St Clair River Rail Tunnel, Sarnia
Evolution of the Design and Construction Methods for the TBM Cutterhead Retrieval

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Abstract

In 1994 the world's largest underwater tunnel was constructed to link Canada and the U.S.A. This new tunnel was large enough to accommodate double-decker railway cars. The construction of an unplanned Retrieval Shaft was required to allow removal and servicing of the Cutterhead of the Tunnel Boring Machine before it passed under the St. Clair River. This paper, which is a revision of that published in Canadian Tunnelling, has been modified here to emphasize construction considerations and describes the evolution of the design and construction of this "Rescue Shaft" under extreme schedule pressure, and changed ground conditions..

Introduction

An existing tunnel under the St. Clair River between Sarnia, Ontario and Port Huron, Michigan completed by the Grand Trunk Railway in 1890 was the first international submarine tunnel. It is recognized as an outstanding engineering achievement under severe conditions. Shafts were attempted during this construction, all resulting in failure, including base failure of a 7m diameter shaft on the Canadian side at a depth of 27m. Modern double decker automobile transporter cars required a tunnel of larger diameter, located parallel to and approximately 27m north of the older tunnel which will be taken out of commission. This would replace the expensive system of ferrying across the river.

Mining began in the fall of 1993 and by late 1993 difficulties encountered with the Tunnel Boring Machine (TBM) required the removal and servicing of the Cutterhead before the TBM continued under the St. Clair River.

This paper describes the evolution of the design and construction of the retrieval shaft, under mounting schedule pressure and difficult conditions.

Cutterhead Repairs Required

In December 1993, leaking seals protecting the bearings at the cutting head allowed the intrusion of contaminants.

In January 1994 the St. Clair Tunnel Company elected to remove and service the Cutterhead, rather than risk a failure or further problems under the River.

Traylor Associates, as agents of the St. Clair Tunnel Company solicited proposals from three specialist contractors to provide a shaft to access the TBM Cutterhead.

The shaft was to be located on Imperial Oil refinery property approximately 130m from the edge of the river in a 45m deep deposit of near normally consolidated clay. At this location the TBM invert would be 29m below the ground surface. The shaft required a clear hoisting space of 10.1m x 3.7m to allow the 9.5m diameter cutterhead to be retrieved intact.

Retrieval Shaft Proposals

Deep Foundations Contractors Inc. (Deep) had previously constructed a deep interlocking caisson wall near the Sarnia portal as part of the advanced protection work for services.

This wall, 350m to the east was drilled "open hole" to a depth of 24m, not the 33m required for the new shaft.

Deep had extensive experience in caisson wall installations in difficult saturated soil conditions, but not to this depth.

The most important requirements of the construction were speed and minimal vibration.

Deep believed that it was worthwhile attempting "open hole" vertical drilling with soil augers as an extrapolation of their local experience. Open hole drilling had an additional critical benefit. It would allow visual inspection of caisson interlocks, ensuring the integrity of the system.

Two proposals were received from the invited contractors and reviewed by the Owner's consultants.

One proposal was for a 15.8m diameter polygonal diaphragm wall to allow excavation to 15m. From this level to 3m below the TBM a soil-crete mass would be constructed by jet grouting. Additionally, soil anchors were proposed below the base to resist uplift forces on the plug under a central 8 x 10 x 11.5m deep excavation.

Deep proposed an interlocking caisson wall arranged to form walls around a rectangular shaft. This would be surrounded by a cylindrical compression wall. All caissons would be drilled 33m deep at a diameter of 1.22m, using "open holes", without casing, slurry, or any other means of support. Figures 1 and 2 show the proposed geometries.

Deep's proposal was subject to the successful installation of a test caisson to the depth and diameter required and acceptance of the scheme by the Engineer.

Schedule did not permit extensive exploratory or testing programs.

Various schemes to prevent base heave had been discussed using concrete or soil but none had come to the forefront at this time.

Drilling Tests

Deep was given a go-ahead on the test program. At the same time, one deep exploratory borehole (BH-1, see Figure 1) was drilled.

The 1.22m diameter test caisson was drilled using a 155 Caldweld drill mounted on an 80 ton Linkbelt crane and left open for a 24-hour period before concreting. It was visually observed for clay squeeze by a down the hole camera mounted on the kelly bar of the drill. In addition, the hole was sounded in order to detect base heave.

No movements were observed and Deep was awarded an approximately $2,000,000.00 contract with Traylor on January 28, 1994. The contract was based on preliminary design sketches and specified a 12m deep 5 MPa concrete plug into which the TBM would bore.

The time allowed for this work including excavation of the internal shaft was 38 calendar days, with bonus and penalties. The contract provided for extension of the contract period for causes beyond the control of Deep.

As time was of the essence, work commenced on January 31, 1994, on a seven-day per week schedule, and upon the basis of preliminary drawings.

Preliminary Design

During the concept stage Deep consulted with Isherwood Associates (Isherwood) and retained them when awarded the contract.

The preliminary design by Isherwood is illustrated on Figure 3 and was based on Deep's schematic sketches. The concept was to create a circular unreinforced compression ring comprising 1.2m diameter interlocked caissons at 0.9m centres as an outer line of defence. The smaller rectangular shaft would be excavated inside this ring employing similar secant wall shoring reinforced with steel beams in every second caisson. The steel beams would terminate above the area to be bored by the TBM. The ring was to be constructed with 5 MPa concrete and intended to reduce soil pressure on the internal cross walls, which could not feasibly support the full soil pressure without strutting. The 'D' shaped areas between the walls were treated as bins, and soil load on the straight walls estimated by bin theory. A tentative plug design comprising a global pattern of 1.5m diameter caissons was included. The total number of caissons in this preliminary design was 78-1.2m and 42-1.5m diameter for a total of 120 caissons.

The TBM data indicated that overcut in the concrete could result in a 50mm gap outside the shield. The design position then adopted was to assume no contribution of support by the TBM within the shaft structure. High strength reinforcing caissons were added in the interim whilst the effect of the resulting large voids was being further analyzed.

Because of the challenge of the project, the time restraints and the potential impact on the tunnelling operation, Isherwood sought design review from several sources during the project. In the early stages the primary focus was the design and installation of a plug to withstand uplift. Design alternatives under consideration included extending the cut-off walls to the underlying till, or providing anchors either to the rock or inclined within the plug as reinforcement.

Installation

Open hole caisson installation commenced January 31, 1994. Eight of nine attempted caissons were successfully installed in the first two days. The plan was to drill every fourth caisson around the ring. A blow-out occurred at the second location in a granular seam at a depth of 24m when attempting to drill three diameters from the freshly poured first caisson. A repeat of this problem was avoided by staged pouring, but the remaining caissons took between 5% and 40% excess concrete over theoretical volumes. By the afternoon of February 3, 1994 clay squeeze in the holes prevented full depth drilling and only one caisson was successfully completed.

Various alternative approaches to the drilling methods were tried over the next several days. An open hole closure (or interlock) caisson was attempted on the east side of the shaft (numbered 12 on Figure 3), but encountered saturated collapsing ground.

Drilling under water or slurry at other locations allowed holes to be completed but was unsatisfactory for maintenance of alignment. Different configurations of liners and vibrators were tested to achieve fifteen more caissons, by which time it was clear that major revisions to the original scheme would be necessary.

As these new methods were being tested and the design revised, Deep was instructed to work 24 hours per day, 7 days per week until completion of the shaft. It was agreed, at Deep's insistence, that two 11-hour shifts would be employed with a 2 hour period for maintenance. This also allowed the two shift superintendents to evaluate the previous shift and modify procedures as required.

Shaft as designed

The design incorporating the eye reinforcement was completed during this time and is illustrated in Figure 4. The reinforcement was achieved by providing additional concrete bearing area above and below the openings by doubling the wall caissons. At the same time the plug was revised to employ 68-1.2m instead of 42-1.5m diameter caissons, so that the caisson count was now 122 plus 68 for a total of 190 caissons.

