles were 1.1, 1.3 or 1.5 m diameter. The majority of the piles were founded in mudstone at toe depths up to 62 m and with cylindrical rock sockets ranging from 2 to 25 m long.

A new settlement-based method was used in the design of these rock socketed piles (Williams et al, 1980; Pump and Evans, 1982). The socket design employed empirical load-settlement relationships determined for both base and shaft resistance. The necessary geomechanical parameters were obtained from a foundation investigation in which a borehole was drilled at each pile position. The main parameter controlling settlement was the rock mass modulus, which was usually measured with a pressuremeter. The other parameters used in the design were obtained from laboratory tests on the rock core. The individual piles were designed for a maximum settlement of 15 mm and a maximum differential settlement between adjacent piles in a pier of 5 mm.

In the rock socket design, certain assumptions were made in regard to (i) the socket dimensions, (ii) the materials in the socket walls and bases, (iii) the rock disturbance caused by construction, (iv) the base cleanliness, (v) the wall surface conditions, and (vi) the structural integrity of the concrete. This paper discusses how construction practice invalidated these assumptions.

1.3 Construction of Bored Piles

The mudstone-founded piles were constructed generally as follows. A sacrificial steel casing was installed through the overburden by vibration, oscillation, or percussion and seated about 1 m into the Silurian bed-rock. The overburden material was removed from within the casing by spiral flight auger or drilling bucket. The rock socket was normally excavated using a drilling bucket. The pile was concreted in 2 stages: (1) socket pour - concrete tremied under bentonite or water, finishing at least 2 m into the casing; (2) stem pour - concrete placed in the dry, after removing inferior concrete and placing steel reinforcement.

The rock sockets were constructed as follows.

Classification 1 (dewatered) Piles

A study of the rock core obtained at the pile location had indicated that the socket walls would be stable after dewatering. The socket was drilled under the water that naturally drained into the excavation. Following the drilling of the socket, it was dewatered, the base cleaned by a miner, and the socket walls and base were directly inspected, visually and manually, by a geotechnical engineer. The socket was then concreted by tremie under a full head of water. The design assumed a full base resistance component of load capacity.

Classification 3B (bentonite) Piles

A study of the rock core had indicated that the socket walls would be unstable or marginally stable after dewatering. The sockets for these piles were drilled and concreted under a full head of bentonite slurry.

After the discovery of excessive filter-cake on some socket walls drilled under bentonite, all further sockets in this classification were then drilled under a full head of water instead of bentonite, and called Classification 3W (water) Piles. The bored piles were constructed during four contracts by four different contractors, three of which are well-known international contractors. Therefore, this was a good opportunity to critically examine some of the conventional methods of bored pile construction currently being used in Australia and in other countries.

The detailed observations on which the following discussions are based are recorded in a comprehensive report (Holden, 1983a).

2 SOCKET DIMENSIONS

The designer assumes that the socket is excavated, within certain tolerances, to the correct diameter, length and base level.

The diameter of the socket is governed practically by the largest size of drilling bucket that can be readily lowered into the casing under working conditions. Sockets were designed with a diameter equal to the casing ID. However, measurements taken in Class 1 (dewatered) piles showed that this cannot be readily achieved in practice, thus resulting in a significant reduction in load capacity of the smaller diameter piles. Consequently, socket designs should be based on a practical diameter, which is 50 mm less than the casing ID.

Because of breakage and wear on the reaming teeth, the largest diametrical dimension of the bucket had to be checked regularly using a special gage, especially before the final drilling run.

Another major reason for not achieving the design diameter was that sometimes a significant distortion of the pile casing occurred during installation. The distortion was mainly observed after penetration through an overlying layer of completely to highly weathered basalt, whether using vibration, oscillation or hard percussive driving, and with or without predrilling.

The problem was eventually overcome by predrilling through the basalt layer and over-reaming the hole to a diameter slightly greater than the cutting edge OD with a special reaming tool.

