SETTLEMENT OF UNDERPINNED STRUCTURES IN SINGAPORE

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SETTLEMENT OF UNDERPINNED STRUCTURES IN SINGAPORE

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SYNOPSIS

The paper presents the settlement records for four buildings which were underpinned during the construction of the Mass Rapid Transit System in Singapore. The first two are modern, reinforced concrete buildings of 12 and 20 stories in height. The third is a pre-World-War-II building of 3 stories in height and the fourth is a chapel built in the 19th century. The observations were: (1) underpinning operation caused settlements of various magnitudes, (2) transferring building loads prior to excavation reduced settlements, and (3) even so, settlements were still significant during excavation.

INTRODUCTION

During the construction of Mass Rapid Transit System in Singapore, the authors were involved in the underpinning of four buildings, one of which is the oldest church in Singapore built in the 19th century and has been preserved as a historical monument. Underpinning was carried out for the reasons that, in the sequence of the cases to be discussed: (1) cut-and-cover tunnels were to pass underneath and underpinning was necessary to support the building so foundation piles could be removed, (2) deep excavation was to be carried out within a couple of meters and underpinning was carried out as a precaution against pile failure, (3) columns had already settled and underpinning was carried out in attempt to arrest settlements and (4) bored tunnels were to pass underneath and underpinning was carried out as a precautionary measures to maintain the safety of the structure.

Two types of underpins were used, namely, slurry wall, and micro-piles. The underpins were preloaded in the first case only. The paper summarizes (1) the settlements of the buildings during the underpinning work and (2) the settlement of the underpinned buildings during tunneling and adjacent deep excavation.

BLOCK 206

Description of the Structure and Reason for Underpinning

The structure, built in 1974, is a reinforced concrete, 12- story residential building founded on concrete piles. The underpinning of the building was necessary because cut-and-cover tunnels run directly beneath the building, and the foundation piles were directly in the way of the tunnels. Photo 1 shows the cut-and-cover tunnel passing under the building. The tunneling work affected 37 reinforced, cylindrical concrete piles of 300 to 450 mm in diameter. There were a total of 10 pile groups consisting of 1 to 8 piles in each group.

Ground Conditions

Figure 1 shows a plan of the building together with the tunnel alignment. Also shown in the lower part of the figure is a soil profile along the tunnel. The ground here is the residual soils derived from the complete decomposition of granite rock. The material consists of about 30 % of sand size particles, 30 % of silt size particles and 40 % of clay fraction. The N-value of the standard penetration test (SPT) near the ground surface is about 5 and increases with depth. The N-value at a depth of 25 m is greater than 50 at the site of Block 206. Todo and Pauzi (1989) may be referred to for the geotechnical properties of the residual soil from the granite in Singapore.

Underpinning Design Concept

Figure 2 shows the sequence of the construction of the underpinning and the tunnel. The underpins for this building are 800 mm thick diaphragm walls, 11.8 m center to center built along two sides of the tunnel box. The column loads of the building were to be supported on a 1.5 m thick concrete slab, which spans between the diaphragm walls.

Procedure for Underpinning Work

The construction work started in early February 1984 by erecting hoarding around the building. While allowing the residents on the higher floors to stay, the residents on the first (ie. the ground floor) and the second floors were evacuated and the floors were removed to provide space for the construction machinery for the installation of diaphragm walls. Settlement markers were installed in early March 1984 on 17 columns to be affected by the tunneling work.

Following the construction of the guide wall, i.e., stage 2 in Figure 2, the contractor installed 14 diaphragm wall panels from mid-April to the end of May 1984 at an average rate of one panel per 3 days. Bentonite slurry was used to maintain the stability of the trench. The concrete was cast through tremie pipes after pumping up slime from the bottom of the trench. In the contractor's design, the bearing capacity of the diaphragm wall is sufficient with a factor of safety much greater than 3. The founding level of the slurry wall was RL 83.7 m (about 23 m below the ground) with the cone resistance varying from 3.2 to 7.8 MPa at this level.