Further finite element analysis was undertaken to model behaviour of the structure, the effect of the tunnel eye openings, and load paths in the plug. These provided confirmation of the assumed arching behaviour and a closer appraisal of the more highly stressed areas.

Approach of TBM

As work was commencing on the shaft caissons the TBM was advancing under greatly reduced face pressures. It had just passed under the last oil storage tank on the Imperial property where surface settlements up to 130mm were reported, and then passed under a number of pipe racks before parking under 14th Street (roughly 20m east of the shaft) on February 4, 1994.

Monitoring points along the tunnel centreline showed surface settlement generally in the order of 100mm following passage of the TBM. Point LT30, 7m ahead of the parked position settled from 30mm to 115mm on Feb 4. It was expressed by others that this drawdown was possibly due to the drilling for the shaft 13m away. Figure 9 compares distance in tunnel diameters and caisson diameters from this point and shows correlation between TBM approach and the settlement.

Other possible causes or contributors were disturbance by the drilling and concreting operations, and electrical disruption of clay bonds either by the electrical system in the original tunnel or the new tunnel.

A curious phenomenon occurred when using vibrated liners. When the liner was withdrawn clay up to 200mm thick would cling to the outside of the liner, possibly due to a local electrical field.

Changed Conditions

Whatever the cause, it was clear the clay with a sensitivity measured by field vanes between 2 and 6 and with a typical value of 3 was being disturbed, and the design should consider soil strengths less than peak in-situ strengths. Further, the most efficient method for reliably installing the caissons was to vibrate in liners with inevitable disturbance of the immediately surrounding clay.

The TBM in its parked position was settling, and there was concern that entry of the TBM into the shaft would cause shaft settlement. Several schemes involving additional caissons for support of the TBM were examined including piled underpinning of the whole shaft as illustrated in Figure 5.

Numerous alternatives were considered; these included relocating the shaft to undisturbed ground, jet grouting or freezing below 20m depth, and a scheme employing stiff steel sheet piling for the lower shaft as shown on Figure 6.

The problem which now faced the contractor was that although he could install caissons to the full 33m depth with the liner technique, he could not feasibly achieve satisfactory interlock. This impasse was overcome when Deep devised a satellite caisson scheme. In essence this involved a pattern of tangent caissons installed with liners, plus open hole closure (or dowel) caissons to achieve interlock. This scheme required a greater number of cased holes, which took more than twice the time to install as open drilled holes, and lengthened the projected schedule considerably.

After considering the available options, the owner decided to continue with the caisson scheme but rely on the contractors to solve the technical problems and complete the extended work in the shortest possible time.

The revised design had to consider all the caissons by this time installed, and the resulting complex pattern employed 2-1.5m, 155-1.2m, 20-1.05m and 50-0.9m diameter caissons for a total of 227 caissons (See Figure 7).

Additional equipment now on site, included a 300 ton crane and ICE 1612 vibratory hammer. All major pieces of equipment had a backup standing by in case of breakdown or extended maintenance.

Quality Assurance

After the majority of the caissons had been installed and before attempting the excavation, additional measures were reviewed to provide further quality assurance. Much of the concrete supplied had tested significantly below strength, and records of the early installation indicated three caissons of doubtful continuity. In order to remedy these, 29 additional caissons were incorporated as indicated on Figure 8.
The final number of vertical holes installed was 256, resulting in over 10 km of drilling. The volume of concrete was 10,000 cubic metres.

The interlocks in the remaining closure holes were to be inspected by camera, and additional test holes during excavation, where necessary, were to probe for clay intrusions.

Two extensometers through the plug and underlying clay to the till would be installed; temporary struts would be used between the walers as added security; strain gauges would be used to monitor stresses in the walers, and additional inclinometers to measure lateral movements would be installed in the shaft. The settlement of the shaft structure was to be assessed based on estimates of weight at different stages of excavation and TBM entry, and monitored at eight top-of-shaft survey locations.

Settlement and TBM Entry

Because the concrete weighed about 15% more than the soil, additional load on the underlying clay increased steadily during caisson installation. The liner technique required some of the casings to penetrate 2m below the base, which may account for disturbed founding soil, found in additional boreholes (BH-4, BH-5 and BH-6, see Figure 1) drilled in May, 1994. The settlement history during caisson installation is shown on Figure 10. The additional vertical stress on this underlying soil was estimated at a maximum of 93 kPa, which occurred after caisson construction and prior to excavation. Subsequent operations would unload the base to an average negative surcharge of 80 kPa at full excavation. After backfilling of the shaft the surcharge stress was estimated at 42 kPa above overburden.

Preparation for TBM restart commenced early May, and excavation of the rectangular shaft commenced May 17. The TBM passed under the road on May 17 and drilled into the base of the shaft on May 21. A pronounced settlement trough appeared at the road, and the fence on the west side settled an additional 700mm (Figure 11), for a total settlement of 900mm (Figure 12).

The inclinometers and top-of-shaft survey recorded approximately 15mm additional eastward tilt of the shaft structure. As well, the TBM arrived in the shaft some 250mm low.

Shaft Excavation

The plug caissons were installed from ground surface and therefore all the shaft excavation was in concrete. The upper portion was excavated by backhoe, but below its' reach excavation was assisted by using a large diameter auger to break the concrete. Some clay intrusions between caissons were encountered on the west and south sides of the structure as it was excavated, but these virtually disappeared below 12m. The concrete at critical depths appeared consistent and sound. Test results on cores all exceeded design strengths. Monitoring indicated small deformations of the walls and low stresses in the walers. Based on better than expected performance the lower bracing was reduced by eliminating the poured concrete side walls and two lower walers within the depth of the TBM (Figures 13 and 14). The excavation was completed June 21. Unfortunately no meaningful information on base heave was obtained from the extensometers.

Correction of Alignment

It was decided to raise the TBM to the correct elevation before removing the cutterhead. Explosives were used to create a 0.3m clearance in the shaft concrete above the TBM. This caused "considerable damage" to the machine (Reference 4), but had no apparent affect on the remaining shaft structure. A substantial steel mat was installed under the leading edge to spread load (Figure 14), while the articulation of the machine was used to raise the front of the TBM.

The Cutterhead was removed from the TBM and hoisted on June 30, 1994.

Concluding Comments

Due to the adverse conditions encountered the sinking of the shaft proved considerably more difficult than anticipated. In hindsight, significant improvements could have been made, particularly in information flow and inter-party co-operation. However, we believe the method used for TBM rescue was the best choice available, and provided a shaft which fulfilled its purpose.

It is hoped that this case history of the sinking of an emergency rescue shaft in difficult soils may benefit others faced with a similar challenge.

ACKNOWLEDGEMENTS

The authors wish to thank the following who provided valuable review, comment and input:

Dr. J.H. Curran, University of Toronto; Professor N.R. Morgenstern, University of Alberta; Peter Sheffield, P.Eng., Principal, Peter Sheffield Associates; Roy Walker, P.Eng., Principal, RWB Engineering Ltd.; Richard Anderson, P.E., Tim Bedenis, P.E., Soil and Materials Engineers, Plymouth, Michigan; R. Loughney, P.E., New Milford, Connecticut; and Antonio Blanco Amador, Director General, Tecnosuelo, Mexico.