3 EXPECTED MATERIALS

The designer assumes that (i) the end-bearing "layer" and (ii) the materials in the socket walls are those expected from the bore logs.

In over half the Class 1 (dewatered) piles, the investigation bores finished up outside the socket boundaries due to the rake of pile (1 in 120 allowable) and incorrect positioning and non-verticality of the investigation bore. The construction of deep piles socketed into steeply dipping rock layers or fault zones should therefore be monitored closely.

In Class 3 piles, which are constructed under a drilling fluid that prevents the direct inspection of the socket, special allowances should be made in design. It is also recommended that, at the start, the rate of socket drilling be correlated with the rock quality shown in the bore logs and verified in dewatered sockets, as well as being related to the cuttings of excavated rock. Using such relations an experienced geotechnical engineer can then check the rock quality during the socket drilling of Class 3 piles.

4 ROCK DISTURBANCE

The designer assumes that the rock materials in the socket walls and below the base are not significantly disturbed or altered by the construction process. For piles end bearing onto competent rock, the disturbance of the base material did not constitute a major problem, so only the socket walls will be discussed.

There was little evidence of mechanical disturbance from drilling tools of the wall material and besides the design method was based on research performed on rock sockets also excavated by drilling bucket (Williams, 1980); furthermore, chiselling methods were not permitted in the low quality Silurian rocks.

4.1 Rock Softening

Tests were performed to determine the softening (or degradation) of the Silurian rocks in contact with water or bentonite for prolonged periods of time. The results of these tests are summarised in a paper by Bamford and Washusen (1981). As a result of these findings, the specifications required that sockets which stood open in water for more than 6 days had to be reamed out by 25 mm radially.

4.2 Wall Instability

Instability of the socket walls can range from minor fretting of the walls to a major collapse.

4.2.1 Class 1 (dewatered) piles

There were some piles where minor collapses of rock occurred against the inspection safety shield. In these cases, the excavation was then filled up with bentonite and construction continued under bentonite. These collapses illustrate the difficulty in accurately classifying the stability of the whole socket from bore logs, especially by geotechnical personnel not experienced in making these engineering judgements. This point was highlighted by a major collapse that occurred in one dewatered socket during the construction of the initial piles.

4.2.2 Class 3B (bentonite) piles

There were cases where minor and moderate collapses of the rock wall occurred. These were caused by allowing the bentonite level in the pile to drop too far.

On some occasions a sand blow-in occurred, once again because the bentonite level was allowed to drop too far in piles for which a good seal of the casing in rock had not been obtained. Usually the situation was immediately rectified by raising the bentonite level close to the top of casing.

These occurrences emphasise the need to maintain the level of bentonite at least 1 m above the water table and preferably above natural ground surface, especially just prior to and during concreting. The practice of pumping the bentonite out of the pile during the concrete tremie pour was observed to be unsatisfactory because of the difficulty in matching the concrete pouring rate with the bentonite pumping rate. In the case of a high water table, it is recommended that a simple overflow system such as that shown in Figure 1 be specified, so that the bentonite level can be maintained at the top of casing.

4.2.3 Class 3W (water) piles

Because the sockets of these piles had been classified as potentially unstable, the water level was generally maintained between ground surface and top of casing, which was about 1 m high.

After the switch from bentonite to water as the drilling fluid, there were many piles in which fretting and minor collapses occurred, the resulting debris being observed by the Socket Inspection Device (see below). The socket of a pile at one anchor pier suffered a major collapse and steps had to be taken to ensure the integrity of the rock sockets of the three neighbouring piles.

Consequently, an alternative method for constructing sockets in unstable rock was tried, in which the socket was progressively excavated and lined with concrete using a "ream and line" method. The socket was further reamed out (by about 150 mm radially) over a certain depth interval, filled with concrete, and drilled out to the design diameter after the concrete had partially set. The process was repeated for the next depth interval.