The second floor was then rebuilt after the installation of the diaphragm walls, see stage 3 of Figure 2. The ground excavation reached a depth of 4.5 m by the end of June 1984 and pile caps were exposed. Below the underside of the pile caps, a 1.5 m thick concrete slab (support slab) was cast in mid-July, 1984. The support slab spanned the top of the two diaphragm walls at a depth of 3.1 m below the ground level. The piles were separated from the slab by wrapping the piles with plastic sheets. The first floor slab was then re-built by mid-August 1984.

The excavation below the support slab started mid-October to create working space for the cutting of the piles. The column loads were first transferred to the diaphragm wall through the support slab before piles were cut. To control the settlement of the building, a flat jack was inserted into the gap between the pile cap and the support slab, and inflated to the maximum pressure of 120 bars. The maximum stroke of a single jack was 25 mm. The gap was shimmed by thin steel plates. Jacking pressure indicated that the load was being transferred. Jacking continued till the column load was fully transferred to the slab. The operation was repeated column to column until all the column loads were transferred. Jacking was completed in mid-March. Piles were cut at a point below the underside of the support slab.

The excavation below the support slab proceeded with two levels of struts (RL 99.2 and 95.3 m) and reached the final level (RL 92.5 m) in late June 1985. The construction of the tunnel ended in late August 1985 with one level of permanent strut remaining in place. The last set of settlement readings were taken on December 13, 1985.

Settlement Record

All the 17 settlement markers were installed on columns and therefore, registered the settlements of columns. Figure 3 shows time settlement plots for settlement marker No. 15, which registered the maximum settlement among the 17 settlement markers installed. The figure also indicates the construction events and the progress of the excavation.

Relation between Construction Sequence and Settlement

Figure 2-(1) shows the condition of the building before the construction work. Settlement monitoring started on May 2, 1984. When the construction of the diaphragm wall started, there was no immediate settlement. Figure 2-(2) shows the construction of the diaphragm will in progress. The settlement started mid-way through the installation of the diaphragm wall around early to mid-May, 1984. At the completion of the diaphragm wall installation, the

settlements were 1 to 6 mm with an average of 3.2 mm.

Figure 2-(3) shows the excavation at the top of the diaphragm wall and the casting of the support slab. Figure 2-(4) shows the pile cut-off and further excavation. Before the completion of the pile cut-off in early May 1985, some additional settlement occurred as a result of the reduction of shaft friction on piles as the excavation proceeded. The settlements were 4 to 12 mm with an average of 8.3 mm when the cutting of the piles was completed. At this moment, the bottom of excavation was at RL 98 m, giving a total depth of excavation of 8.5 m.

The purpose of jacking was not to raise up the structure, but to transfer the column loads to the support slab. It was observed that the gap between the underside of the pile caps and the support slab widened by 20 to 30 mm. The settlements of the diaphragm walls were not monitored. It is postulated that they would be of the order of 15 to 20 mm. The remainder would have come from the sagging of the support slab. During the jacking and pile cutting operation carried out in March to May, 1985, the settlements of columns were small and those small settlements could even be the result of excavation under the support slab and may have had nothing to do with the jacking-and-cutting operation. If jacking had not been carried out the subsequent settlement of the columns would, theoretically, have been 20 to 30 mm greater than what was recorded. It is thus concluded that jacking was effective in reducing building settlements.

Major settlement occurred when the excavation proceeded down to RL 92.5 m (additional excavation of 5.5 m) during June 1985. The total settlement was 7 to 18 mm with an average of 13.1 mm when the excavation reached the final level at the end of June 1985. The settlement still continued slightly during the construction of the tunnel box and stabilized in October 1985. The final settlement recorded in December 1985 was 13 to 24 mm with an average of 18.6 mm.