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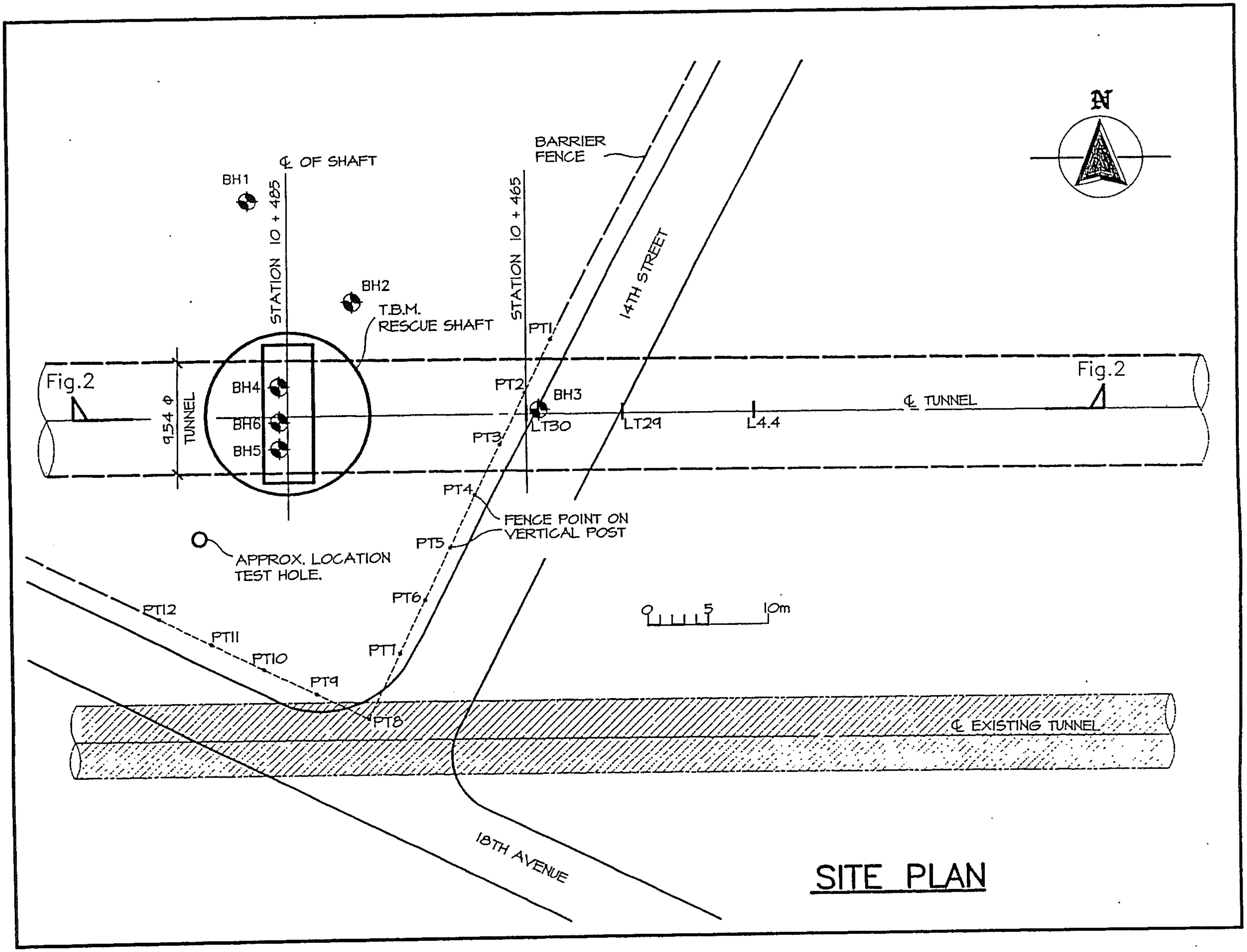