Apart from being an extremely time consuming and expensive method, it does not guarantee the stability of the socket, especially if the arbitrarily chosen depth interval is made large to save costs. Furthermore, problems were encountered with the rate of hardening of the concrete, and in one instance the coring bucket was cemented inextricably in the socket.

4.2.4 Concluding Remarks

It was clearly demonstrated on this project that it can be disastrous to construct potentially unstable sockets under water. At best, it is unsatisfactory because of the possibility of continual fretting resulting in base debris (Sec.5.1.3). The best method is to rapidly drill the socket under bentonite with a powerful drilling rig, preferably using reverse circulation, while maintaining a strict control on bentonite properties.

5 BASE CLEANLINESS

The designer assumes that the base is clean - i.e., free from any debris or clay layer formed during the construction process - and thus that there is good contact between concrete and rock.

5.1 Base Debris

Many workers (e.g. Thorburn and Thorburn, 1977; Fleming and Sliwinski, 1977) have shown that base debris is a major cause of base defects in bored piles.

The compression of a layer of base debris will obviously affect the performance of an end-bearing pile, especially under a settlement-sensitive structure. Also, observations of the test piles recovered from the Middleborough Road Quarry site (Williams, 1980) showed that the fresh concrete forces some of the base debris a considerable distance up the socket walls. The resulting layer of redistributed base debris would therefore significantly affect the side resistance in the lower region of a socket, especially a relatively short socket.

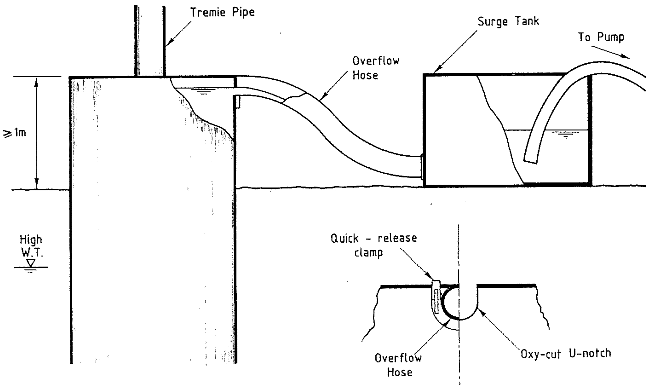

Figure 1 Bentonite Overflow System

5.1.1 Base inspection

The most common method, in Australia and overseas, of checking the cleanliness of the base uses a sounding device - usually a weight attached to a measuring tape. On this project, Clerks of Works used a brass weight attached to a measuring tape.

The limitations of this method are:

1) It is very difficult to feel the difference between some types of debris and the base material. This would be especially true where the pile was founded in soil and not hard rock. Using SID (see below), we demonstrated many times on this project how unreliable the sounding tape method was for detecting base debris (Holden, 1981).
2) For large depths of drilling fluid, it takes a long time for the sounding weight to move across the pile base; hence it is difficult, especially for the inexperienced person, to know if the entire base area has been sounded.
3) For "vertical" piles with a significant rake, the vertical hanging sounding tape cannot detect the presence of debris in the "shadow area" under the overhang.

A socket inspection device (SID), shown in Figures 2 and 3, was developed specifically to inspect and record the cleanliness of the bases of piles constructed under bentonite (Holden, 1981). The detailed description of this device is contained in a report by Holden (1983b). This device overcame most of the limitations of the sounding tape and gave a very clear picture of the condition of the base.

5.1.2 Class 3B (bentonite) piles

On this project, debris on the base arose mainly from two sources:

1) Cuttings left behind by the drilling process
2) Sediment that settled out of suspension.

Debris was also produced by (i) construction tools knocking, scraping, or scouring off material from the socket walls, and (ii) partial caving of the socket walls or a "blow-in" of sand due to a reduction in stabilising pressure caused by rapid drilling bucket withdrawal and/or a non-permissible temporary lowering of the bentonite level (Sec. 4.2.2).