Lessons from the Work

(1) Installation of underpins, i.e., diaphragm walls in this case, itself caused settlements, and the removal of soils surrounding the foundation piles induced further settlements of columns.

(2) Jacking was effective in reducing settlements of columns.

(3) Even after the column loads were transferred to diaphragm walls, the excavation between the two walls still resulted in significant settlements of columns because of the reduction in frictional resistance on the walls. In other words, underpinning did not eliminate settlements.

Not withstanding the above, the structure of the building did not experience damages and the construction proceeded smoothly to completion.

BLOCK 116

Description of the Structure and Reason for Underpinning

The building is a 20- story, reinforced concrete structure built in the 1970s. Precast, square concrete piles of 430 mm in diameter with a working load of 100 tons each support the building. Deep excavation of 13.5 m was proposed close to the building for the construction of the Braddel Station. The building is only 1.5 to 2.7 m away from the diaphragm wall installed for the excavation. The diaphragm wall was 800 mm in thickness and 19 m in depth. Photo 2 shows the building together with the proposed site of the excavation.

Ground Conditions

Figure 4 shows a plan of the building together with the station. Also shown in the lower part of the figure is a soil profile along the station. The ground at the building is the residual soils derived from the weathered granite, as at the Block 206. The SPT N-values at top 10 m of the ground range from 10 to 20. The N-value gradually increases with depth and reaches 50 at a depth of about 25 m.

Underpinning Design Concept

Figure 5 illustrates the concept of the underpinning for the Block 116. There are a total of 16 piles, arranged in two rows in a group, supporting the last file of columns of the building. A U-shape transfer beam, as shown in Figure 5(b), was cast to hold the pile cap, theoretically, in place. The transfer beam was supported on barrettes, made of diaphragm wall panels, at its two ends. Each barrette was 2.85m long and 600 mm in thickness. They were installed to RL 97.75 m, which is 3m above the bottom of the excavation. The design load of the barrettes is 185 tons each. The concept was that, should any of the 8 piles, with a working load of 100 tons each, in the outermost row fail, the load could be supported by the transfer beam and the integrity of the structure could be maintained.

Settlement Record

The two barrettes were installed in late September, 1984, and station excavation in the vicinity was carried out in the period between early-April and early-July, 1985. Figure 6 shows the time settlement plot for a settlement marker No. 13, which was located at the corner of the building and registered the largest settlement among the 15 settlement markers installed. The maximum settlement at No. 13 was 34 mm.

During the construction of the underpinning barrettes and transfer beam, there was no recorded settlement. When the construction of the diaphragm wall commenced near the building, settlement started to occur. The recorded settlement at this stage at marker 13 was 11 millimeters. Major settlement occurred when the excavation started in late March 1985 and the settlement continued until shortly after the completion of the excavation.

Figure 7 illustrates the settlements of the building at the end of the monitoring period. The settlement decreases with the distance from the excavation. The settlement at the edge of the building was 26 to 34 millimeters. There is an expansion joint at 35 to 40 m away from the excavation separating the building structurally into two parts and the settlement at the location of the joint was 6 mm. The expansion joint opened with the width of 28 mm at 18th story. It is surprising that settlement extended to marker No. 7, 80 m away from the edge of the building.

Lesson from the Work

(1) The underpinning does not seem to be effective for Block 116, partly because building loads had not been transferred to the transfer beam prior to the excavation and settlement was necessary to effect such transfer.
(2) It is postulated that part of the column loads was originally taken by the stiff clay underneath the pile cap. As the ground settled and the pile cap was no longer in contact with the ground, this part of the loads was transferred to the piles causing the piles to settle. Furthermore, the settling ground dragged the piles and, since the piles were not long enough to provide resistance to the movement, the piles practically moved together with the ground.
(3) Doubtless, some of the load was transferred to the transfer beam, however, the barrettes could not offer much resistance to the ground movement either.

