

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

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Abstract

The planning, design and construction of the new St Clair River Tunnel has been described in several previous papers with some mention of the unplanned Retrieval Shaft which was necessary to remove and service the Cutterhead of the Tunnel Boring Machine before it passed under the St. Clair River. This paper describes the design and construction of the shaft and touches on the difficulties and risks involved with crash-programme rescue operations.

Introduction

In late 1993 difficulties were encountered in the operation of the Tunnel Boring Machine (TBM) during mining for the new rail tunnel in Sarnia. These necessitated removing and servicing the Cutterhead before the TBM continued under the St Clair River. This paper describes the design and construction of the retrieval shaft from the viewpoint of the specialist contractor and consultant charged with its execution. Previous papers by other authors (References 2 and 4) have described the overall project and provided some comment on the shaft.

The new tunnel replaces an existing 1890 rail tunnel, and accommodates modern

double stacked automobile transporter cars. It is located parallel to and approximately 27m north of the older tunnel which will be "mothballed".

The original 1890 tunnel under the St Clair River between Sarnia and Port Huron, built by the Grand Trunk Railway, continues to be recognised as an outstanding engineering achievement. It was the first international submarine tunnel.

Shaft proposals

In January 1994 the St Clair Tunnel Construction Company through its agents, Traylor Associates, invited proposals from

specialist contractors to provide a shaft for retrieval of the TBM Cutterhead for servicing. The shaft was to be located on the Imperial Oil Refinery property about 130m from the edge of the river, in a deep (45m) 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 in one piece.

Traylor received two proposals which it presented to the owner and owner's consultants for review:

One proposal was to construct 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 placed by jet grouting. Additionally, soil anchors were proposed below this base to hold down the plug under a central 8x10x 11.5m deep excavation.

Deep Foundations Contractors Inc. (Deep) proposed an interlocking caisson wall scheme comprising drilled caissons 33m deep, arranged to form walls around the rectangular shaft and surrounded by a cylindrical compression wall. Various methods for a soil and/or concrete plug were still under consideration.

The owner's consultant recommended the caisson wall scheme based on potential speed of construction. Figures 1 and 2 show the site geometry.

Deep had extensive experience in caisson wall installations and success in installing watertight walls in difficult saturated soil conditions, but none to this depth - the practical limit of their equipment. They had considered a number of different configurations of walls including patterns of

rectangular cells and a global pattern of caissons to form a solid cylindrical mass, before offering the compression wall scheme. Their proposal to Traylor was subject to further investigations including a full-scale drilling test, and approval of the design.

Deep had already installed an open hole caisson wall on the Imperial property 350m to the east in July 1993 as part of advance protection works for the Christina Street sewer. This was to a maximum depth of 24m, not to the 33m depth required for the proposed shaft.

Shaft Contract

Traylor gave Deep the go-ahead for the test programme on January 21, and Deep retained Isherwood Associates (Isherwood) for the design. During the next week, Deep successfully completed the test caisson, a deep exploratory borehole (BH-1, see Figure 1) was sunk at the site, and much other data needed for design was collected.

Deep's approximately two million dollar contract with Traylor dated January 28, 1994 was based on Deep's proposal and pre-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 was 38 calendar days, with bonus or penalty of \$1,000 per day to a limit of \$10,000. The contract provided for extensions of the contract period for causes beyond the control of Deep.

Because of the urgency, Deep commenced work on January 31, 1994 based on preliminary drawings.

Preliminary design

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.

Busbridge et al (1993) provided historical background and information on the soil conditions (Reference 1). Four previous shafts, two on each side of the river had been sunk in early tunnelling attempts in the 1880's, all of which were abandoned after severe difficulties with soil conditions were met, including base failure of a 7m diameter shaft on the Canadian side at a depth of 27m.

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 blowout 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.

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.

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).

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 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). The total settlement of 900mm (Figure 12) agrees with the figure quoted by Kramer et al (Reference 5) although not with their comment that this was due to the shaft excavation.

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 cooperation. 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

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REFERENCES

1. Busbridge, J.R., Shirlaw, J.N., Feberwee, J.J. and Ruel, M.A., (1993). "A Review of the Problems Experienced During the Construction of the 1890 St. Clair Tunnel Using Recent Geotechnical Data", Canadian Tunnelling 1993, pp. 155 - 164.
2. Charalambu H., Finch A.P., and MacLennan D.G. (1993). "The New St. Clair River Tunnel - An Overview", Canadian Tunnelling 1993, pp. 137 - 154.
3. Gilbert, Clare, (1991). "St. Clair Tunnel, Rails Beneath the River", Stoddart Publishing, Toronto.
4. Harrison, N., Kerrigan, R.E. and MacLennan, D.G., (1994). "The New St. Clair River Railway Tunnel, The Project - Concept and Construction", Canadian Tunnelling 1994, pp. 277 - 289.
5. Kramer, G.J.E., Tavares, P.D., Drooff, E.R., (1994). "Settlement Protection Works for the New St. Clair River Rail Tunnel", Canadian Tunnelling 1994. pp. 291 - 302.