The effectiveness of air lifting, which is the most common method of base cleaning, was found to be reduced by (i) the existence of a shadow area, which can be greater than half the base area, (ii) non-straight suction pipes, (iii) large pieces of debris,

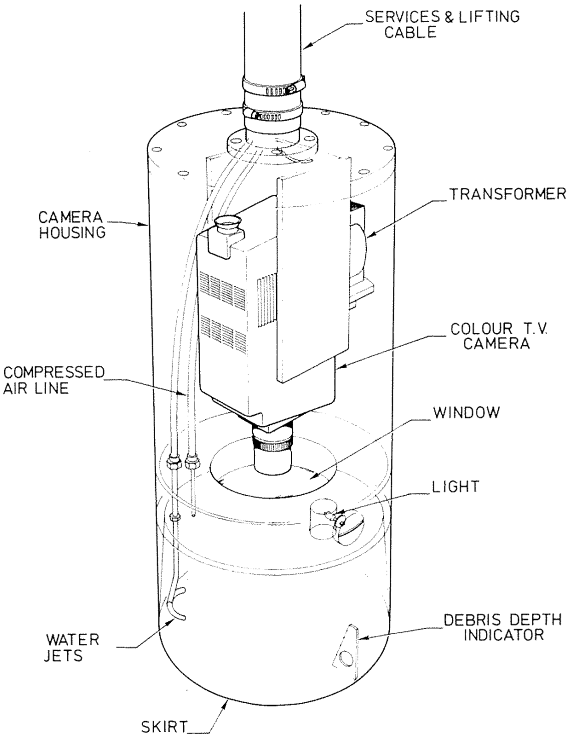

Figure 2 Socket Inspection Device (SID)

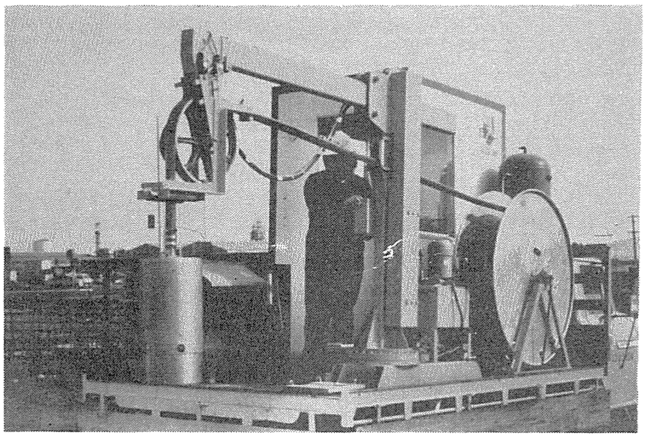

Figure 3 SID Truck

(iv) poor air lift inlet design, (v) a cohesive layer adhering to the base, and (vi) poor air lifting techniques. Using SID we showed conclusively, during all contracts, that the conventional method of cleaning pile bases using an air lift was not satisfactory in removing all debris. Moreover, because the air-lift pipe often blocked and its lateral movement was mainly random, the method was slow and inefficient. The ineffectiveness of conventional cleaning buckets was also clearly demonstrated using SID.

During the project, equipment and methods were developed that will effectively and efficiently remove all types of debris from the entire base area giving a very high degree of cleanliness, a fact which was verified using SID. Two base cleaning methods were developed during this project and each involved three basic operations:

1) Planing the base horizontal with a relatively even surface. The provision of a horizontal base is desirable for good SID inspections.
2) Recycling or replacing of drilling fluid to remove particles that would settle out of suspension.
3) Sweeping the base with a cleaning tool, while air lifting, to remove all remaining debris.

The disadvantages of conventional base cleaning methods and the development of satisfactory methods are described in detail in another report (Holden, 1983c).