GOVERNMENT OFFICE

Description of the Structure and Reason for Underpinning

As shown in Photo 3, the building is a 3- story, colonial style, brick structure built before the World War II. Wooden piles (locally known as bakau piles) of 4.5 m long and diameters of 50 to 100 mm supported the building. The cut-and-cover tunnels pass close to the Government Office with an excavation depth of 27 m. The nearest column of the building is only 3 m away from the excavation and the edge of the pile cap for the column is 2 m from the excavation. During the excavation for the tunnel, settlement of the building occurred with widespread cracking. The contractor then underpinned the front of the building. However, the cracks continued to widen and the front end of the building was shored by using steel frames as shown in Photo 4. Figure 8 shows a cross section illustrating the building and the excavation.

Ground Conditions

Figure 9 shows a plan of the building together with the area of the excavation for the cut-and-cover tunnel. Also shown in the lower part of the figure is a soil profile along the tunnel. The ground at the building is covered with a 3 m thick fill, which overlies a 2 to 3 m thick beach sand layer and then a very thick layer of Old Alluvium. The SPT N-value of the fill and beach sand layer is less than 5. The Old Alluvium is Pleistocene sediments consisting of stiff to hard clay layers and medium to dense, often cemented sand layers. The SPT N-value of the Old Alluvium at the site is greater than 50 except for the top 15 m where the N-values are 20 to 50.

Underpinning Design Concept

Only the 4 columns in the front row facing the excavation were underpinned. The contractor used micro piles of a diameter of 107 mm for this. The piles were installed to depths of 26 to 28 m, which is 5m below the zone of influence as shown in Figure 8, but is approximately the same depth of the excavation. The micro pile consists of (1) a steel bar with a diameter of 38 mm and a yield stress of 465 N/mm^2 and (2) sand-cement-mix-grout with the compressive strength of 30 N/mm^2. The allowable load of the pile was 24 tons based on a factor of safety of 1.5 applied to the yield stress of the steel. The design considered the reduction of the cross sectional area of the steel bar at the thread. The allowable load of the micro piles does not include the strength of the grout.

Excavation, Underpinning and Settlement

The construction in front of the building started in January 1984. The contractor used the soldier piles with timber lagging method for the excavation together with short walls of steel sheet piles to cut off seepage of the groundwater from the beach sand layer. The soldier piles were driven into pre-augered holes. The augering continued from late January to April 1984 near the Government Office followed by sheet piling from mid-April to mid-May 1984.

The excavation started in late May 1984 with 7 proposed levels of struts and continued until the end of December 1984. The struts were initially preloaded to 50 % of their design load. Cracks became apparent at the building in early July when the excavation reached a depth of about 10 m with 3 levels of the struts in place. The excavation was then suspended until late September. The contractor shored the building as shown in Photo 4 in late July 1984 and underpinned the columns in the period between 10 and 23 August 1984.

The excavation restarted on September 21, 1984 and new cracks appeared on the building with the progress of the excavation. When the excavation reached a depth of about 13 m and the 4th level of the struts installed, an additional strut was installed at level 2 at mid-October. The additional strut was necessary because one of the second level struts was overstressed compared to the design. In late October, the second row of the columns (which were not underpinned) from the excavation started to subside. In early November the excavation was about 18 m deep with 5th level of the struts installed. At the end of November, the excavation was 22 m deep and 6th levels of the struts were installed together with an additional level of the struts between 5th and 6th levels. The strut levels were finally 8 instead of the originally proposed 7.

Settlement Record

Settlements of the building were monitored from March 25,1984 to September 30, 1985. Time settlement plots are shown in Figure 10, which indicates the settlement at the front row of the column (underpinned) and second row of the columns (not underpinned) and surrounding ground.