Figure 1: Site Plan

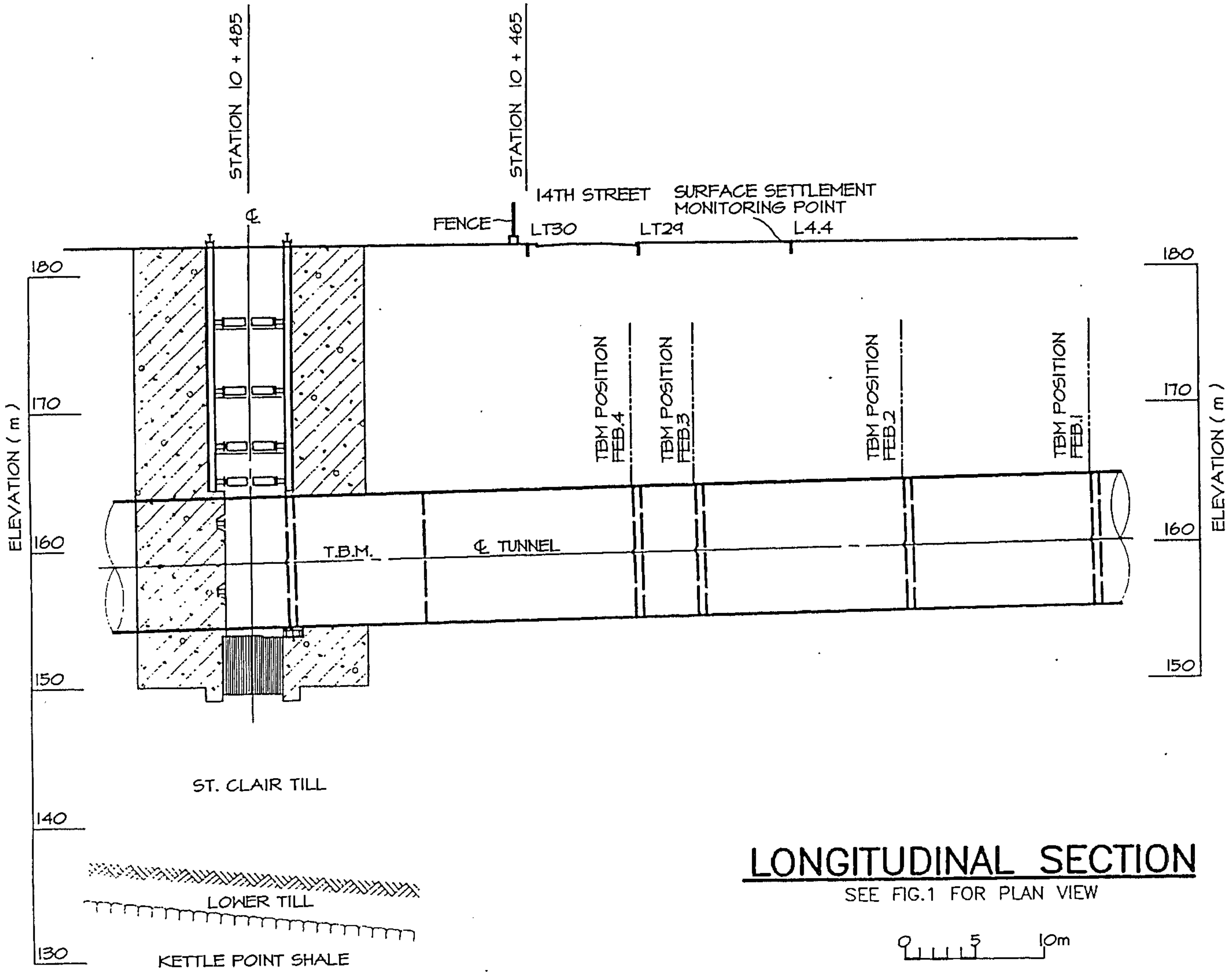

Figure 2: Longitudinal Section

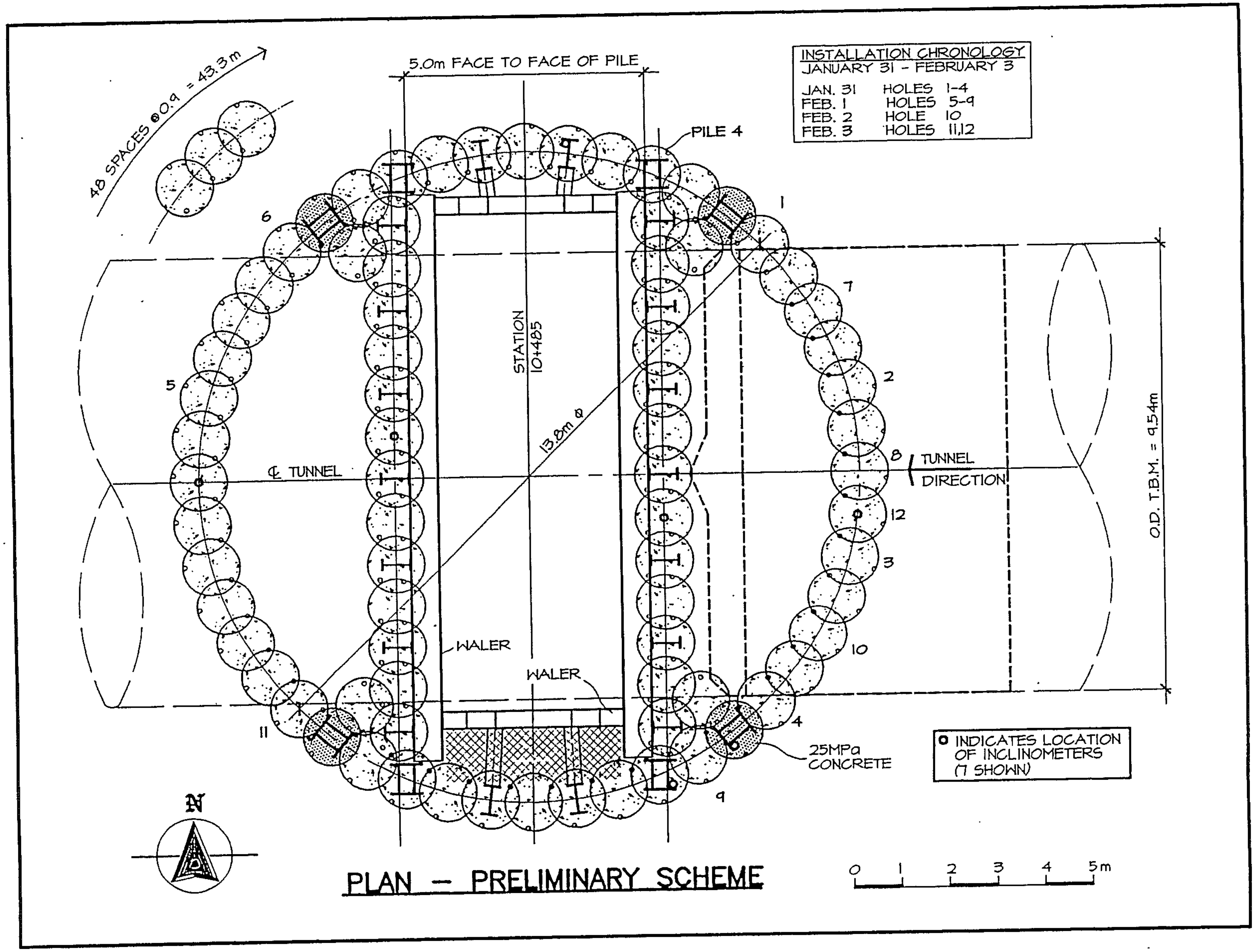

Figure 3: Preliminary Shaft Design

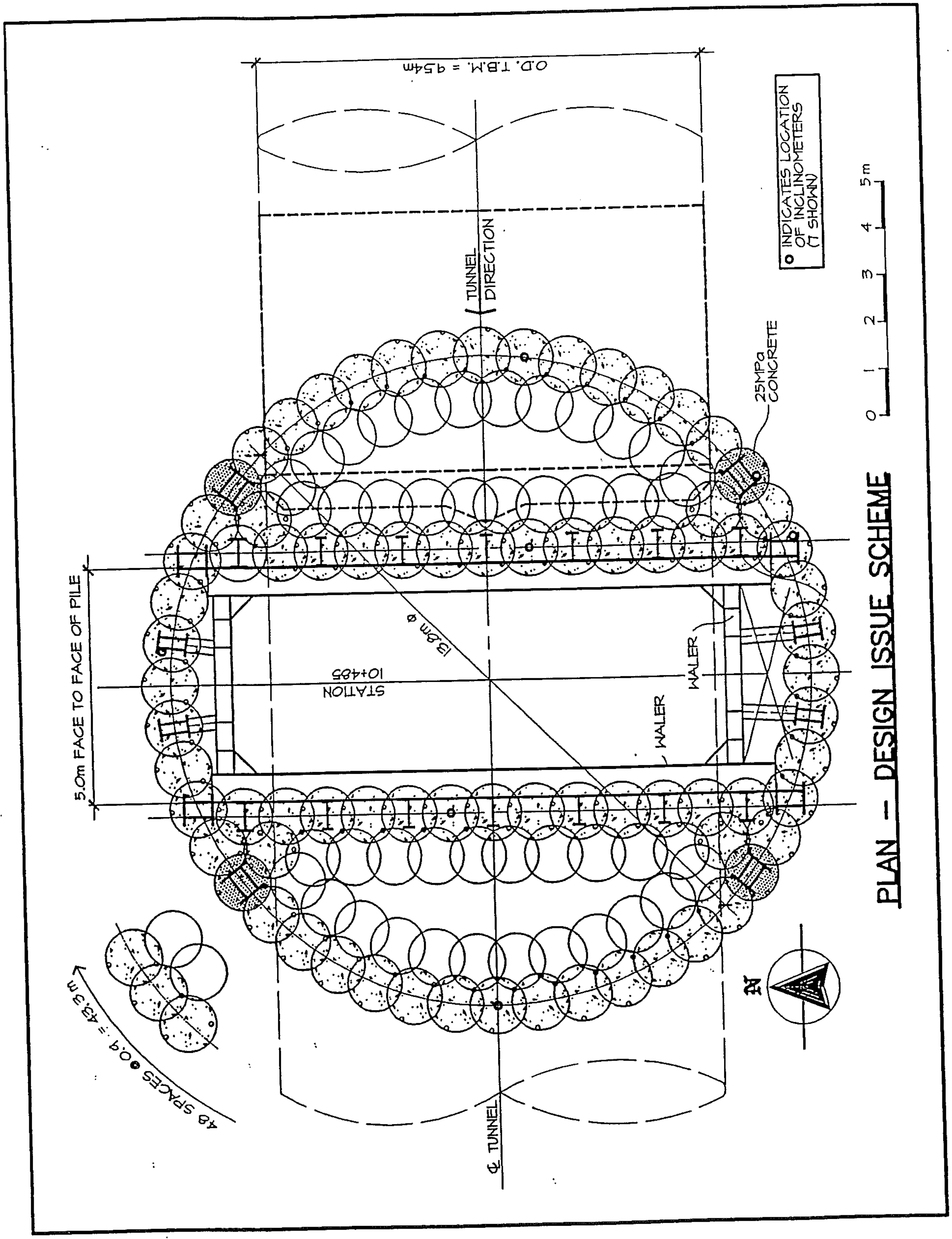

Figure 4: Shaft Design