5.1.3 Class 3W (water) piles

SID also proved to be very successful when used in checking the cleanliness of the bases of sockets constructed under water. As for Class 3B piles, debris resulted from drilled cuttings and sediment. Even very fine material, such as clays, settled out of water very quickly. Another important source of debris was material that came from the socket walls. These piles did not possess the stabilising effect of the bentonite filter-cake that occurred in the Class 3B piles. Consequently, the walls were subject to continual fretting and minor collapses, and material was more easily knocked off, especially by conventional cleaning tools. It was therefore often impossible to produce a clean base.

5.1.4 Class 1 (dewatered) piles

These piles were pumped out and miners cleaned the debris from the base, the cleanliness of the base being checked visually by a geotechnical engineer. After this direct inspection was made, the inspection safety shield was withdrawn and, because of the usual ingress of water into the socket, the pile was completely filled with water before the concrete was placed by tremie. Using SID, we observed that a substantial amount of material was dislodged from the walls during each operation after the inspection and this produced an unacceptable amount of debris on the base.

This observation demonstrated the need to inspect the bases of all sockets constructed in weathered rocks just prior to concreting. It also raised serious questions about the wisdom of constructing so many piles by the Classification 1 method, because a major reason for using this method was that 100% of the allowable end-bearing resistance would be achieved by manually cleaning the base. After also considering (i) safety (Holden, 1983a), (ii) time and cost savings, and (iii) the observation that the under-water cleaning tools produced cleaner bases than the miners, there would be a strong argument to convert all Class 1 piles to Class 3W piles in similar future projects.

5.2 Surface Clay Layer

This was observed to occur in two ways:

1) Filter-cake
   If certain conditions occur in a Class 3B pile, a thick deleterious filter-cake will form on the base of the pile. Observations showed the filter-cake clay to be a reasonably strong, tenacious material, which often formed a matrix for other base debris, and was very difficult to remove by air-lifting.
   This cohesive layer can be successfully removed only from a flat base with a well-designed cleaning tool with a cutting blade.
2) Remoulded clay layer
   In one pile, we observed with SID a layer of remoulded clay material (probably Silurian mudstone) that had been plastered over the base by the action of the conventional flat-bottomed cleaning bucket.

6 WALL SURFACE CONDITIONS

The designer assumes that the walls have a sufficient roughness to produce the required side resistance behaviour and that they are not covered with a deleterious clay layer formed during the construction process.

6.1 Wall Roughness

Research by Williams and Pells (1981) and others has demonstrated the importance of wall roughness, in particular the minimum asperity height, in developing the maximum peak and residual side resistance.

On this project, about half of the bored piles were dewatered and inspected. A wall profile was drawn during the socket inspection and the roughness parameters determined from this profile were compared with the minimum values recommended by Williams (1980).

In the initial dewatered piles constructed in the Stage 1 contract, the wall roughness was found to be insufficient and one reamer tooth and later two reamer teeth were attached to each side of the drilling bucket to give the necessary roughness.

In the Stage 2 contract, reamer teeth were not used on the drilling buckets and reliance was unwisely placed on the action of the protruding outer drilling teeth. Consequently, in certain sockets containing less fractured rock, smooth socket walls resulted and these had to be specifically roughened. These discoveries were made during the visual inspections of the socket walls of dewatered piles.

The danger of relatively smooth walls is particularly serious for sockets drilled under bentonite, where the filter-cake formed on permeable walls (see below) will prevent a concrete to rock bond and severely reduce, if not nullify, the effect of any wall surface texture (refer to e.g. Williams and Pells, 1981).

On a project where all the bored piles are constructed under bentonite and thus there are no dewatered piles that can be inspected to assess the wall roughness produced by the drilling tools, the following alternative approaches are recommended. A remotely-operated profiling device can be used to obtain the wall profile and thus check the roughness, or the socket walls can be specially roughened with a grooving tool. However, the latter procedure involves the risk of triggering a socket collapse in very unstable sockets.