The settlement of the front row columns started when the excavation began in late May 1984. Cracks of the building occurred when the settlement reached 5 mm. Further settlement of 6 mm occurred during the underpinning work. Major settlement started late September when the excavation restarted after the underpinning work. The ground settlement at the opposite side of the excavation and the settlement at the second row of the columns also progressed rapidly. The settlement almost stopped when the excavation reached the final level although a small amount of settlement still continued. The final recorded settlements at the front row of the columns were 37 to 51 mm, which are almost of the same order of the ground settlement as shown in Figure 10. The settlements at the second row of the columns were 30 to 36 mm.

Lesson from the Work

(1) Settlement of 6 mm occurred during the underpinning work. The magnitude of the settlement was of the same order of the settlement recorded before the underpinning work.
(2) A part of the settlement after the underpinning is attributed to the fact that preload was not applied

to the underpins. Settlements were necessary for the underpins to receive loads.

(3) The underpinned columns settled by almost the same amount of the ground settlement. One of the possible reasons is that the micro-piles were installed mostly within the influence zone of the tunnel excavation. The piles probably settled together with the ground settlement because the ground dragged them down.

CHAPEL

Description of the Structure and Reason for Underpinning

The chapel building of the Convent of the Holy Infant Jesus was built in 1854 with a 2- story main building and a 4- story tower constructed with bricks. The underpinning of the whole building was proposed because twin bored tunnels were to pass directly underneath. The convent was classified as a Preserved National Monument. No information was available on the foundation details of the building. Photo 5 shows the rear view of the building.

Ground Conditions

Figure 11 shows a plan of the building together with the tunnel alignment. Also shown in the lower part of the figure is a soil profile along the tunnels. The ground is covered with a layer of 7 to 9 m thick consisting of fill, beach sand and organic soil. The Old Alluvium (with SPT N-values of generally greater than 50) described for the Government Office underlies the surface layers. The twin bored tunnels of 6 m internal diameter pass under the building within the Old Alluvium. The cover of the Old Alluvium above the tunnels varies from 3.5 to 12 m.

Underpinning Proposal

The contractor used micro-piles to underpin the building as shown in Photo 6. The designs of the underpinning for the main building and the tower are slightly different. A 750 mm thick reinforced concrete slab was cast over the entire ground floor of the main building. The columns of the building were structurally connected to the slab by post-stressed concrete column set in the raft, which was in turn supported on micro-piles. The piles are 220 mm in diameter. The steel pipe of 140 mm in diameter and 10 mm in thickness inserted in the borehole is a main member of the pile. The borehole was grouted from the bottom to the top of the pile aided by the holes made on the steel pipe. The working load of the pile was 7.5 to 65 tons and the pile lengths were 10 to 33 m. The top portion of the pile located within the zone affected by tunneling (3 to 20 m depending on pile location) was coated with bitumen to reduce friction between the ground and the piles. The piles were founded deep into the zone unaffected by the tunneling.

For the tower portion, ground beams of 400 mm wide and 600 mm deep structurally connected to the columns were formed. The micro piles of 63 mm in diameter supported the beam. A steel bar of 28 mm in diameter was inserted into the pile and the annulus was filled with cement grout. The top portions of the piles influenced by the tunneling were covered with PVC pipes of 100 mm in diameter to reduce friction. The borehole diameter at the top portion was 140 mm. The pile lengths are 24 to 33 m with PVC sleeve lengths of 11 to 22 m. The design working load was 12 tons.

Tunneling Procedure

The westbound tunnel is stacked vertically above the eastbound tunnel at City Hall station. Leaving the station the tunnels unwind and the east bound rises to be running along side the westbound when east of the chapel.

The Contractor's original proposal for both the drives was to use a top heading and bench NATM method with cast-in-situ lining. After discussion it was agreed to use a shield for the upper tunnel. Precautionary compressed air was used in both tunnels as they passed beneath the chapel.