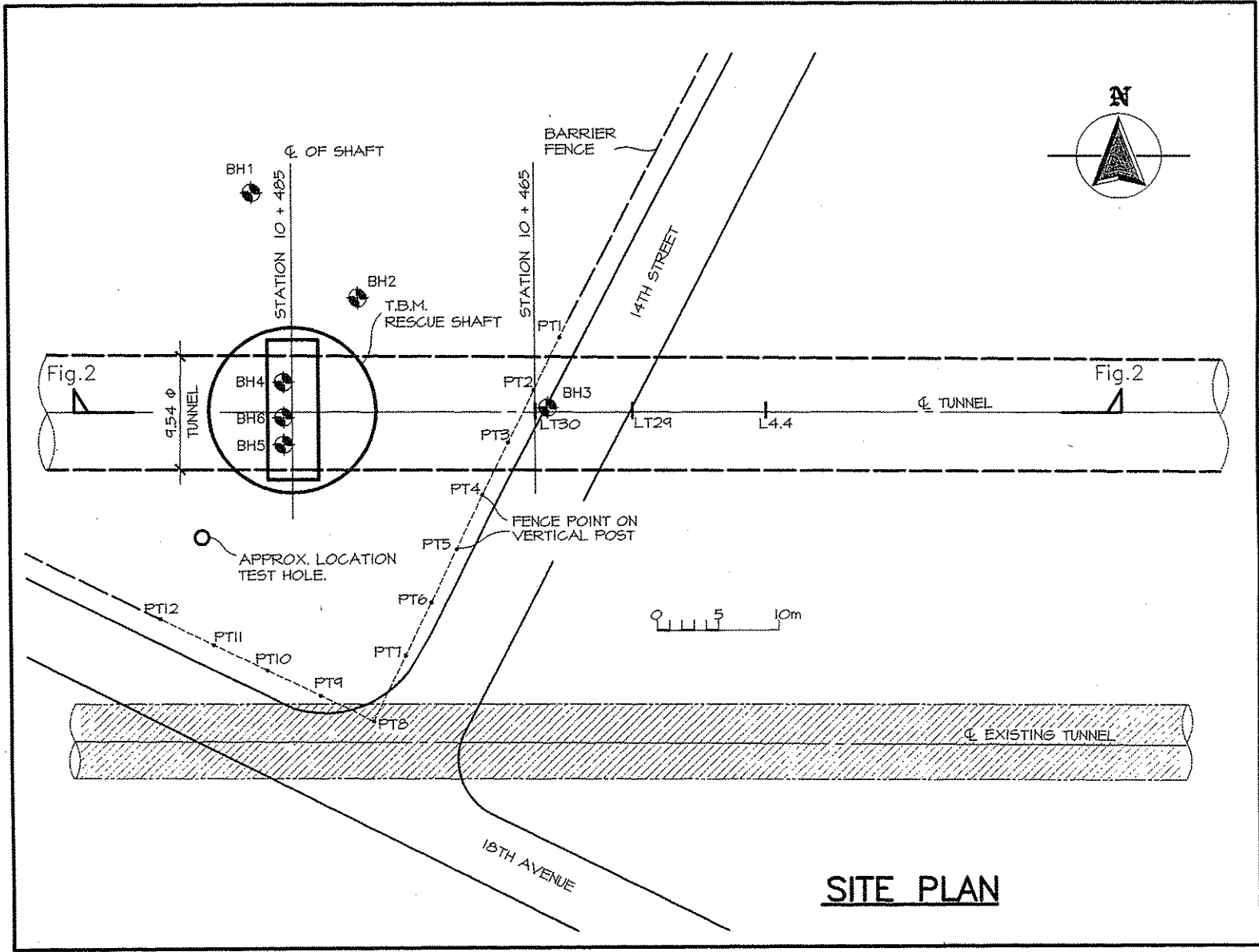


Figure 1: Site Plan

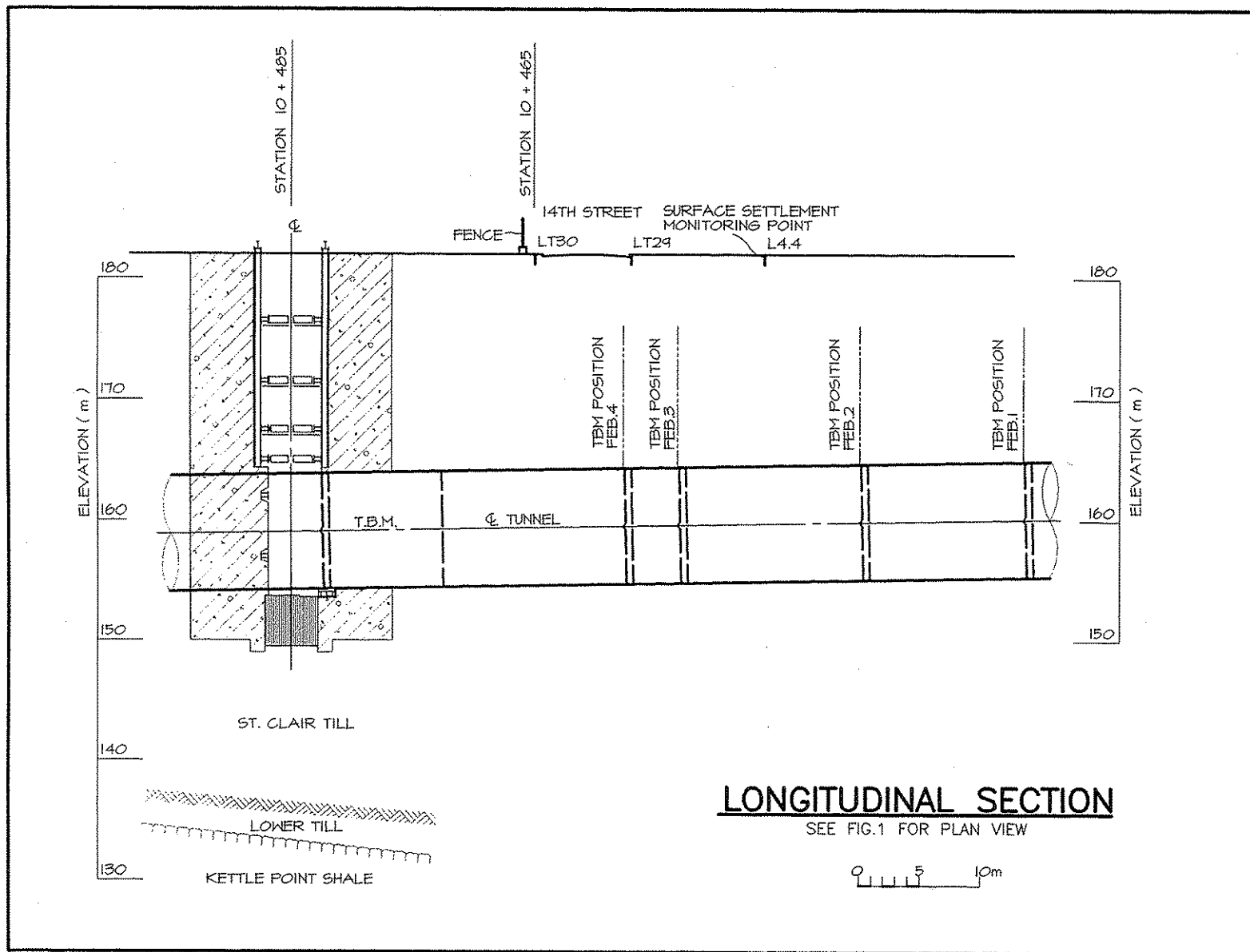


Figure 2: Longitudinal Section

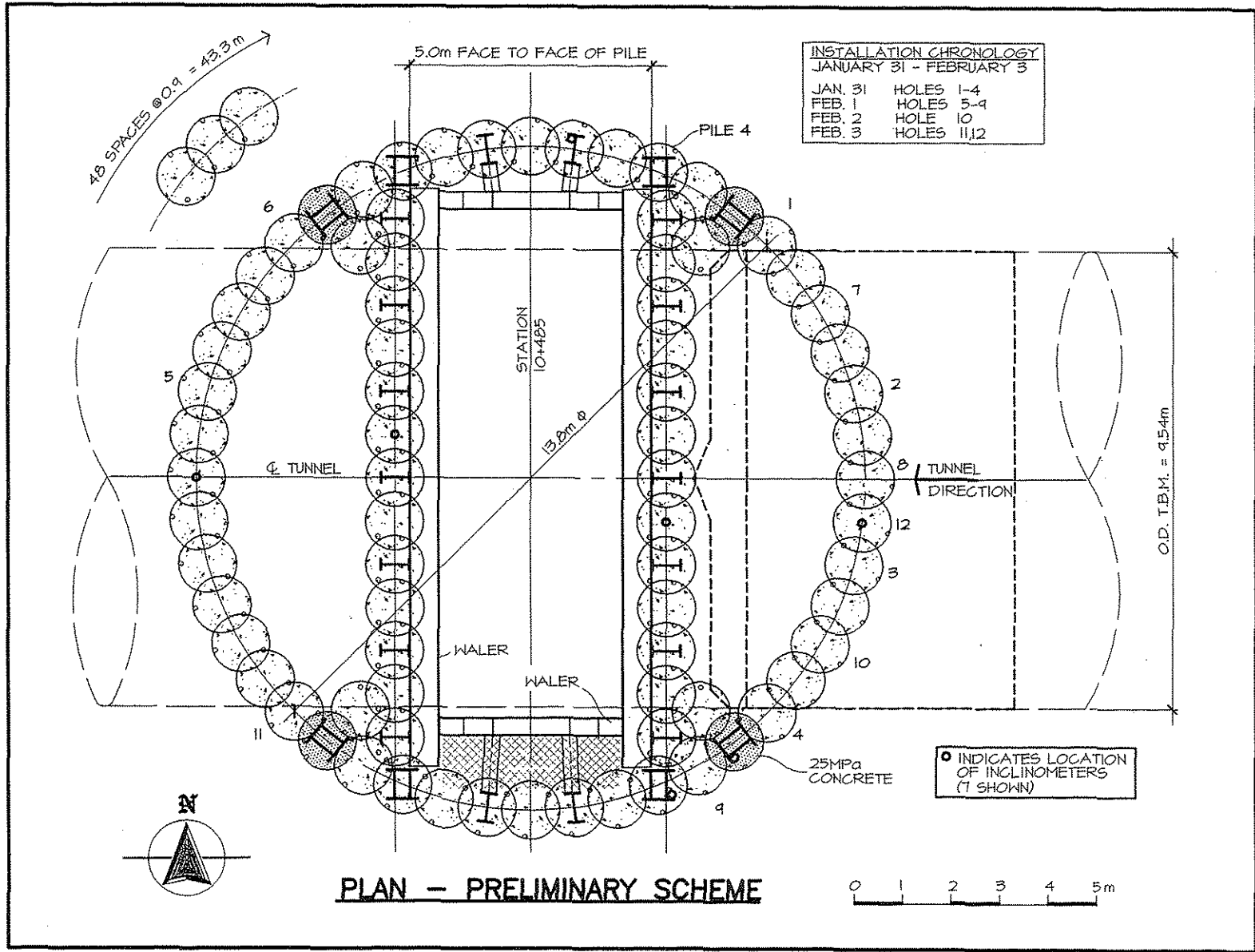


Figure 3: Preliminary Shaft Design

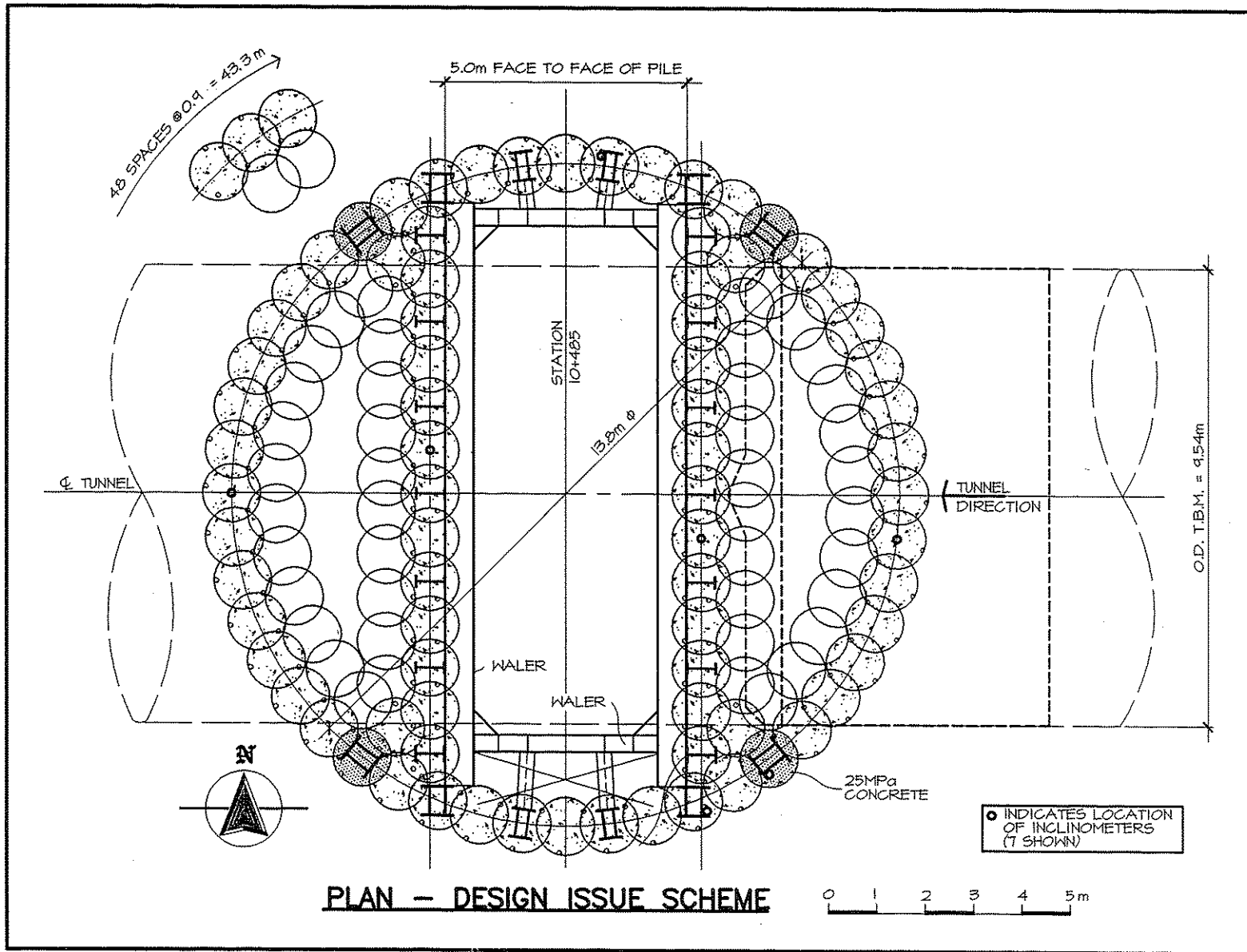


Figure 4: Shaft Design

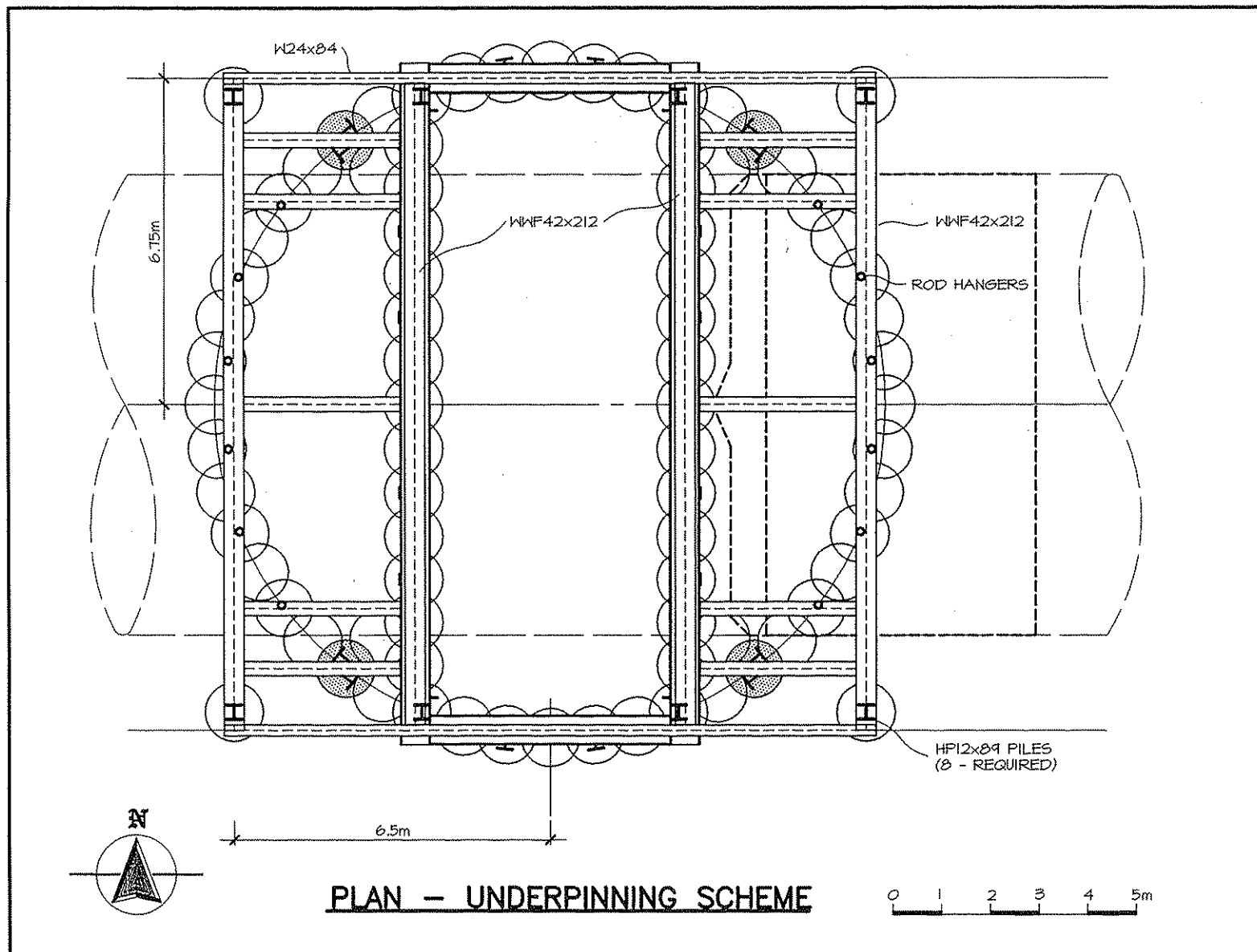


Figure 5: Piled Underpinning Scheme