6.2 Filter-cake

A filter-cake will form on the walls out of the fine material suspended in the drilling fluid if the walls are sufficiently permeable. The final thickness of the filter-cake, i.e. some time after concreting the pile, depends on several causative factors (Holden, 1983d).

Initially, we were led to believe that "there is a considerable volume of evidence to show that the side friction component is not significantly affected by bentonite" (Sliwinski and Philpot, 1979). The research work carried out in Silurian rocks by Williams (1980, p. 5.43) had tended to support this conclusion.

During the socket inspection with SID of some bentonite piles on the Stage 1 contract, signs of the presence of filter-cake were observed. Experiments were then carried out in two dewatered piles with stable sockets to study the formation of filter-cake on the socket walls, using a Socket Inspection Sidewall Sampler (SISS) (Holden, 1983b), shown in Figure 4.

Figure 4 Socket Inspection Sidewall Sampler (SISS)

These experiments showed that, under certain conditions, bentonite filter-cake clay can build up to relatively large thicknesses (i.e. > 100 mm) on both mudstones and sandstones. The filter-cake can therefore fill the indentations between the asperities required by the design roughness. Also, it was shown that the procedure used to "agitate" the bentonite in the socket with a drilling bucket will not completely remove the filter-cake from the walls.

Cores were drilled down the interface between the concrete and rock on 14 completed bentonite piles. These interface cores revealed filter-cake thicknesses ranging from near zero to greater than 100 mm, showing conclusively that the fresh concrete does not displace or scour off all the filter-cake (see also Fleming and Sliwinski, 1977).

Static load tests with instrumentation on two piles with substantial filter-cake verified that the load transfer to the socket walls was markedly affected by the filter-cake. The load capacities of other Class 3B piles were checked by dynamic load tests (Balfe, 1984, in this conference).

6.2.1 Summary of recommendations

With reference to the causative factors, recommendations for minimizing filter-cake are briefly summarised below. It must be remembered, however, that these sometimes only apply to sites with similar conditions to this project.

1) Composition of bentonite slurry. Control tests should be performed on the bentonite slurry to ensure its properties are kept within the limits set out in Table 1 (see below).
2) Wall permeability. Under certain conditions, thick filter-cakes can be expected to also form on relatively impermeable mudstones, if they are jointed and fissured, as well as on permeable sandstones. An indication of wall permeability should be obtained from the logged joint frequency and representative field permeability tests in the investigation bores.
3) Differential pressure. The bentonite level in the various phases of bored pile construction should follow the recommendation in Table 1.
4) Elapsed time. The socket should be excavated and concreted in the same working day. If this is not achieved, a simple check (Holden, 1983d),

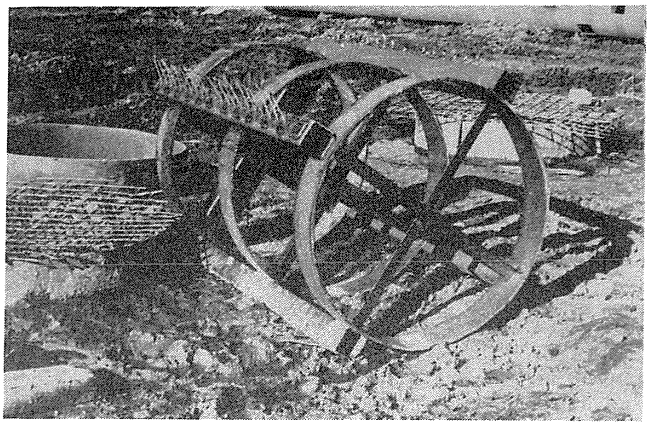

Figure 5 Socket Wall Cleaner

involving the filtrate loss from the pile, can be used to estimate the build up of filter-cake during long interruptions. In doubtful cases, SISS can be used to verify the filter-cake thickness.