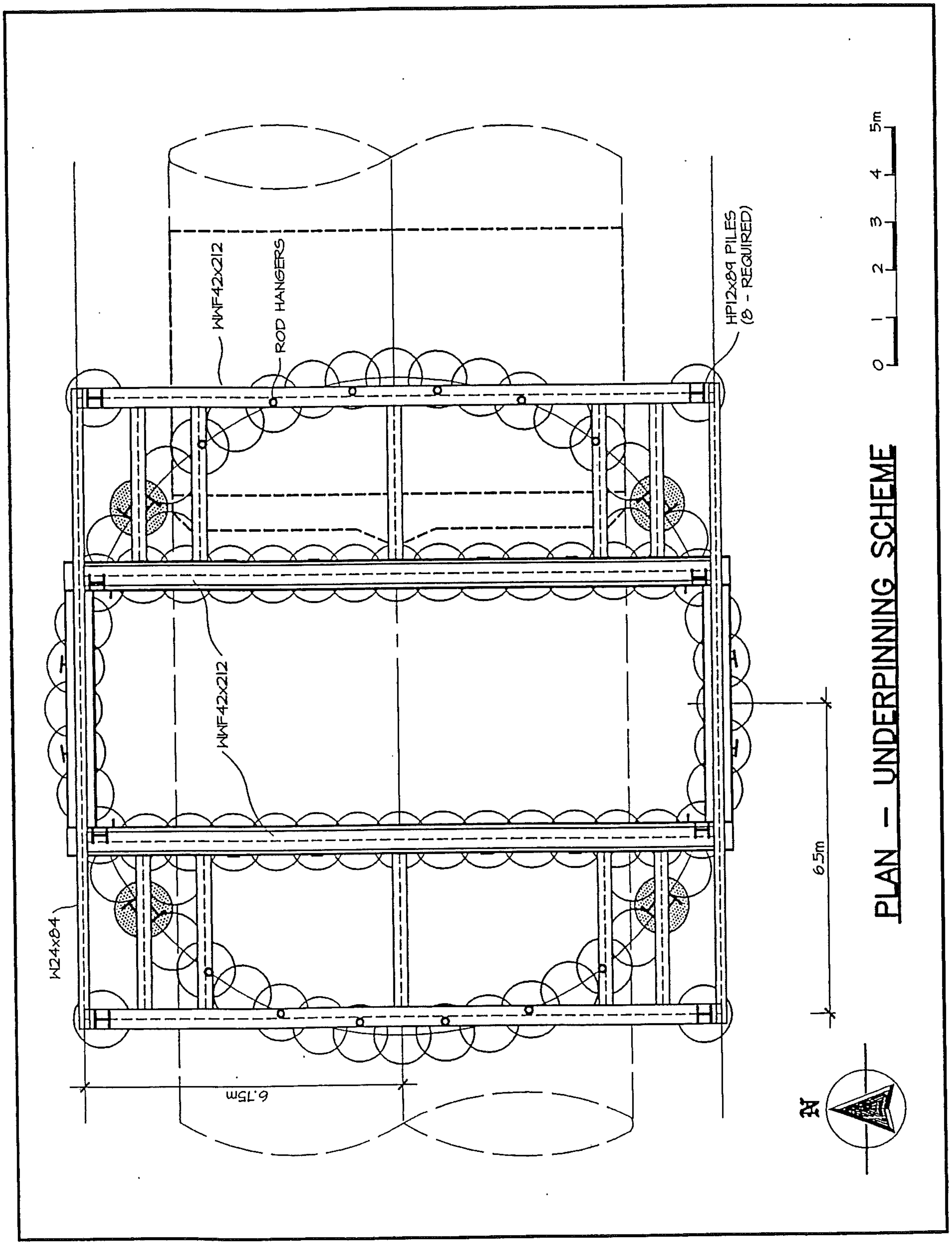

Figure 5: Piled Underpinning Scheme

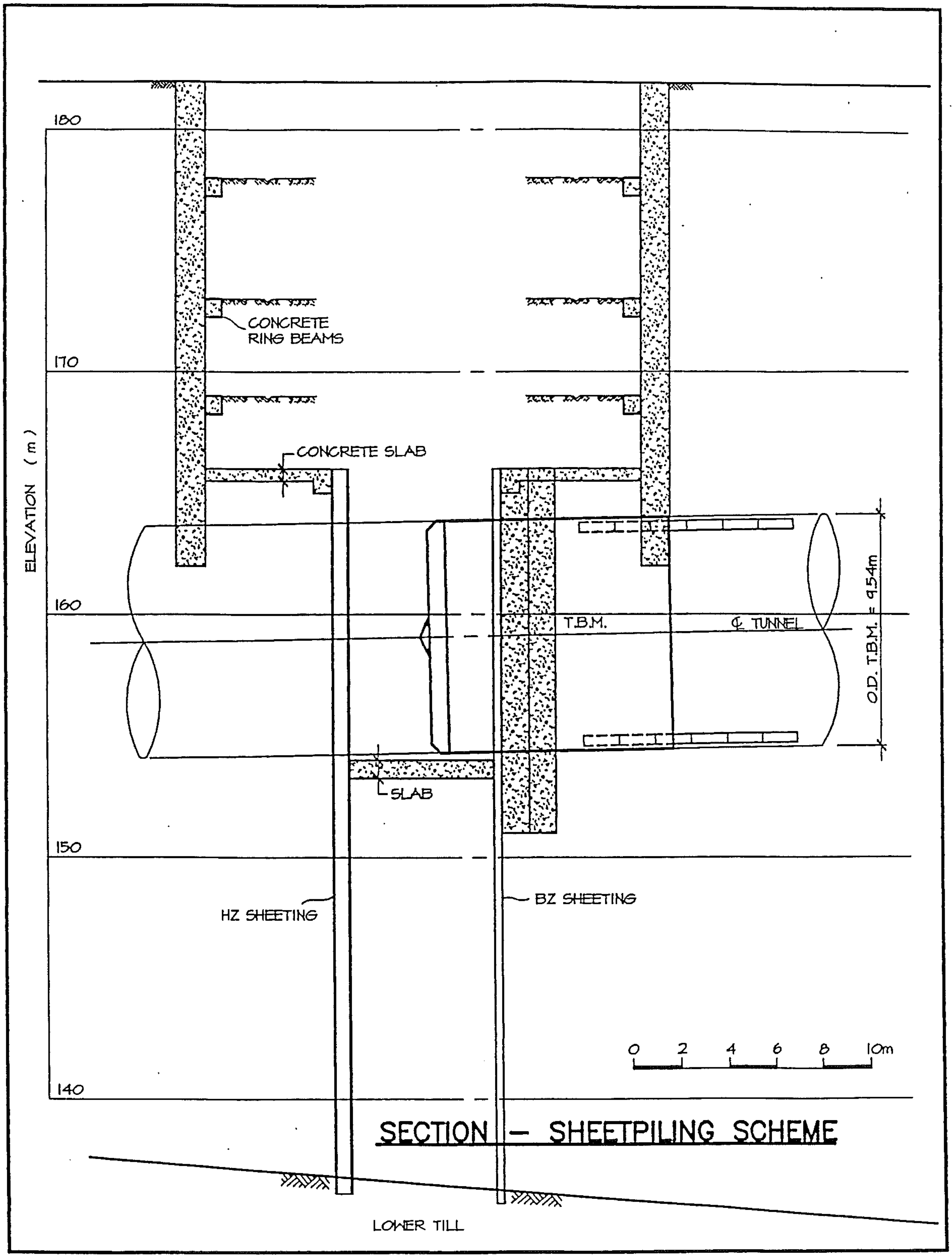

Figure 6: Sheet Piling Alternative Scheme

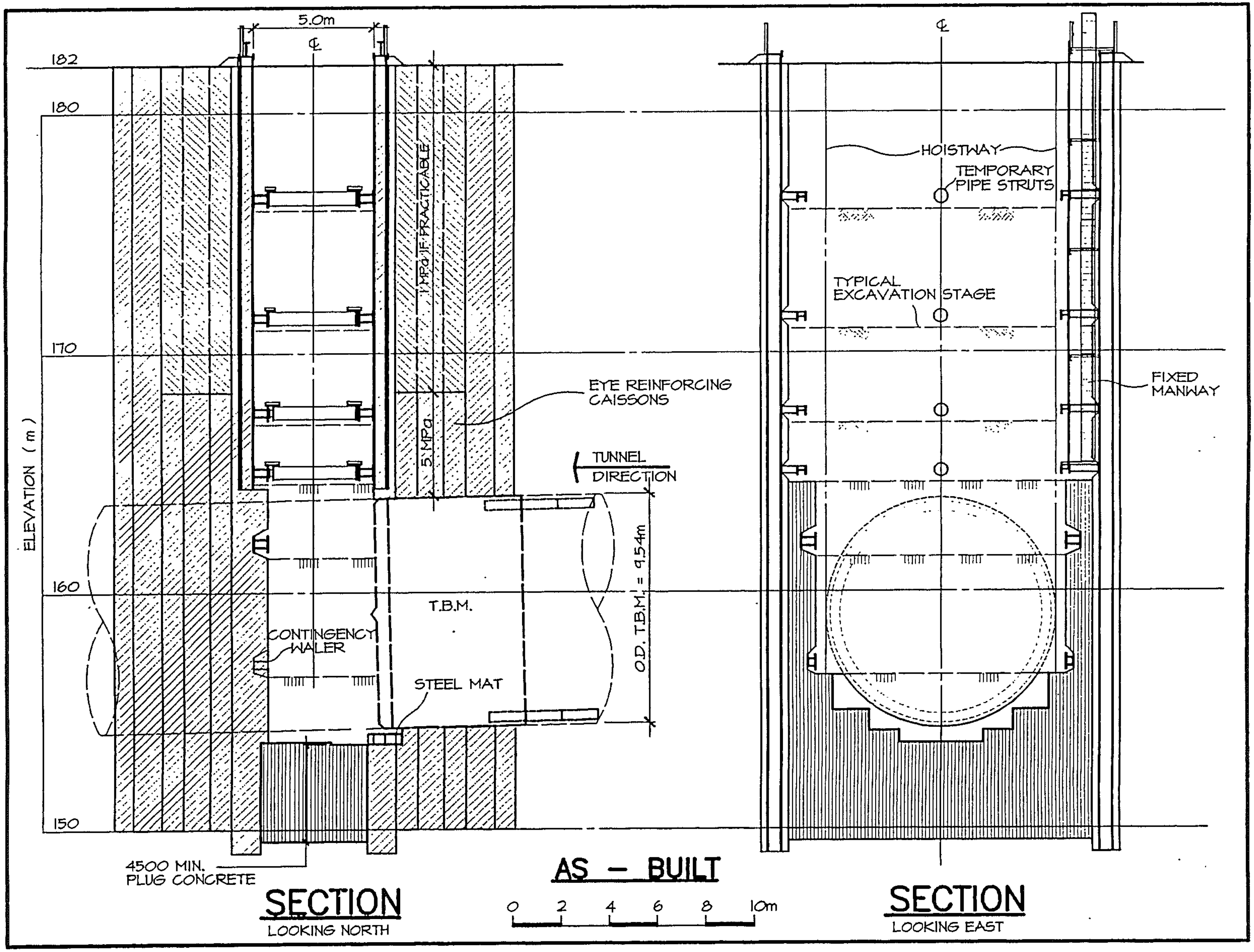