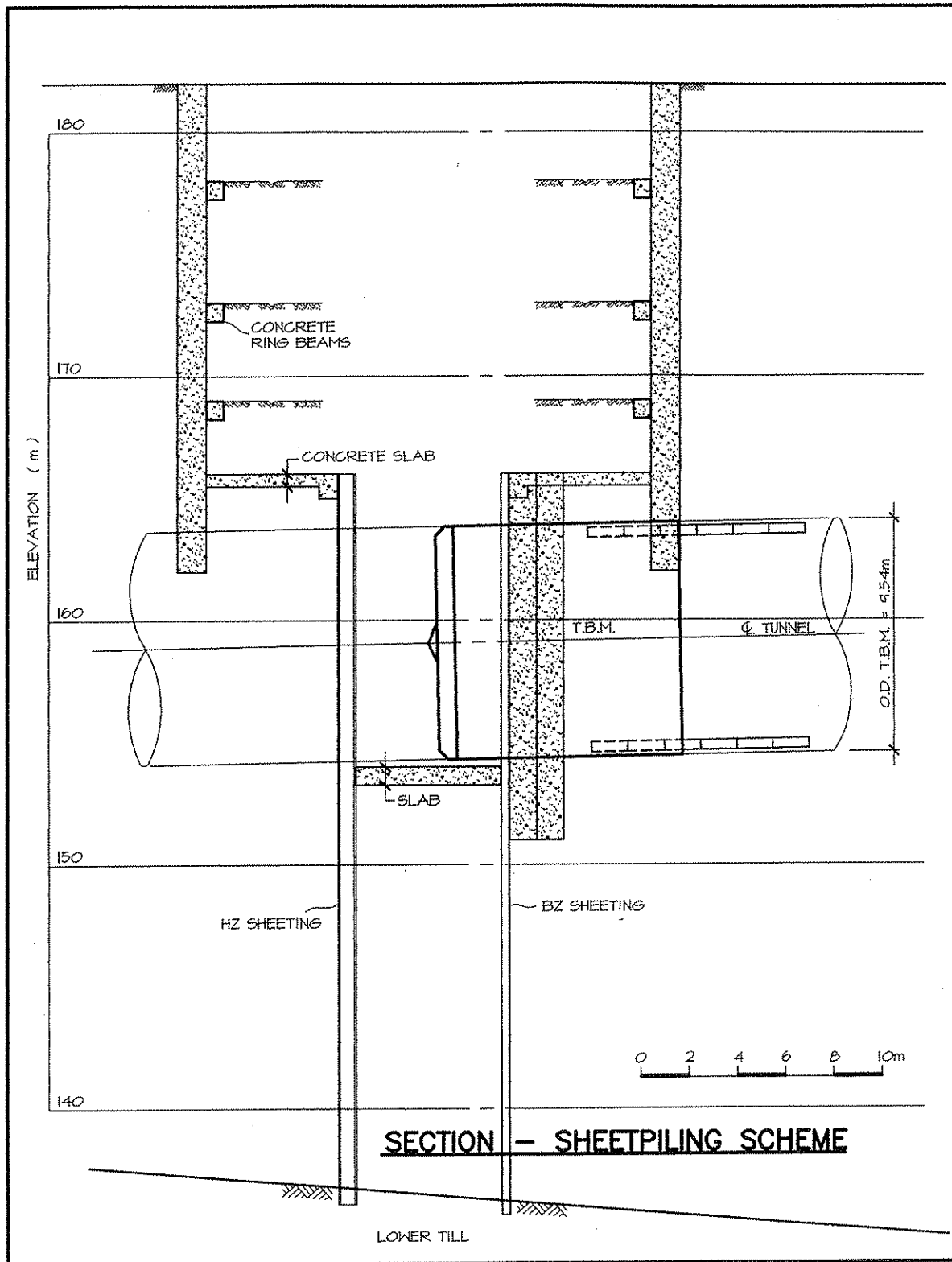


Figure 6: Sheet Piling Alternative Scheme

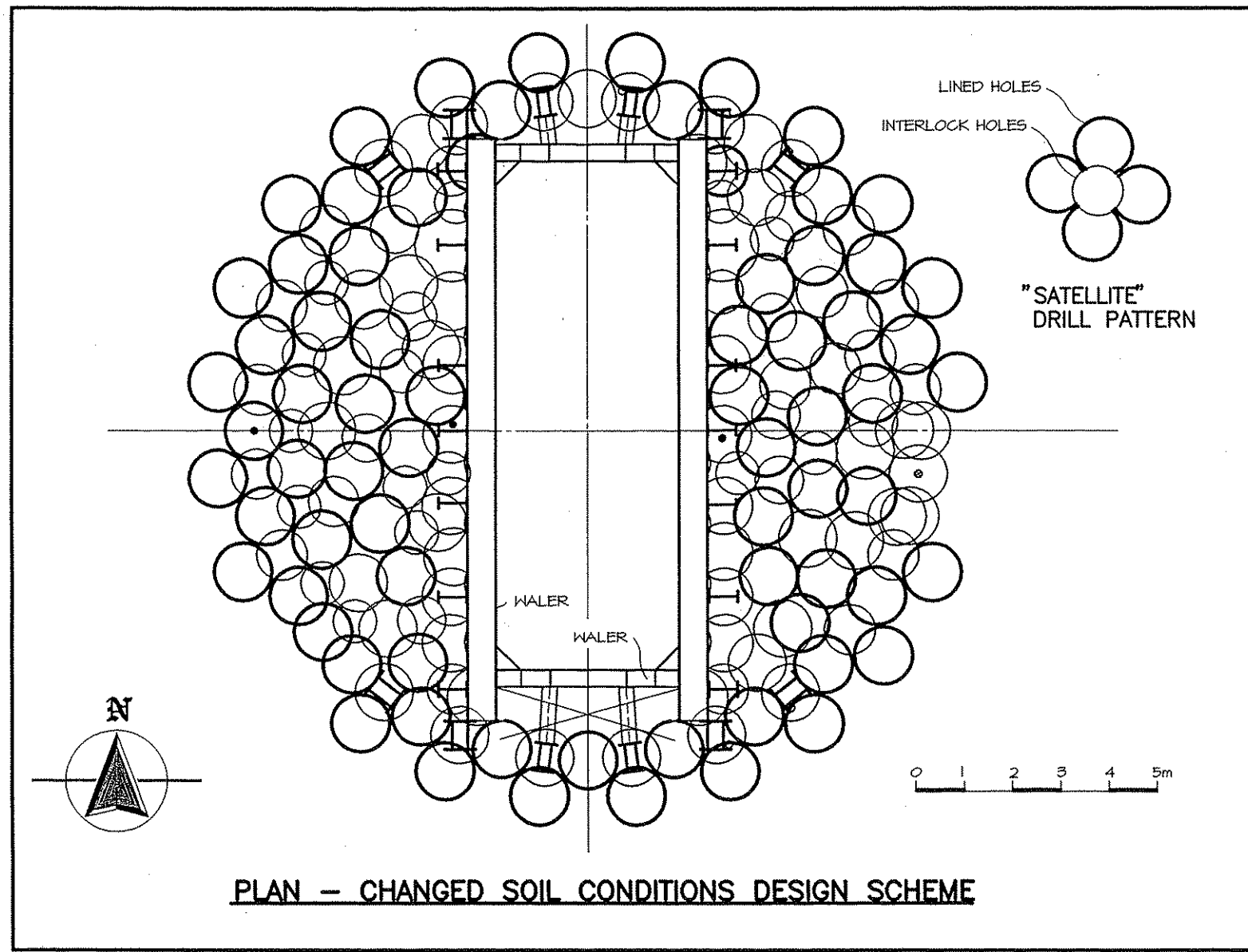


Figure 7: Revised Design for Changed Soil Conditions

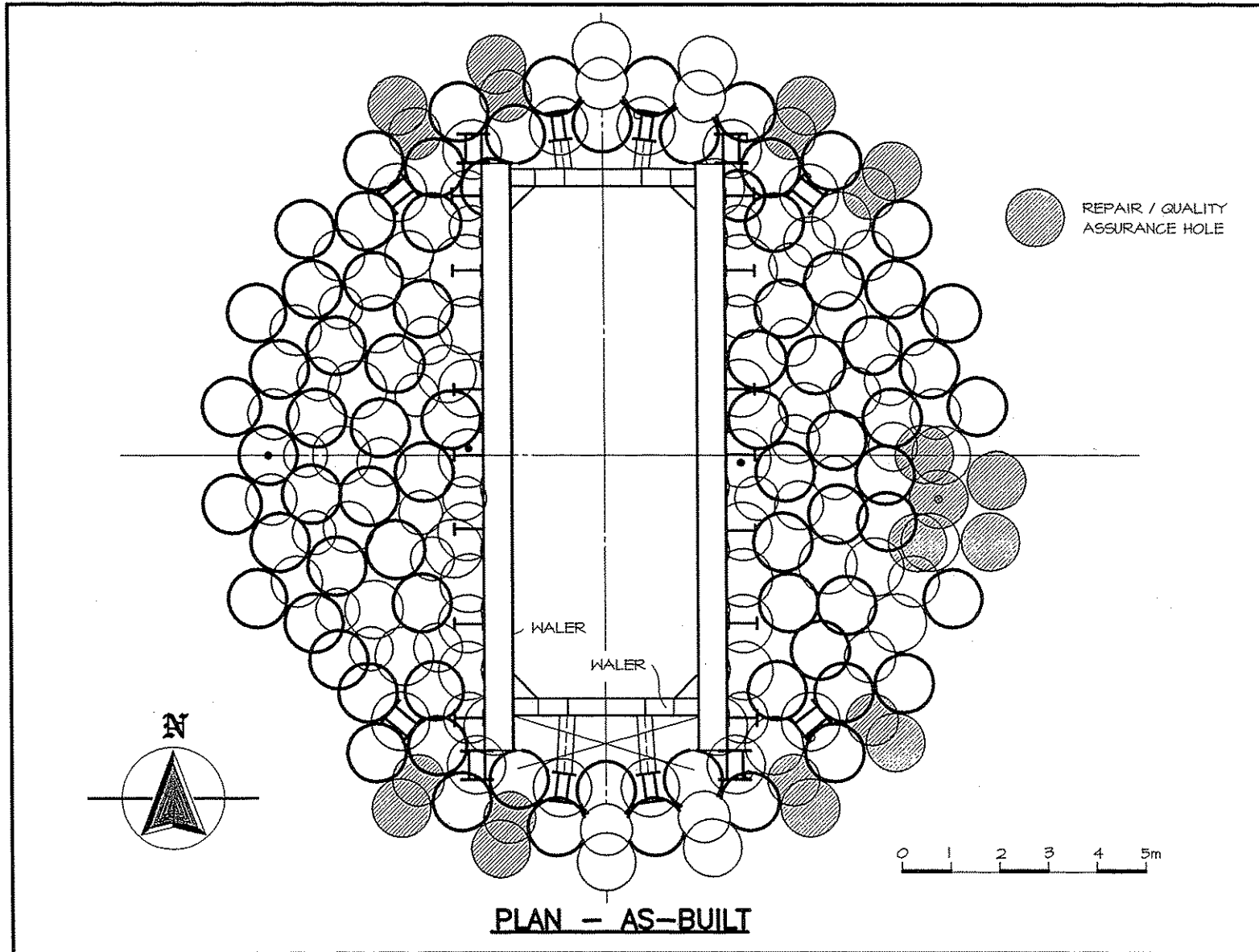


Figure 8: Plan of Shaft As-Built

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 Design and Construction of a Shaft for the TBM Cutterhead Retrieval