5) Electrochemical effects. Deflocculants should be added to the bentonite to overcome the flocculating effect of any salty ground water.
6) Construction procedures. The construction procedures used in base cleaning will affect the thickness of the filter-cake. A thick filter-cake should be substantially removed by using a "wall cleaner" (see Figure 5) after making two passes with the drilling bucket.
7) Concrete placement procedure. To ensure the maximum scouring from plug flow, the tremie should be inserted into the concrete the maximum practical depth, which should exceed 3.5 m. The rate of concrete placement also should be as fast as practical and no large delays should be permitted in the concrete delivery. The tremie should be positioned centrally in the socket and any vertical oscillatory motion should be avoided.
8) Lateral pressure of concrete. The lateral pressure also increases with the insertion depth of tremie and the placement rate as well as the height of concrete in the socket pour. If possible, the reinforcement cage should not extend into the socket.
9) Concrete properties. The concrete should have a high slump, i.e. not less than 175 mm and preferably close to 200 mm. The setting time should be increased as much as practical by the addition of retarders.

6.2.2 Summary of bentonite requirements

The specifications relating to bentonite used in this project were based on the specifications for cast-in-place piles formed under bentonite suspension published by the Federation of Piling Specialists (1975). These FPS (1975) specifications have been criticized by others and found to be definitely inadequate on this project (Holden, 1983d).

The required properties for bentonite used in the different phases of bored pile construction, described in detail by Holden (1983d), are summarized in Table 1. Note that these requirements apply to the construction equipment and methods and site conditions for this project. For other projects, it is recommended that these control limits be modified, after further study, to suit the particular construction equipment and methods and site conditions.

TABLE 1 CONTROL LIMITS FOR BENTONITE PROPERTIES

Bentonite Property	Mud Supply During Excavation	Socket Slurry During Interruptions	Socket Slurry During Concreting
Bentonite type	Sodium bentonite OCMA Spec	-	
Bentonite Concentration % wt/wt of water	4 min	-	
Density gm/cc	1.03 min 1.08 max	1.03 min 1.08 max	1.03 min 1.20 max
API Sand content % by volume	0 min 2 max	0 min 2 max	- 10 max
API Fluid loss ml in 30 min.	10 max	10 max	-
Cake thickness mm	1 max	1 max	-
pH (field check with indicator paper)	8 min 11 max	8 min 11 max	- -
Plastic viscosity (viscometer) cP	4 min 10 max	4 min 10 max	- 20 max
Yield point Pa 10 min Gel strength Pa	14 max 2 min 10 max	14 max 7.5 min -	- 7.5 min 20 max
API Marsh funnel viscosity sec (field check)	30 min 40 max	30 min 40 max	- -
Head of bentonite	1 m above W.T. (min)	1 m above W.T. (min) 1.5 m above W.T. (max)	1 m above W.T. (min)

6.2.3 Filter cake in Class 3W (water) piles

During the drilling of sockets under water, the amount of fine material suspended in the water steadily increases. It will also form a filter-cake against permeable walls. This fact was not recognised until some of the "drilled solids" filter-cake was scraped off the socket walls during the SID inspection of a Class 3W pile.

The construction engineer should be aware of the potential problem of excessive filter-cake, especially in the lower region of the socket if the sediment has settled out of suspension, say, overnight. In this case, steps should be taken to measure the thickness of the filter-cake (e.g. with SISS) and/or remove it.

6.3 Remoulded Clay Layer

During the logging of the interface cores from three of the bentonite piles, a completely separate layer was identified which occurred between the bentonite filter-cake and the rock. The layer, which extended over considerable lengths of the socket, was apparently a remoulded material derived from the cuttings of the Silurian mudstone mixed with some bentonite. It had been plastered or smeared on the socket walls during the drilling. More research is needed into the causes of such a layer.