Figure 14: Shaft Sections - As Built

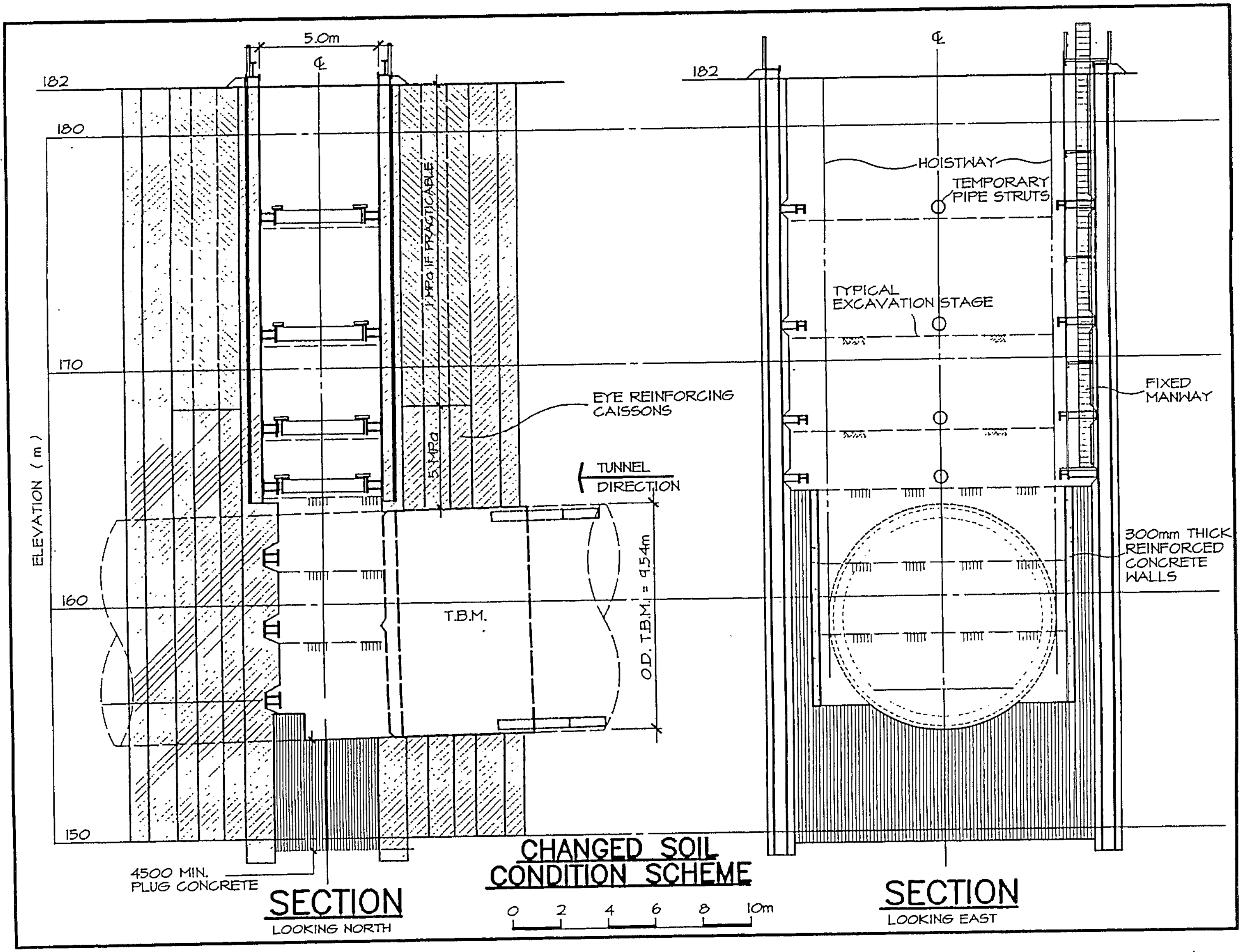

Figure 13: Shaft Sections - Changed Soil Condition Scheme

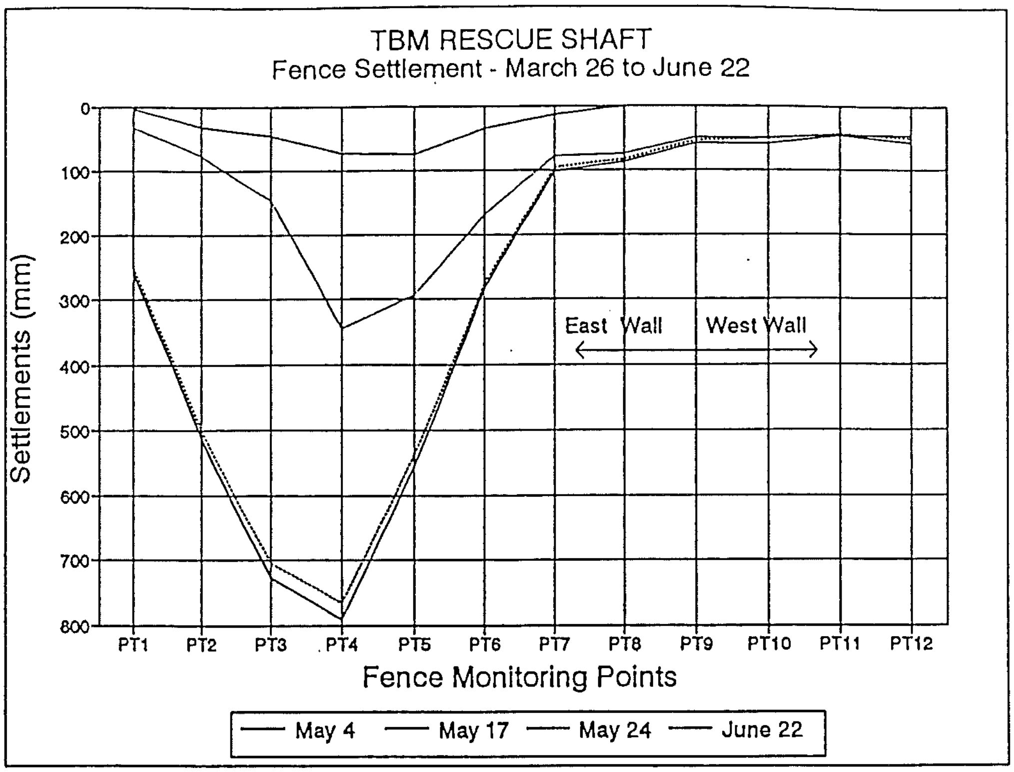

Figure 11: Fence Settlement

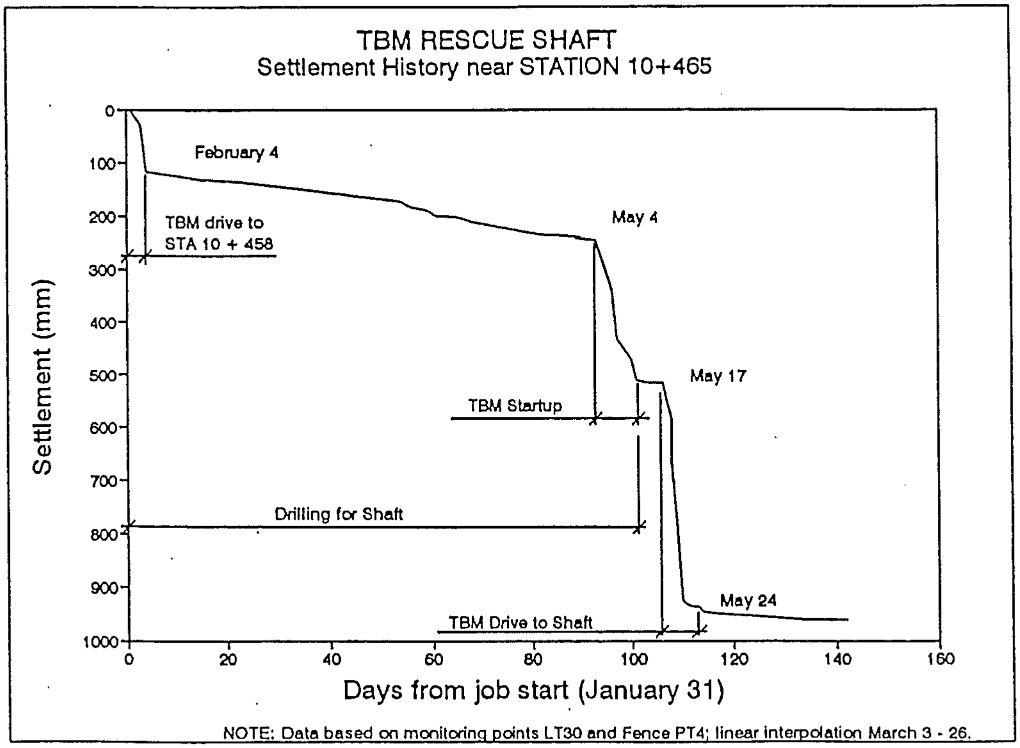