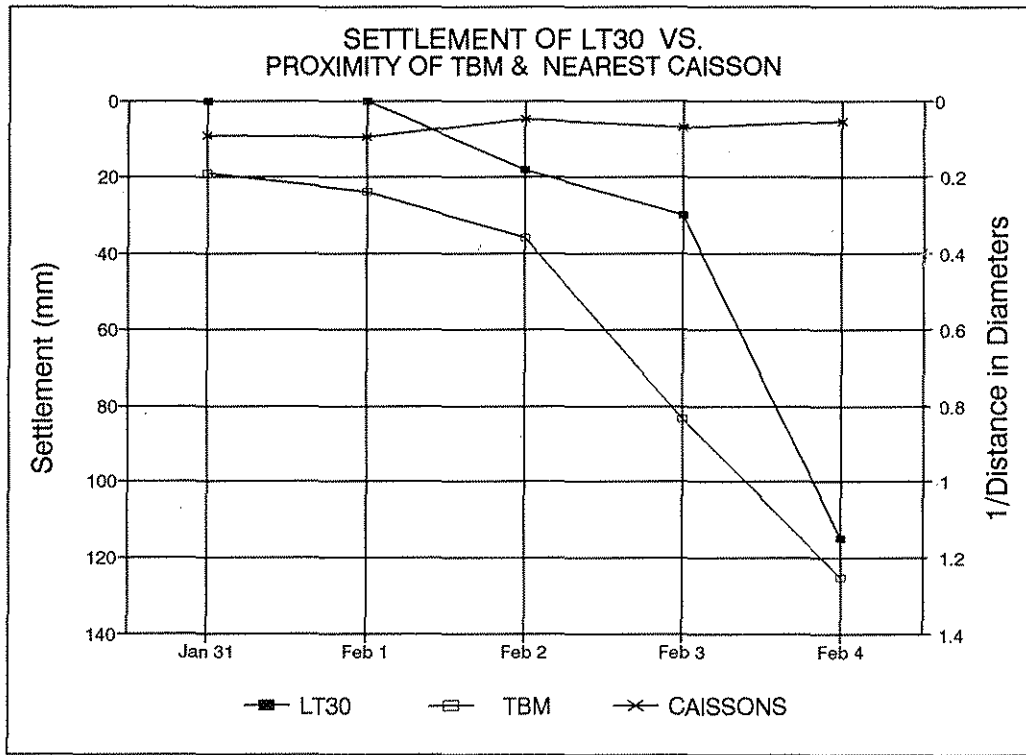


Figure 9: Surface Settlement related to Construction Proximity

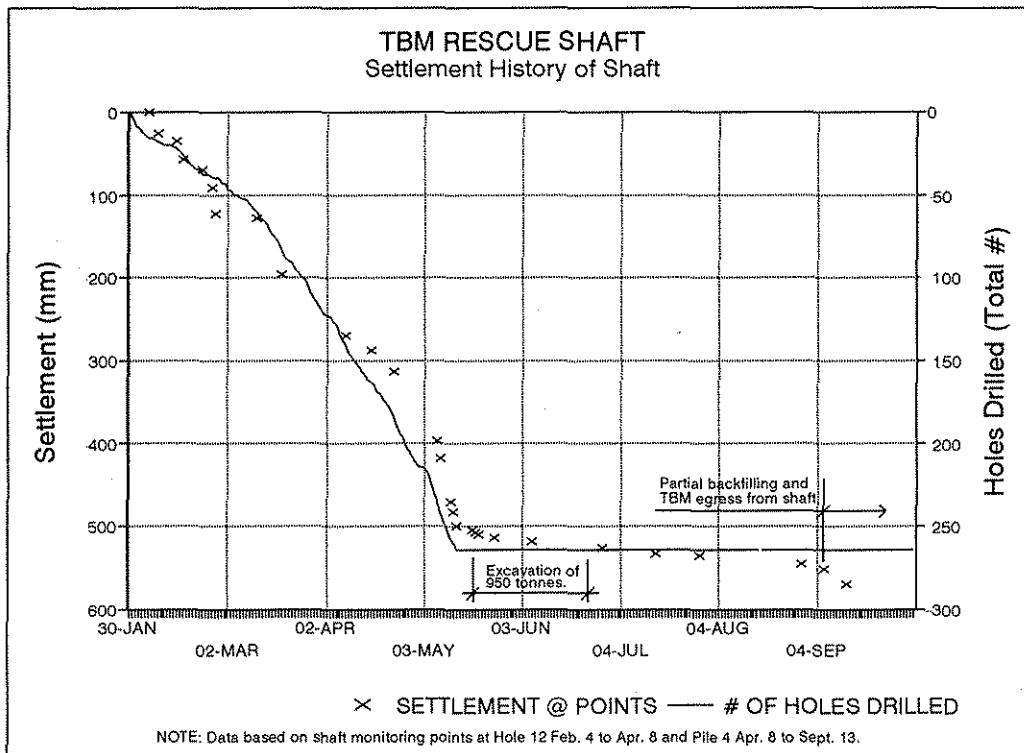


Figure 10: Shaft Settlement History related to Caisson Installation

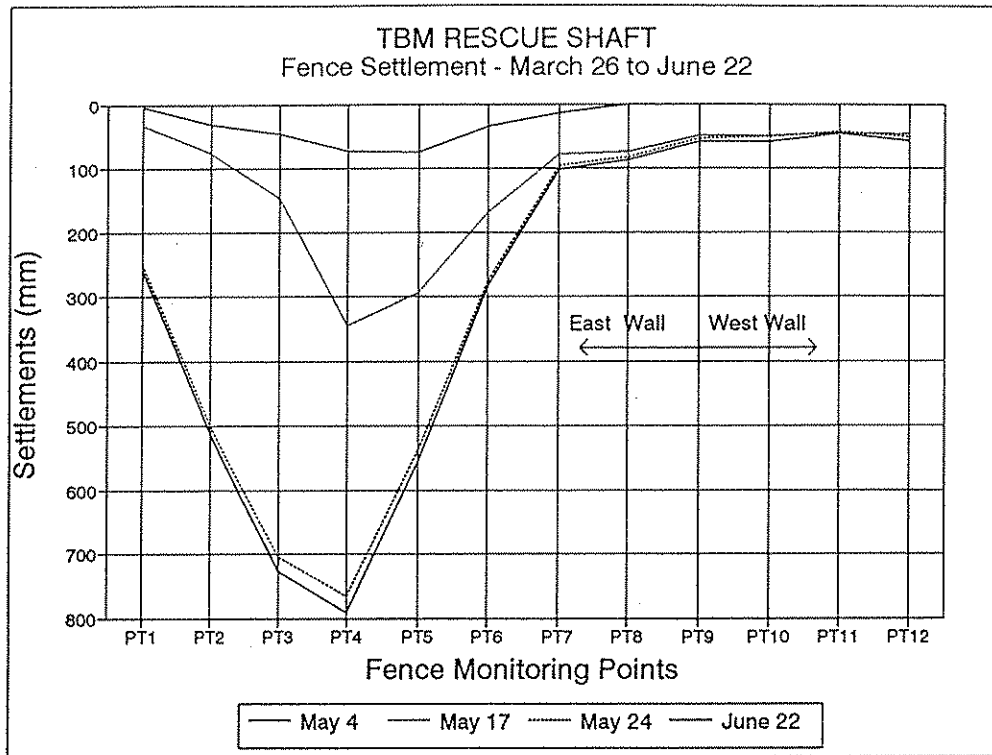


Figure 11: Fence Settlement

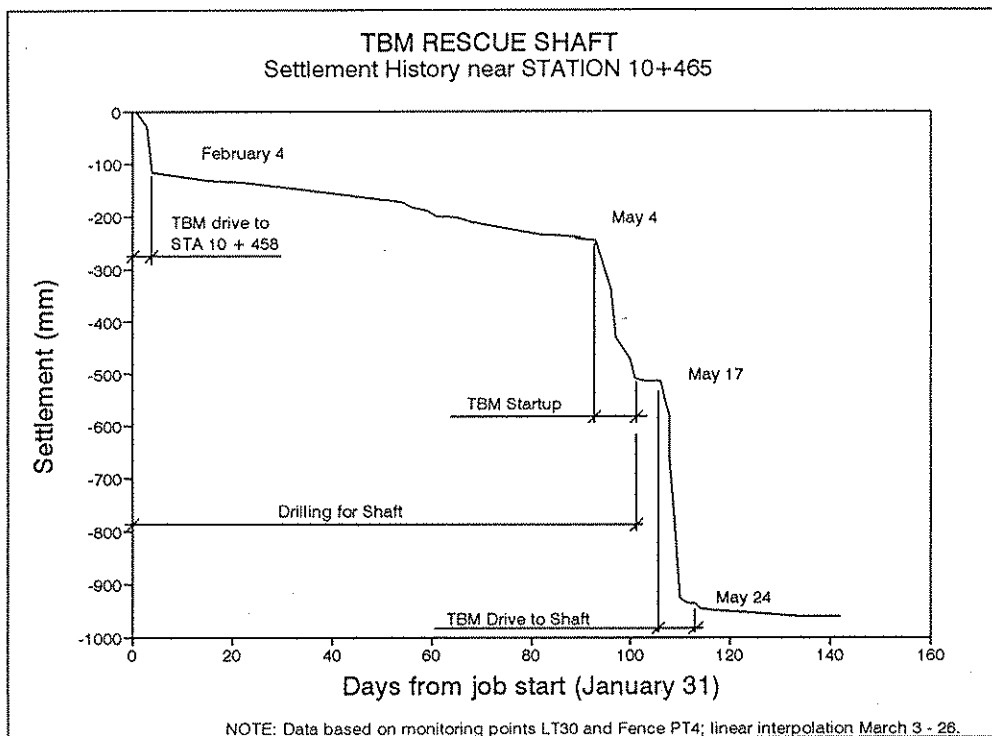


Figure 12: Settlement History of Monitoring Points near Station 10+465