Settlement Record

The building was monitored from August 1985 (a datum reading was taken in March 1985) when underpinning commenced, through February 1986 when the first (lower) drive passed under the site until early 1987 when the lined tunnel drives were some 500m east of the site and settlement readings had been constant for a significant period. Between the first and second drives some additional grouting was carried out below the slab to ensure any relaxation of the ground was tightened up before the upper tunnel passed.

Time settlement plots are shown in Figure 12 for two points, one on the main body of the chapel (supported by the concrete raft) and one on the tower where considerably more movement was registered. The underpinning work started in mid-July, 1985 and continued until early January, 1986. The lower tunnel, started from a nearby shaft in late July, 1985, approached the chapel and stopped in late November, 1985 at a distance away from the building. The tunnel face stayed there until early, 1986.

Major settlement occurred in November to December, 1985, which corresponds to second half of the underpinning work period. During this period, the tunnel face approached the building and then stayed at 23 m away from Settlement

Point 1.73 and at 31.5 m from Settlement Point 1.92 as illustrated in Figure 13. The figure shows that these settlement points were located approximately 45 and 53 degree lines extending from the bottom of the tunnel face. The face was sufficiently away from these settlement points.

During November to December, 1985 settlement at Point 1.92 (which was much away from the tunnel face than Point 1.73) was greater and faster than the settlement at Point 1.73, indicating that the approach and staying of the tunnel face did not directly affect the settlement at these points.

In this period average settlements of 45 mm and 70 mm occurred on the main building and tower respectively with 50 mm and 90 mm maximum values being recorded. The subsequent tunneling works only increased these values by 7 mm during the passage of the first drive and a further 3 mm due to the second drive.

Lessons from the Work

The need to ensure the safety of a historic monument led to the adoption of a much more elaborate underpinning production than was originally envisaged. during this work it became apparent that the condition of the chapel brickwork was poorer than expected and the factor of safety of the foundations low. As a result the underpinning had to be modified during the work to arrest the excessive settlement that was occurring. It is evident therefore that:-

(1) The major component of the settlement was caused by the extensive underpinning works.
(2) The pressure from outside parties to require a guarantee of success in the protection of a historic building inevitably tends to result in an overcautious approach from the client/contractor.
(3) With hindsight a more modest programme of protection before tunneling would have been preferable. This approach, however, presupposes a careful and skilled tunneling contractor.

SUMMARY

(1) The underpinning work itself caused settlement of the buildings. Block 206 settled 1 to 6 mm with an average of 3.2 mm and the Government Office settled 6 mm.

(2) Among the 4 buildings underpinned, preload was applied to the underpins to transfer the column loads only for Block 206. The underpins settled by 15 to 20 mm during preloading.

(3) For Block 206, settlements ranging from 9 to 12 mm, with an average of 10.3 mm still took place during the subsequent excavation. The settlement of the underpins was 14 to 23 mm at Block 116 and 34 to 38 mm for the Government Office.

(4) The total settlements of the columns were 13 to 24 mm at Block 206, 26 to 34 mm at the edge of Block 116 and 37 to 51 mm along the front columns of the Government Office.

(5) At the Government office, the most part of underpins passed through a zone influenced by the excavation. The underpins were perhaps dragged down when the ground subsided during the nearby excavation. The settlements of the underpinned columns were of the same order of the ground settlement.

(6) Since underpinned foundations are stiffer than the foundations without underpinning, part of the loads will be transferred to the underpinned foundations from the adjacent foundations through structural members. Therefore, the underpins should be designed to support greater loads than the columns originally took if only a small portion of the building is to be underpinned.