Figure 12: Settlement History of Monitoring Points near Station 10+465

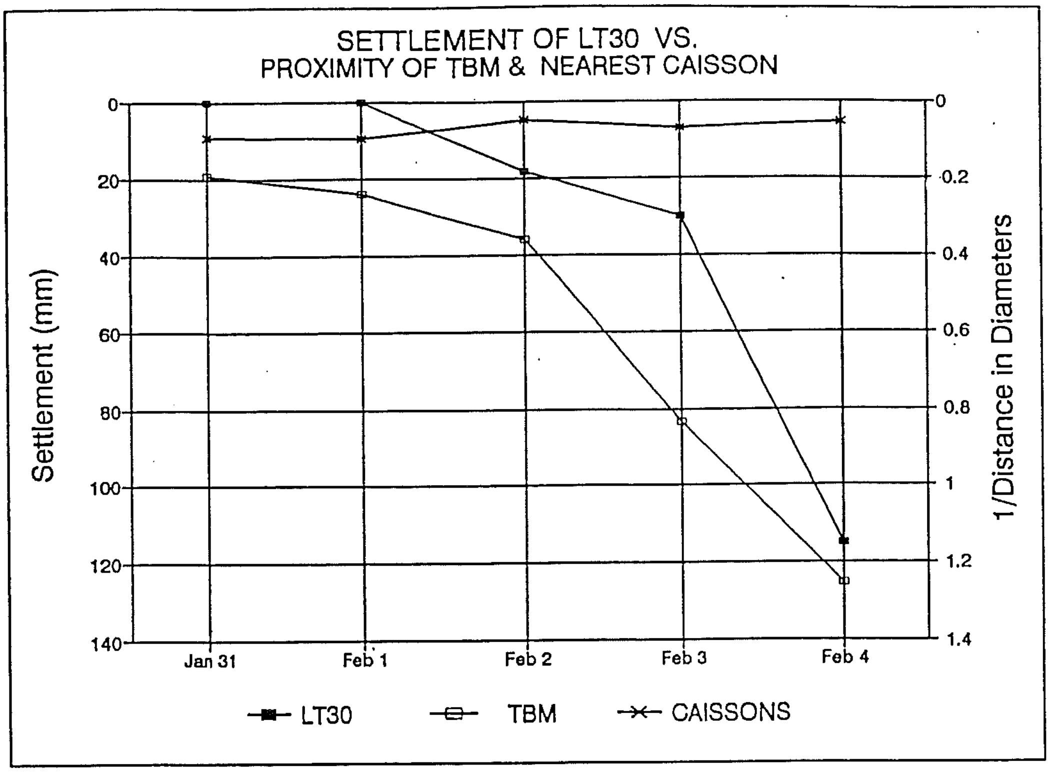

Figure 9: Surface Settlement related to Construction Proximity

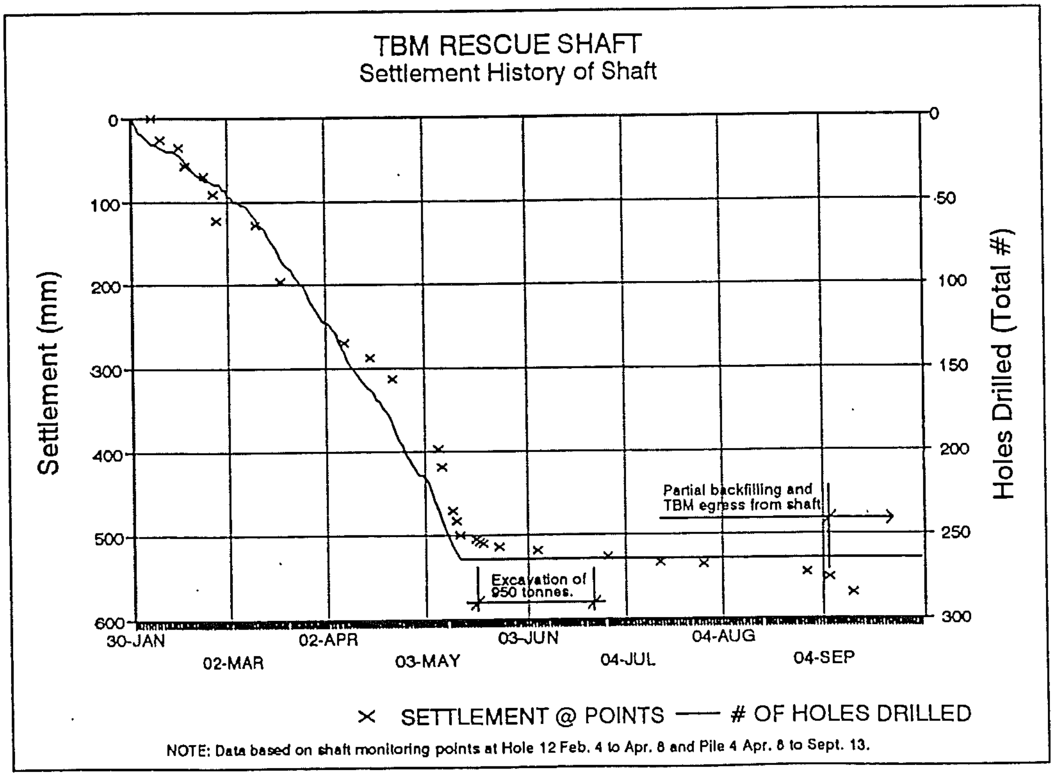