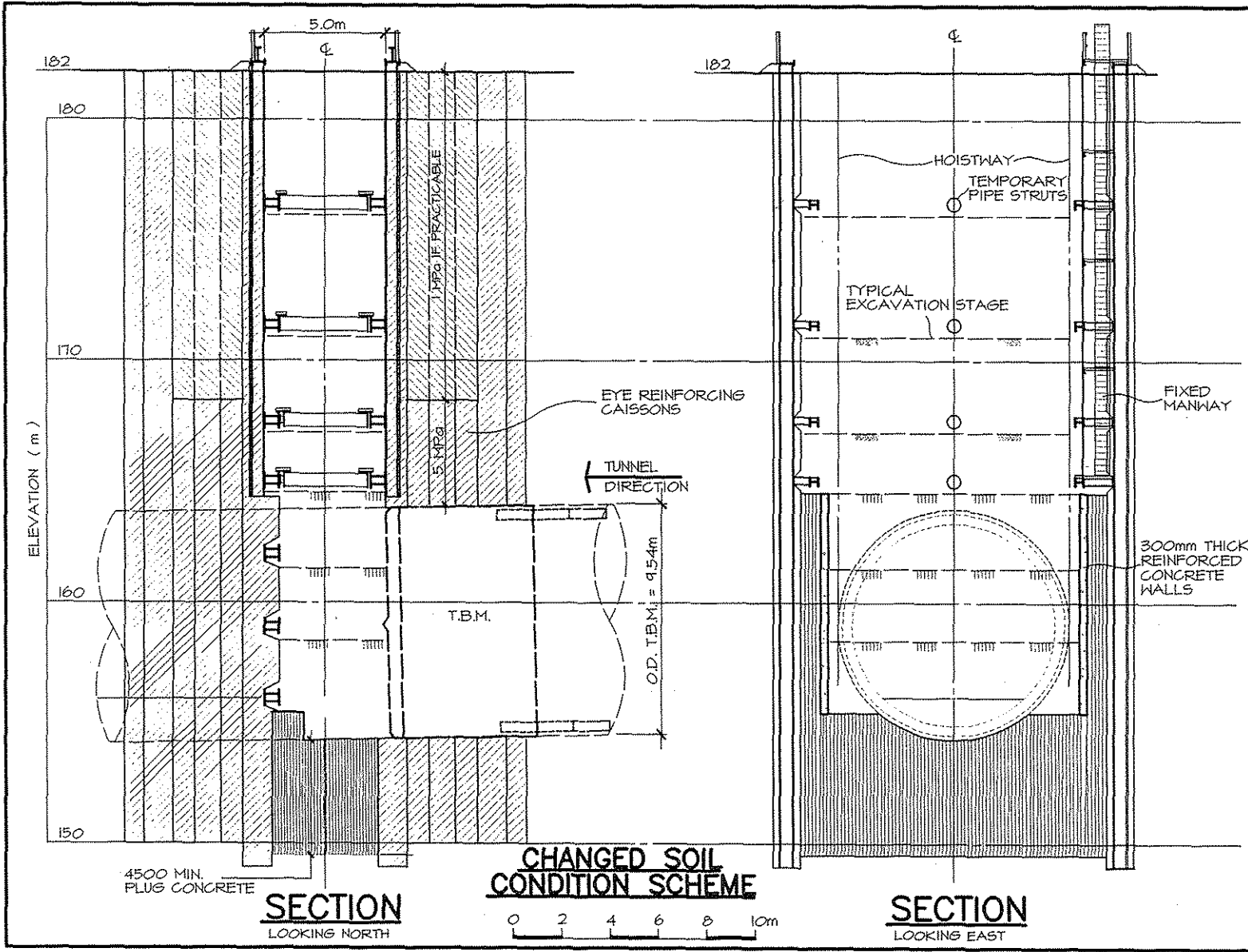


Figure 13: Shaft Sections - Changed Soil Condition Scheme

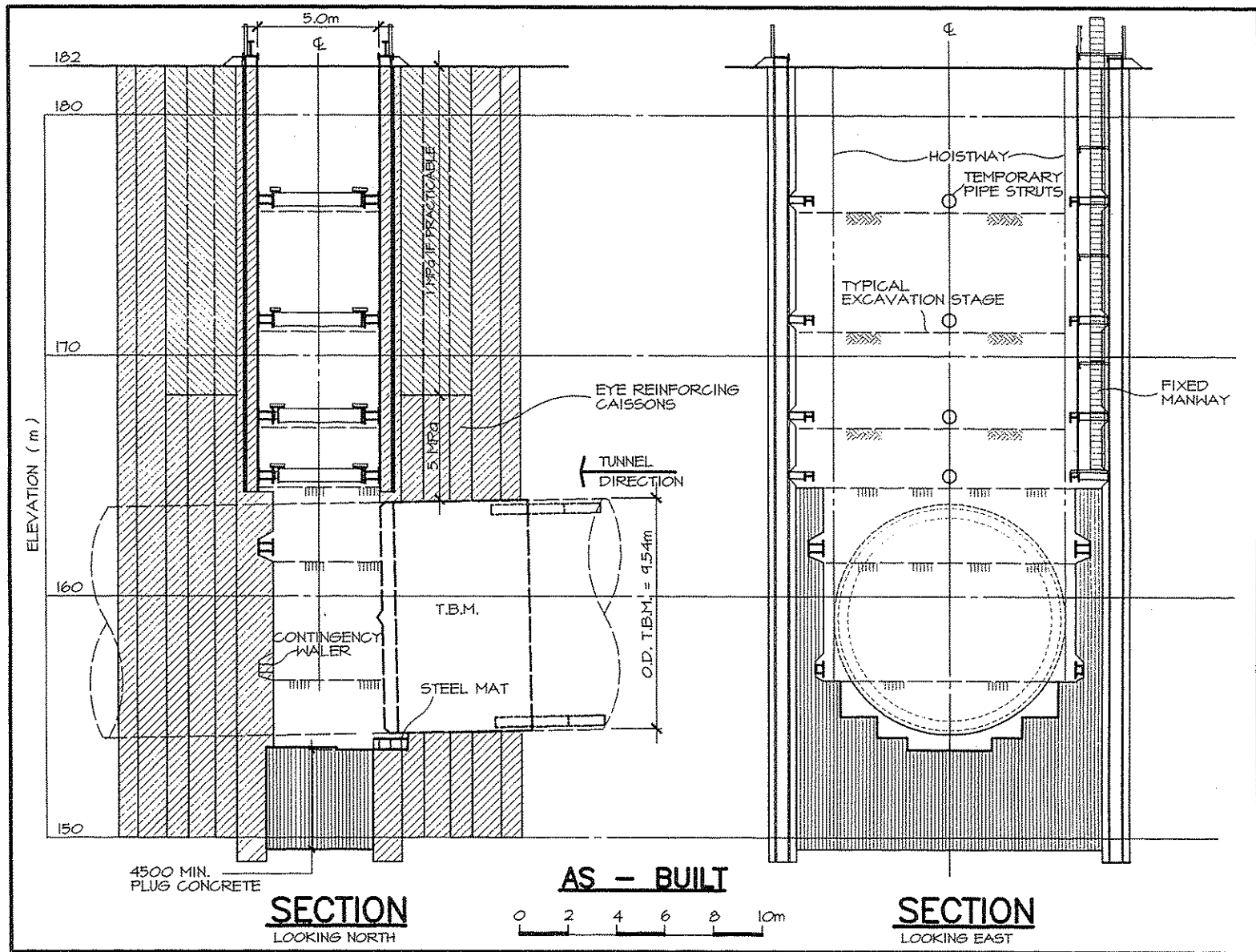


Figure 14: Shaft Sections - As Built

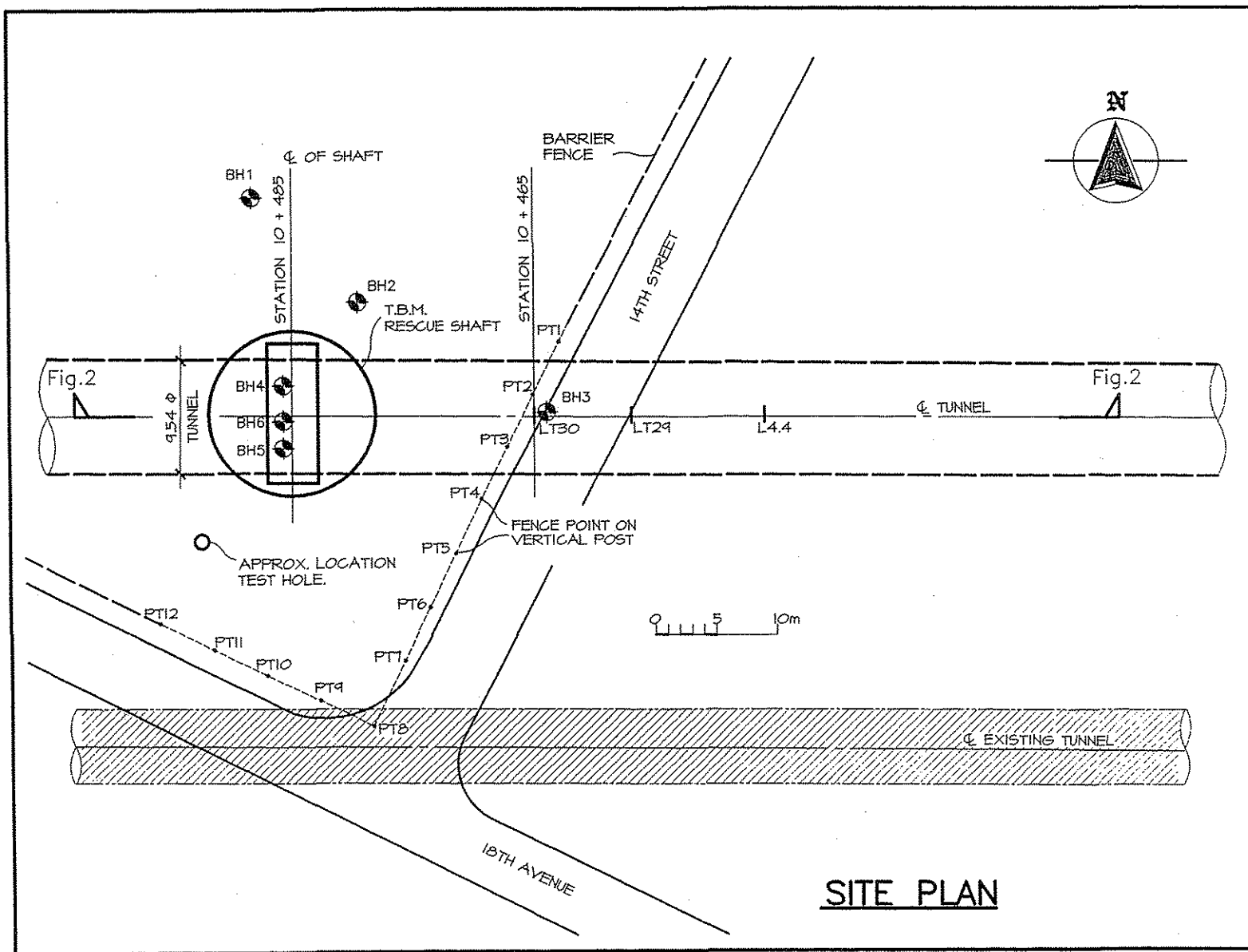


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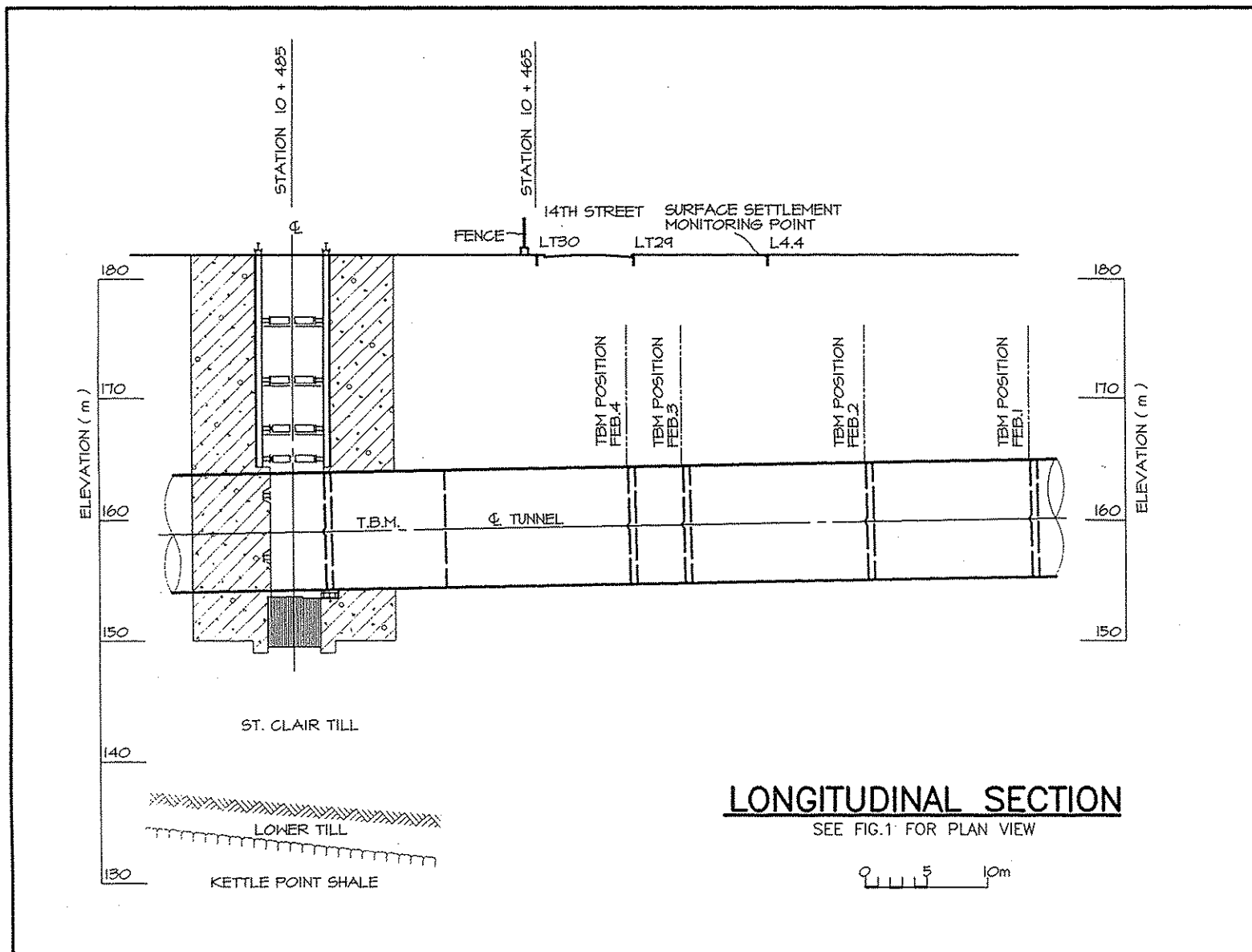


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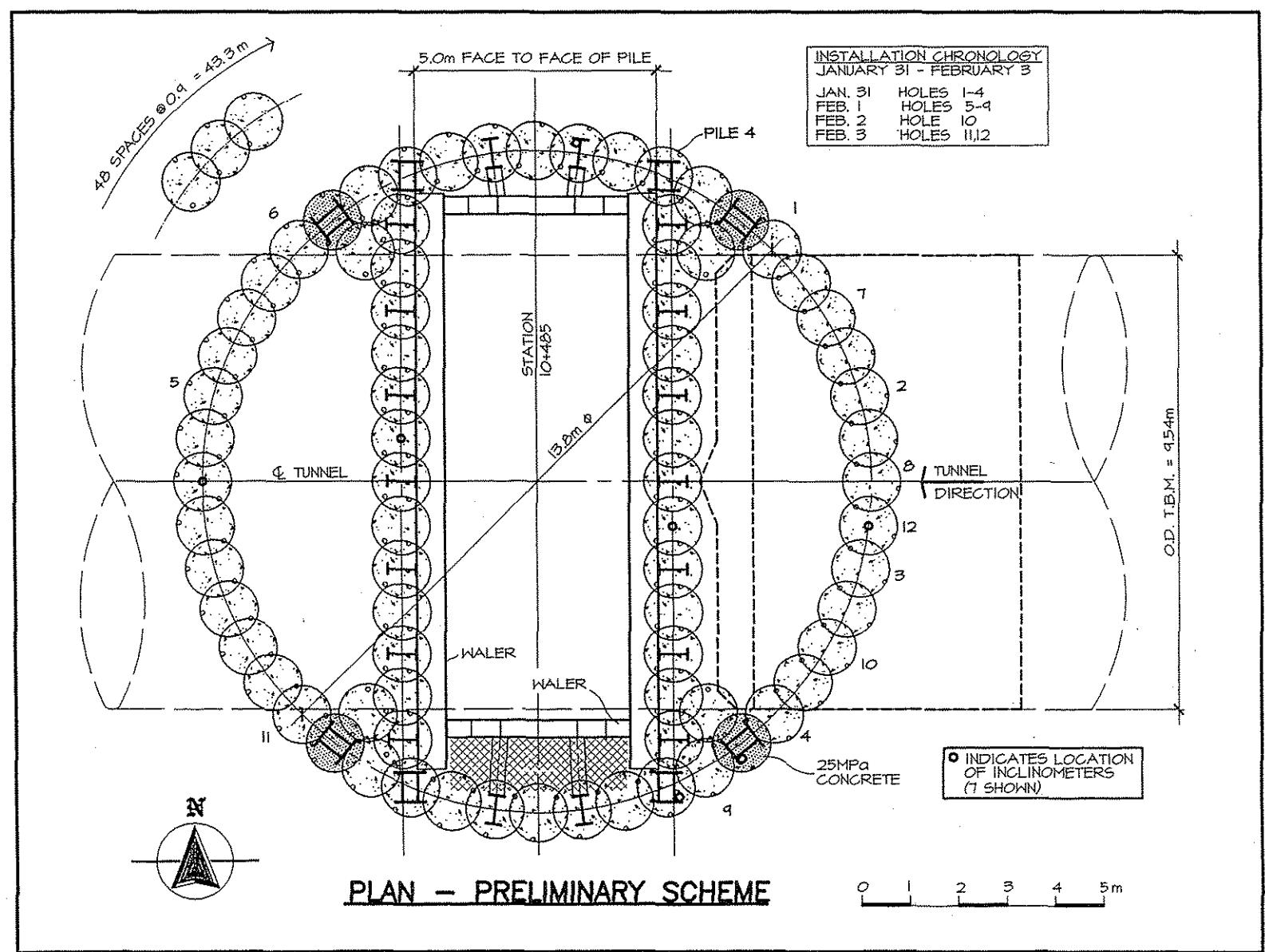