7 CONCRETE INTEGRITY

The designer assumes that the structural integrity of the concrete in the pile will not be affected by the construction process.

Several authors (e.g. Thorburn and Thorburn, 1977; Fleming and Sliwinski, 1977) have already discussed the pile defects that can occur due to poor concreting practice. The following discussion concentrates on an important cause of concrete defects found in the Class 3B (bentonite) piles.

7.1 Bentonite Gel Inclusions

The bentonite can be considered to exist in 3 phases: (i) the liquid slurry, (ii) the gel, which occurs when the thixotropic bentonite slurry has time to set, and (iii) the filter-cake (Sec. 6.2). The slurry and the gel are assumed to be displaced by the fresh concrete. However, the gel will not be displaced in certain circumstances. Sometimes the shear strength of the gel of a badly contaminated bentonite will be close to that of the fresh concrete. In some piles, this relatively high strength gel became trapped in the corners at the base of the socket and in indentations in the socket walls.

There is also much evidence from the interface cores that the gel and/or filter-cake mixed in with the concrete, often completely surrounding the concrete aggregate, in a zone adjacent to the socket walls. Pockets of gelled bentonite were also found trapped within the concrete, near the socket walls. Hence, if contaminated bentonite has been allowed to sit for a fair while - i.e. overnight or longer - then it should be liquefied properly and replaced with "fresh" bentonite.

When the pile is completely constructed under bentonite, however, this is difficult to achieve in the region between the reinforcement cage and the edge of the pile. It is believed that the presence of bentonite gel was a major factor in the entrapment of bentonite behind reinforcement in the outer concrete layer of some early piles that were constructed entirely under bentonite.

This problem can be overcome by (i) controlling the properties of the bentonite slurry (see Table 1) and the concrete within the limits specified, (ii) using correctly designed reinforcement, which does not greatly inhibit the concrete flow, (iii) pouring the concrete on the same day as installing the reinforcement, or liquefying any bentonite gel, especially behind the reinforcement, and (iv) using the correct concrete placement procedure (Sec. 6.2.1).

8 CONCLUSIONS

1) A study of the construction of bored piles socketed into weathered Silurian rocks showed that various design assumptions were invalidated by conventional methods of construction.
2) A socket diameter of 50 mm less than the casing ID can be achieved providing that the drilling bucket diameter is regularly checked and precautions are taken to prevent casing distortion in any overlying rock layers.
3) Because of possible divergence of the socket from the investigation bore, the rate of socket drilling under fluid should be monitored to confirm the expected rock quality.
4) The major cause of rock disturbance was wall instability. In bentonite piles, this resulted from not maintaining the bentonite at a sufficiently high level. It can be disastrous to construct potentially unstable sockets under water; at best, it is unsatisfactory because continual fretting produces base debris.
5) A socket inspection device (SID) was developed to inspect and record base cleanliness, overcoming the limitations of the sounding tape method. Methods of cleaning pile bases using conventional air lifting and cleaning buckets are not satisfactory in removing all base debris. During the project, satisfactory equipment and methods were developed.
6) Attention should be given to achieving the specified wall roughness, especially for bentonite piles. Under certain conditions, a deleterious layer of bentonite filter-cake will remain after concreting. Recommendations, including control limits for bentonite properties, for overcoming this problem are given.
7) Unless certain procedures are adopted, there will be a serious risk of bentonite gel inclusions in the concrete, especially in bored piles constructed entirely under bentonite.
8) Above all, the best method for constructing bored piles in potentially unstable rock is to rapidly drill and concrete the socket under bentonite, using the construction procedures recommended, while maintaining a strict control on bentonite properties.

9 ACKNOWLEDGEMENTS

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This paper is presented with the permission of Mr T H Russell, Chairman and Managing Director, Road Construction Authority of Victoria. The views in the paper are those of the author and do not necessarily represent those of the Authority.

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