Figure 10: Shaft Settlement History related to Caisson Installation

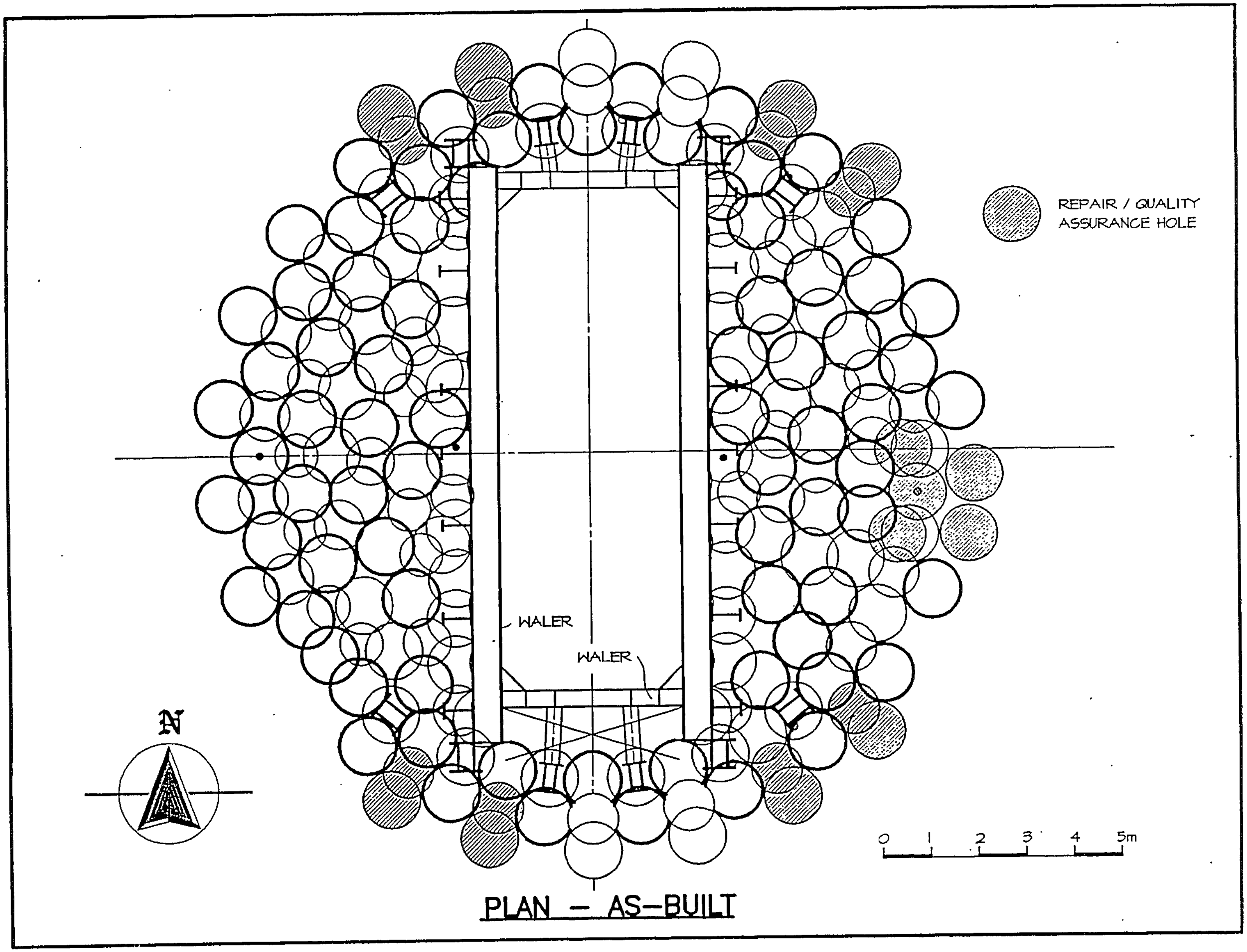

Figure 8: Plan of Shaft As-Built

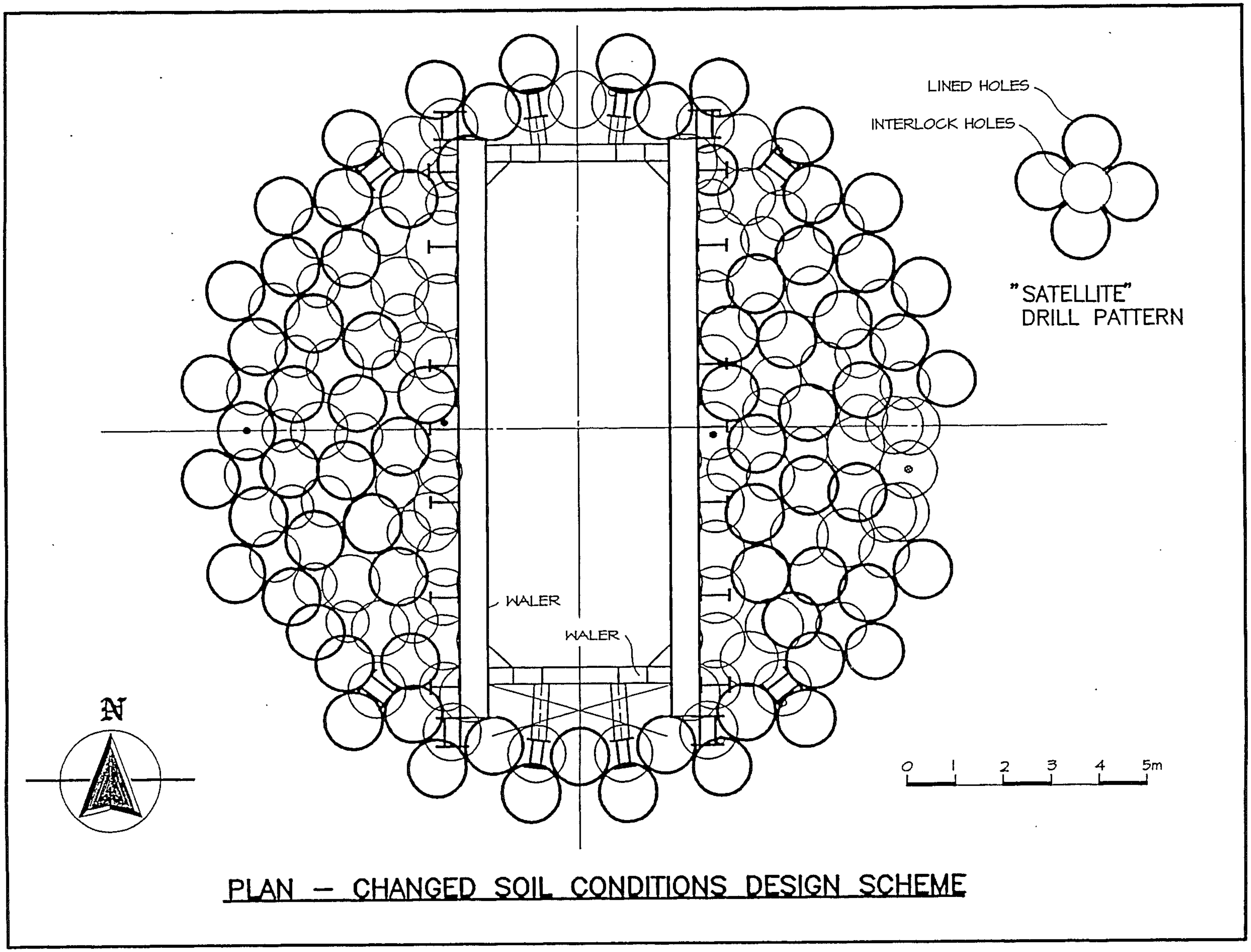

Figure 7: Revised Design for Changed Soil Conditions