Figure 3: Preliminary Shaft Design

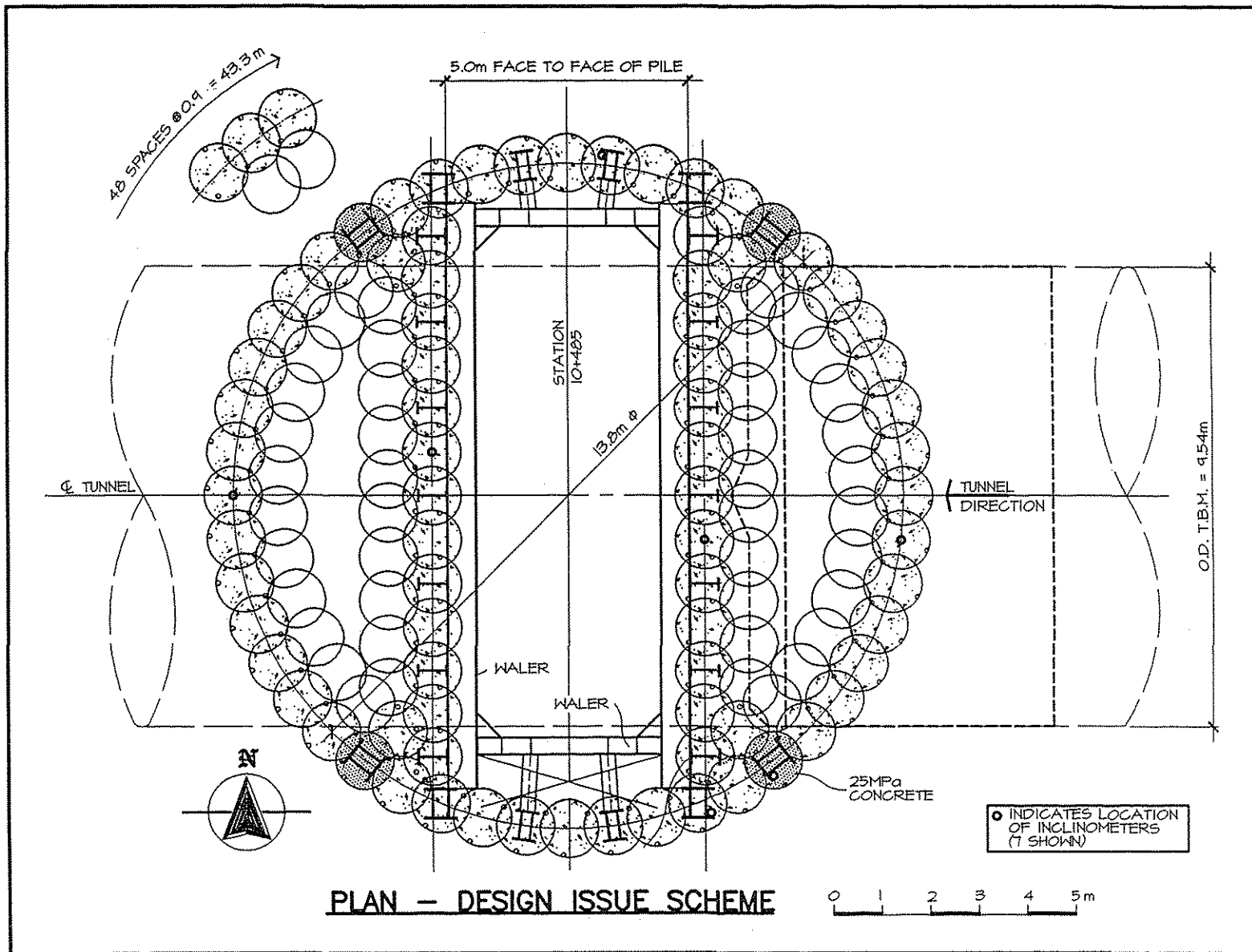


Figure 4: Shaft Design

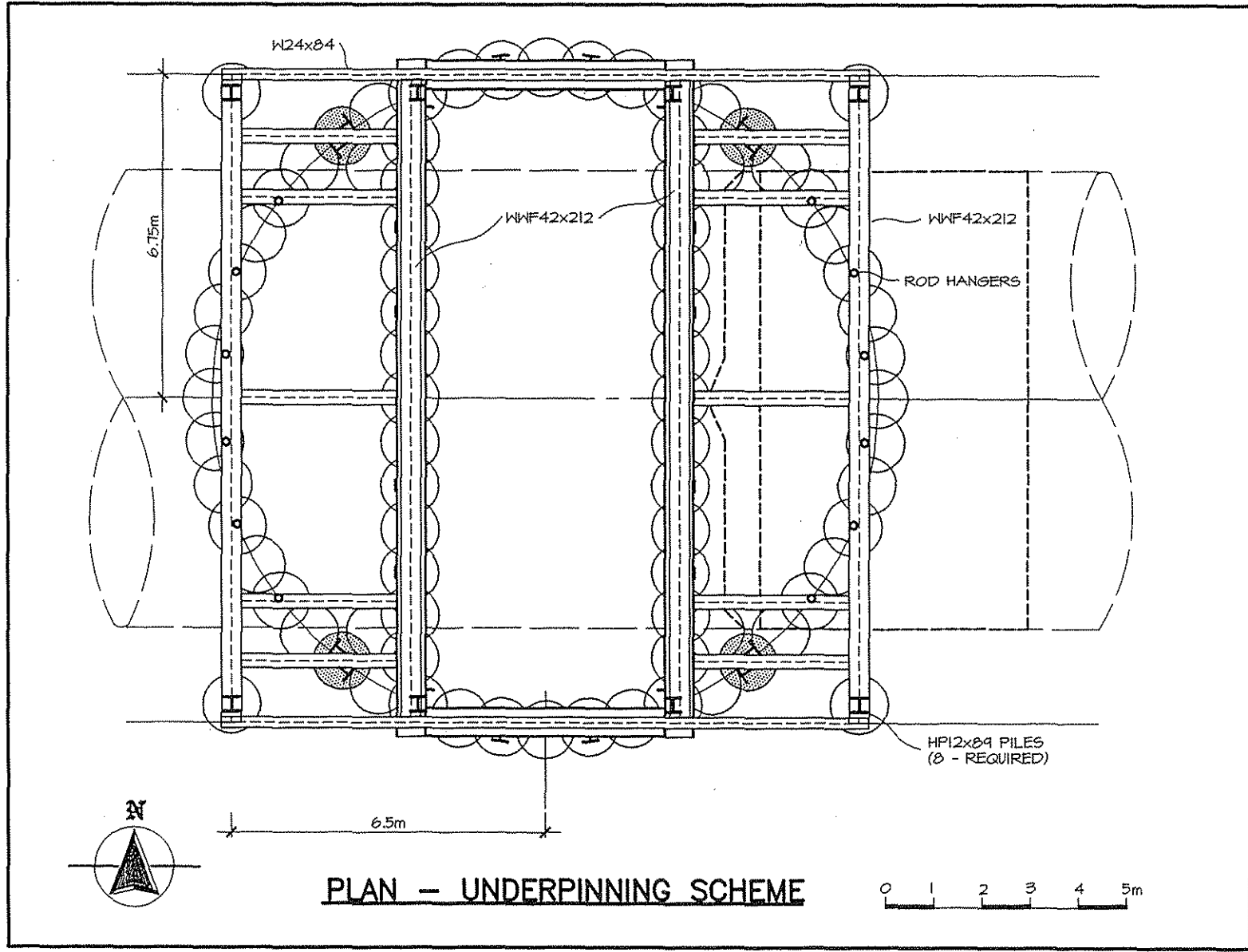


Figure 5: Piled Underpinning Scheme

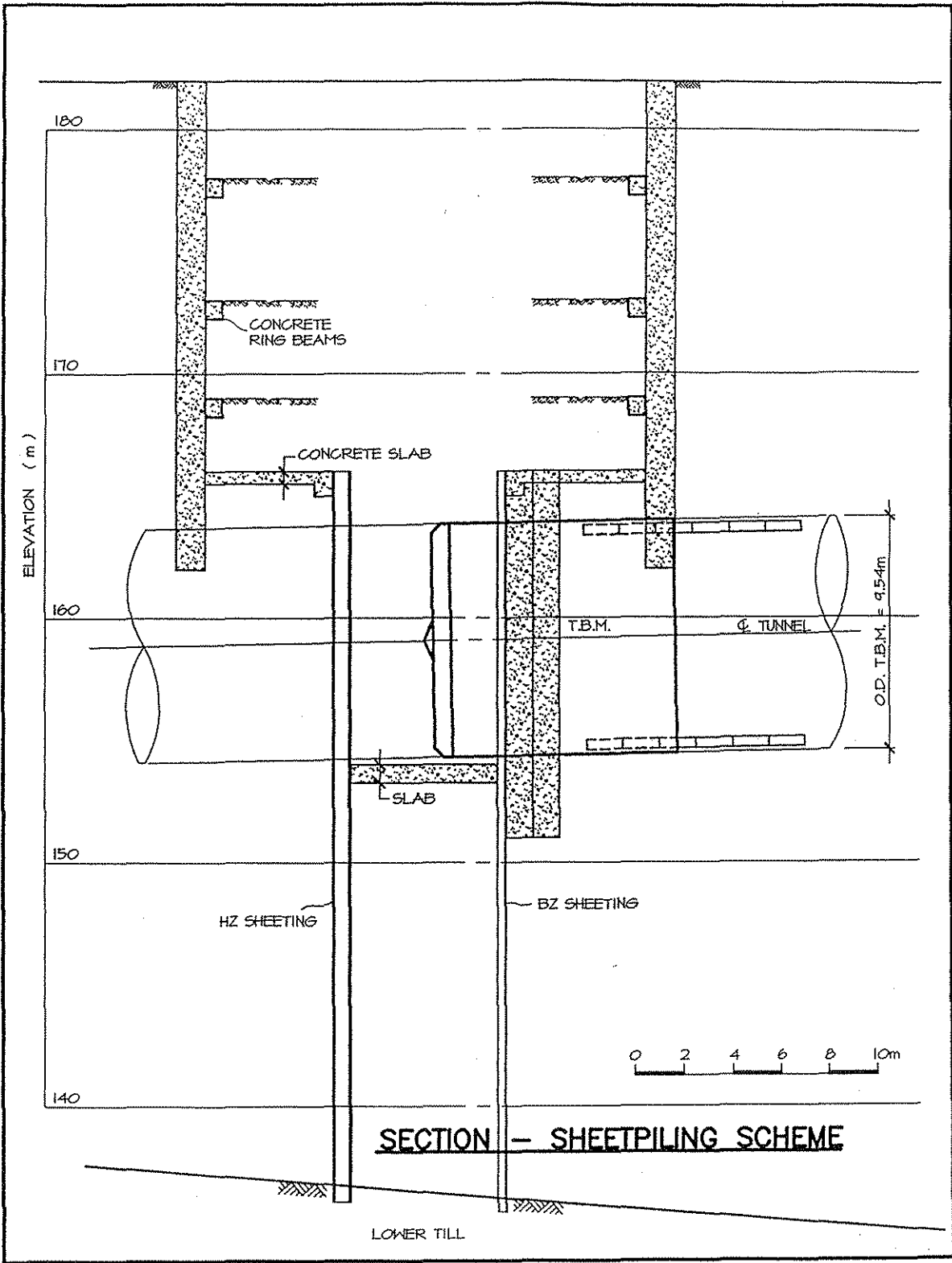


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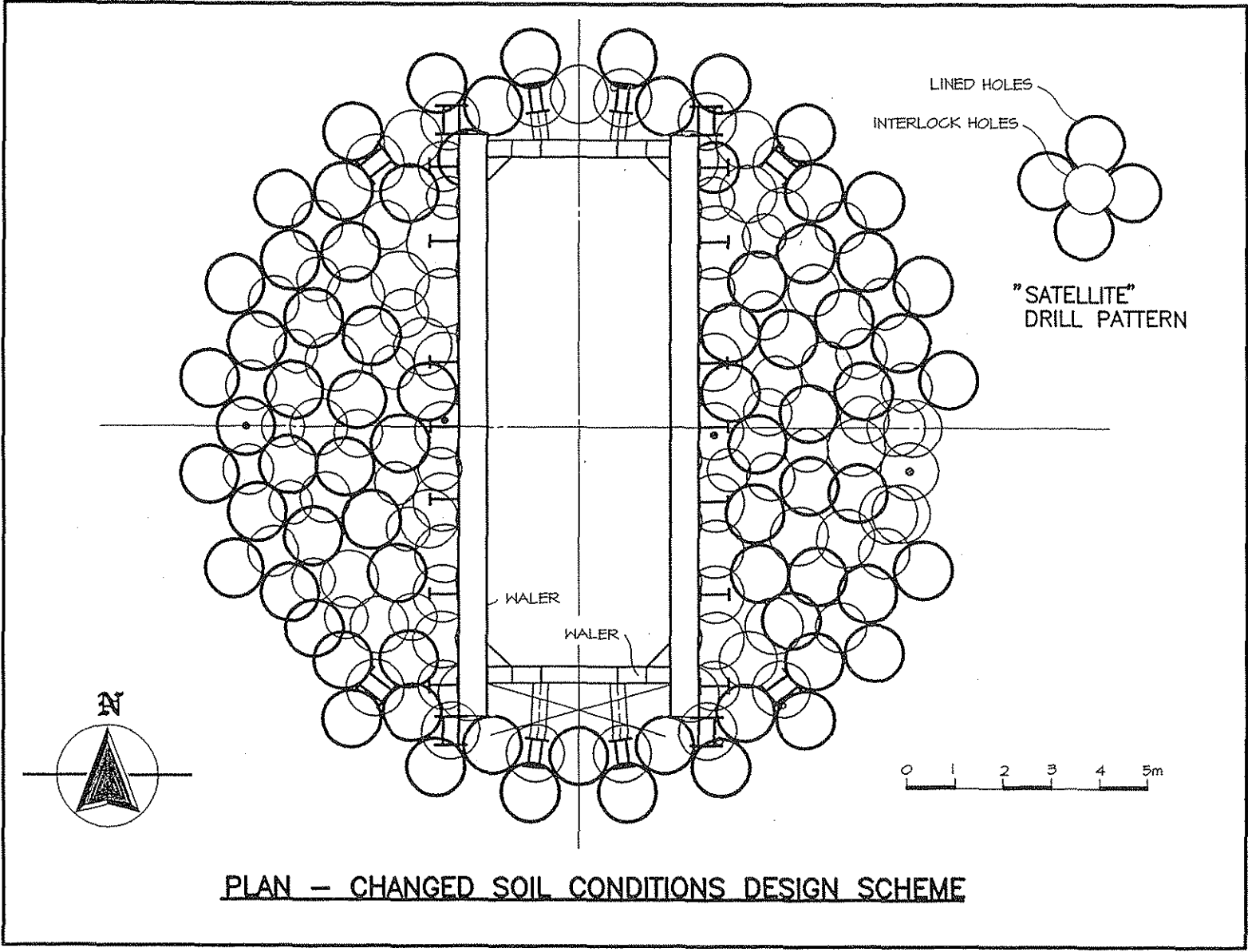


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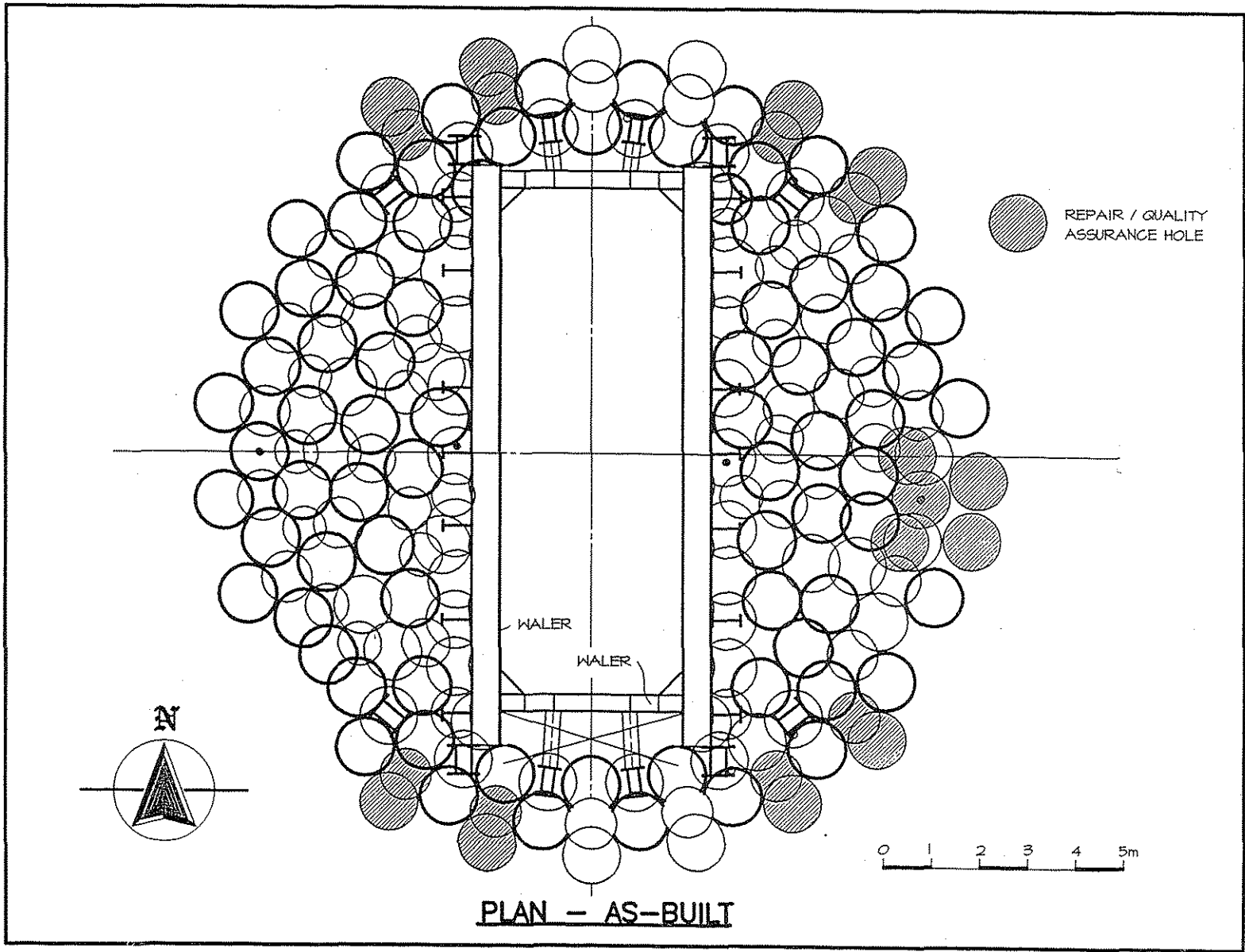


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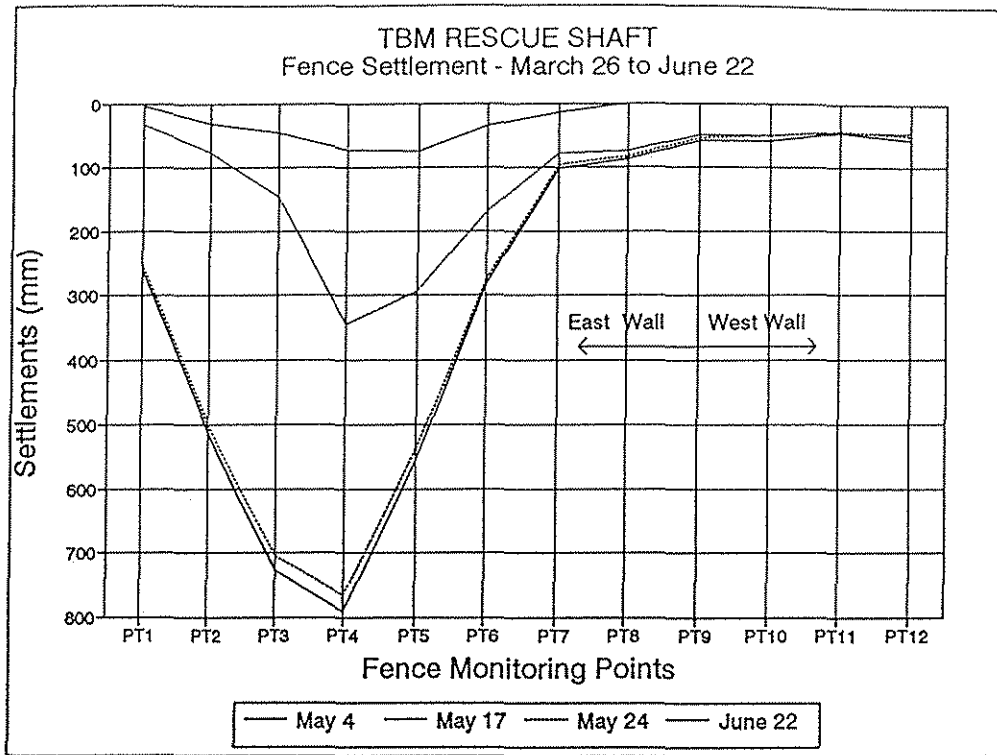


Figure 11: Fence Settlement

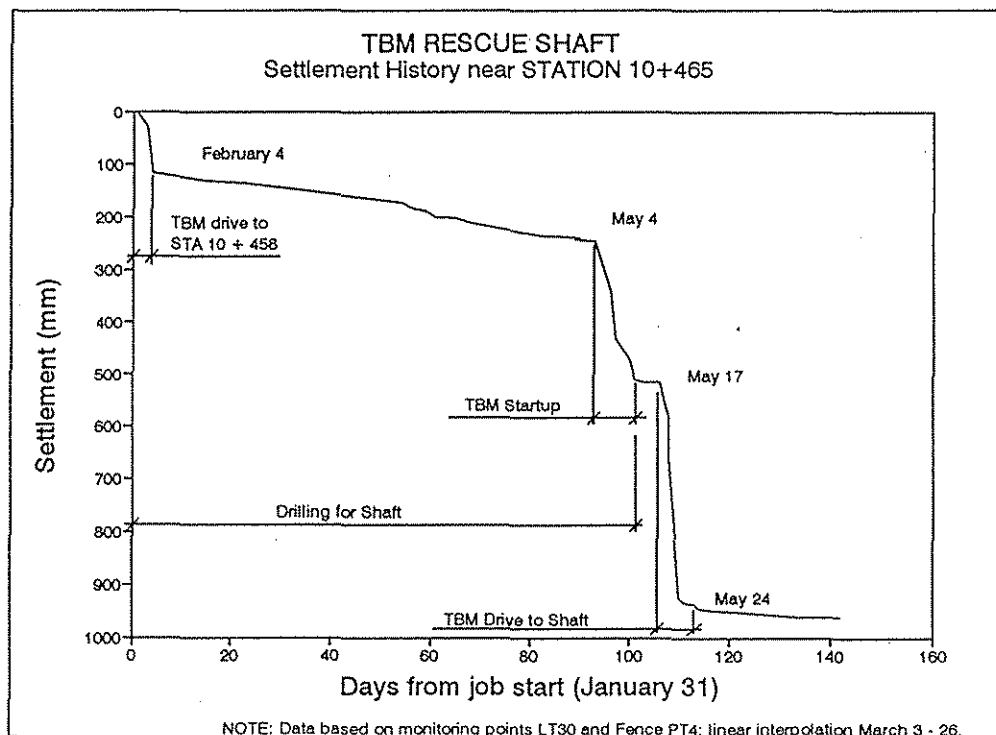


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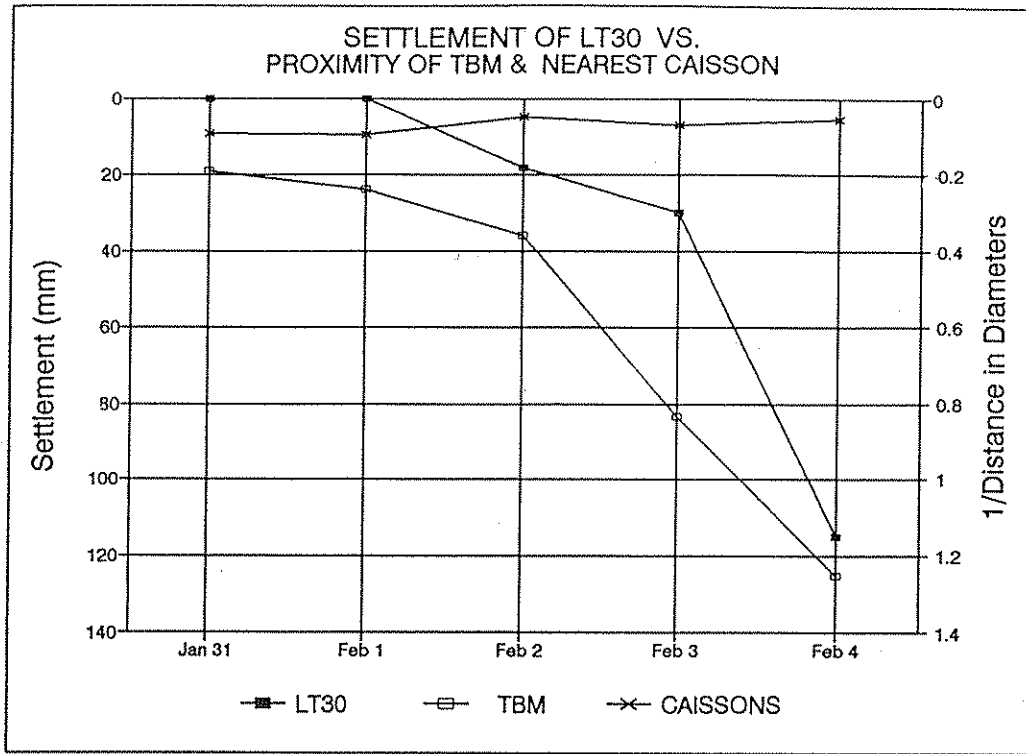


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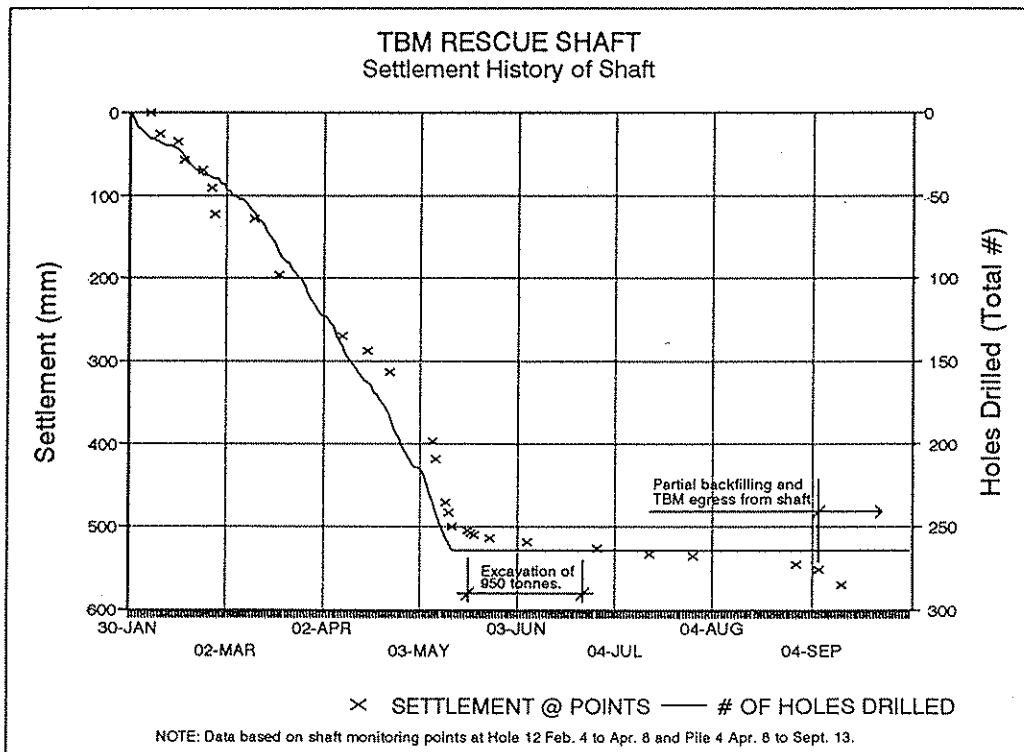


Figure 10: Shaft Settlement History related to Caisson Installation

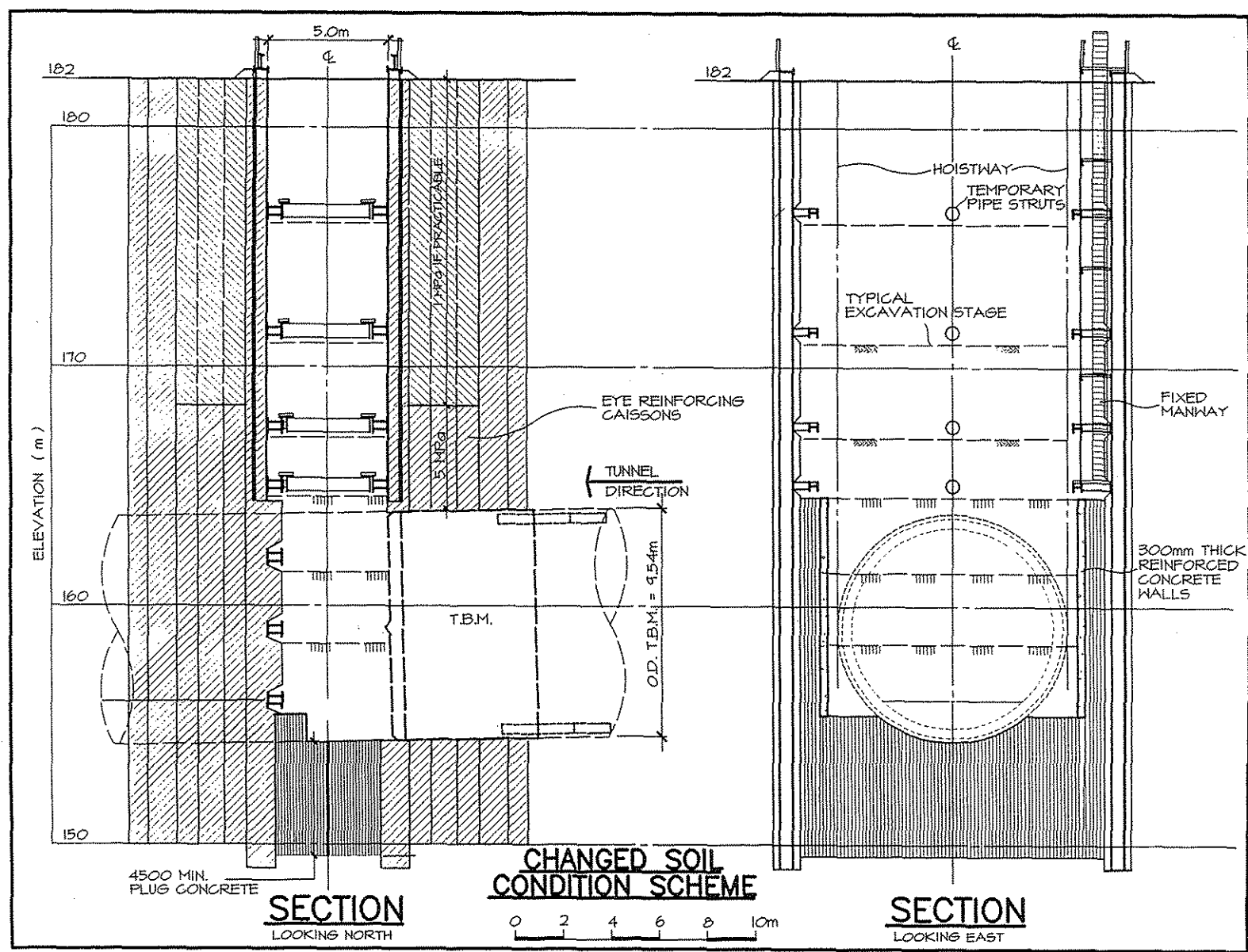


Figure 13: Shaft Sections - Changed Soil Condition Scheme

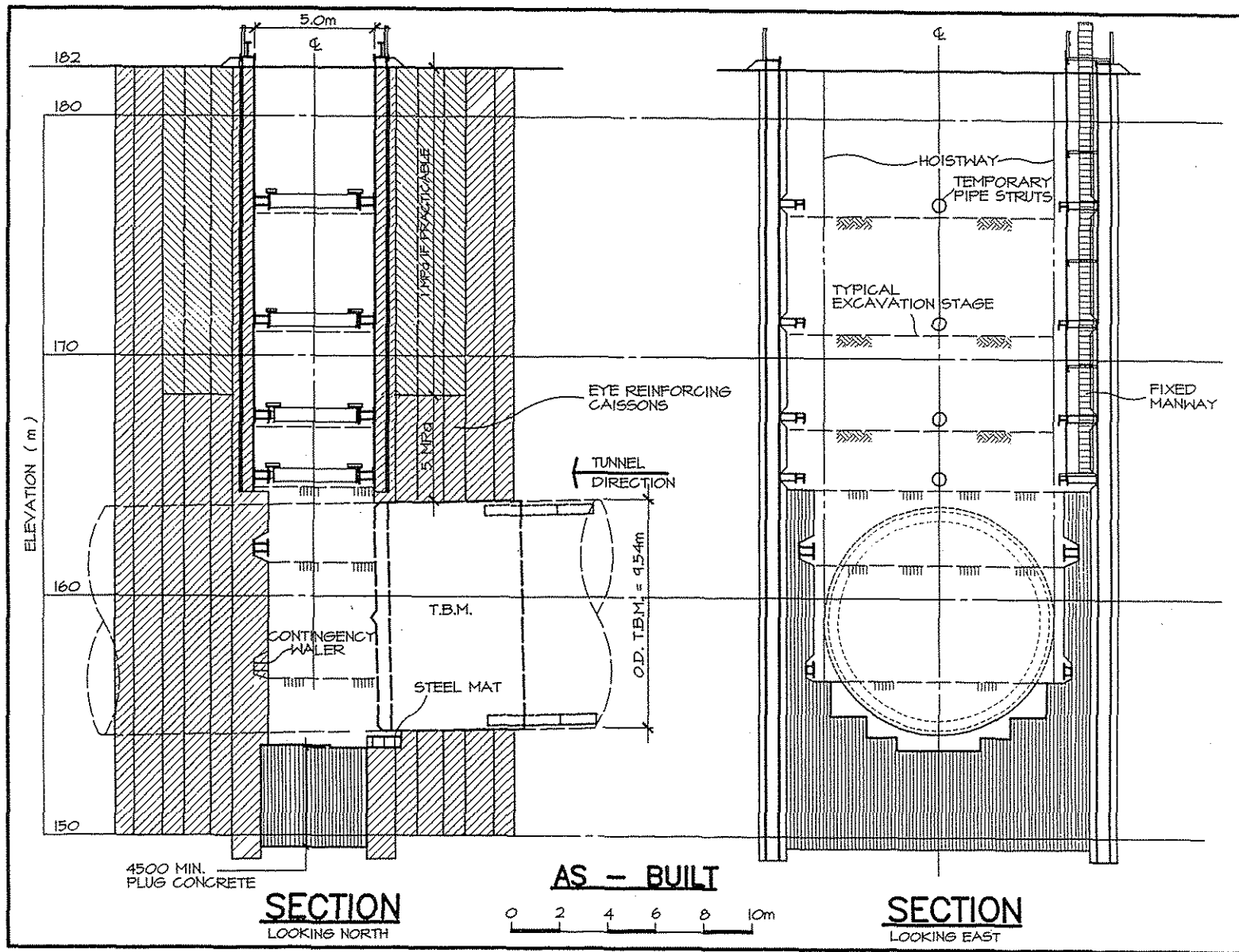


Figure 14: Shaft Sections - As Built