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Todo H. and Pauzi M.M., (1989), "Geotechnical Engineering Properties of Residual Soils Originated from Granite in Malaysia and Singapore," Proceedings of the International Conference on Engineering Geology in Tropical Terrains, Bangi, Malaysia

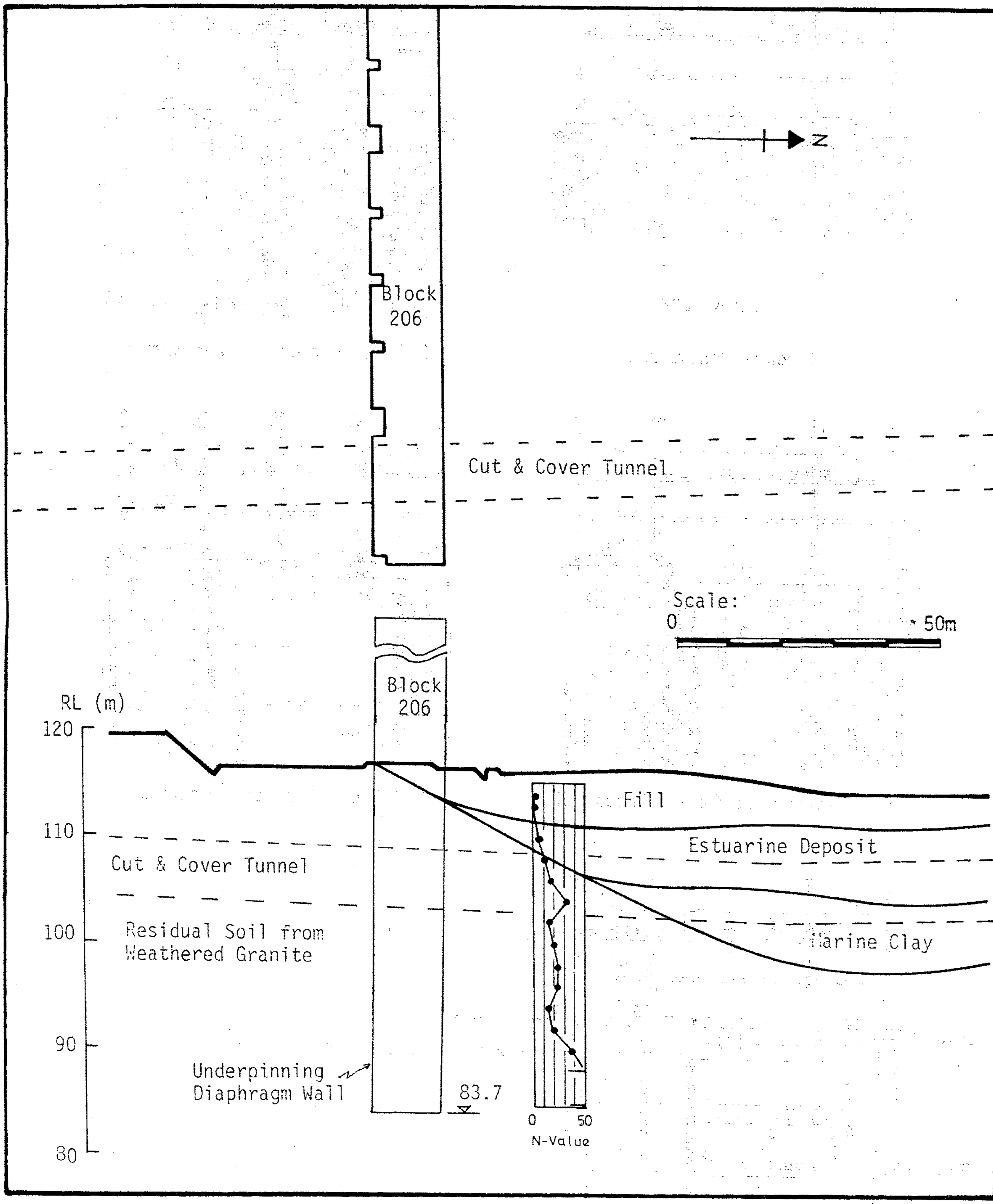

Figure 1 Plan and Soil Profile around Block 206

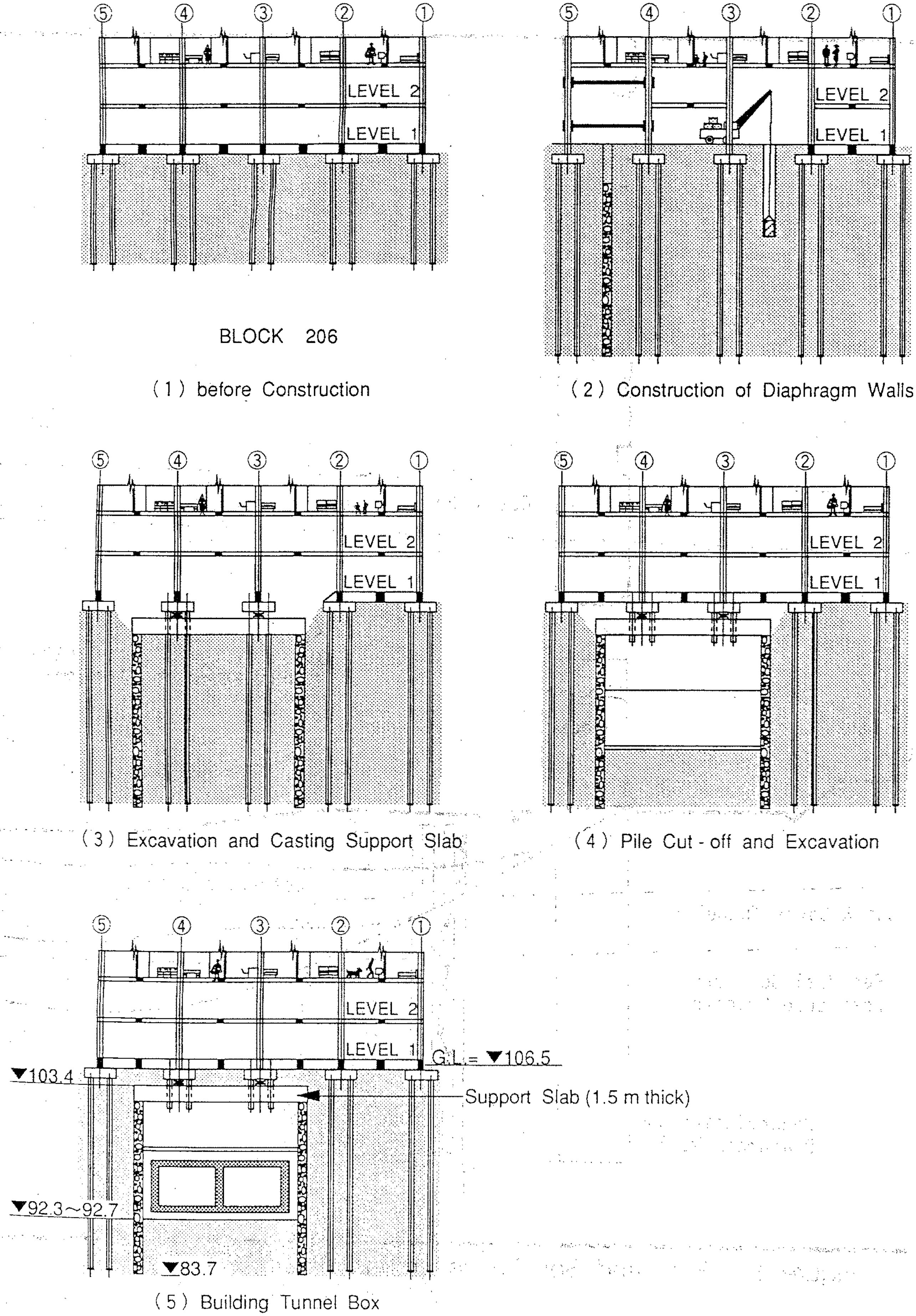

Figure 2 Sequence of Underpinning and Tunnel Construction

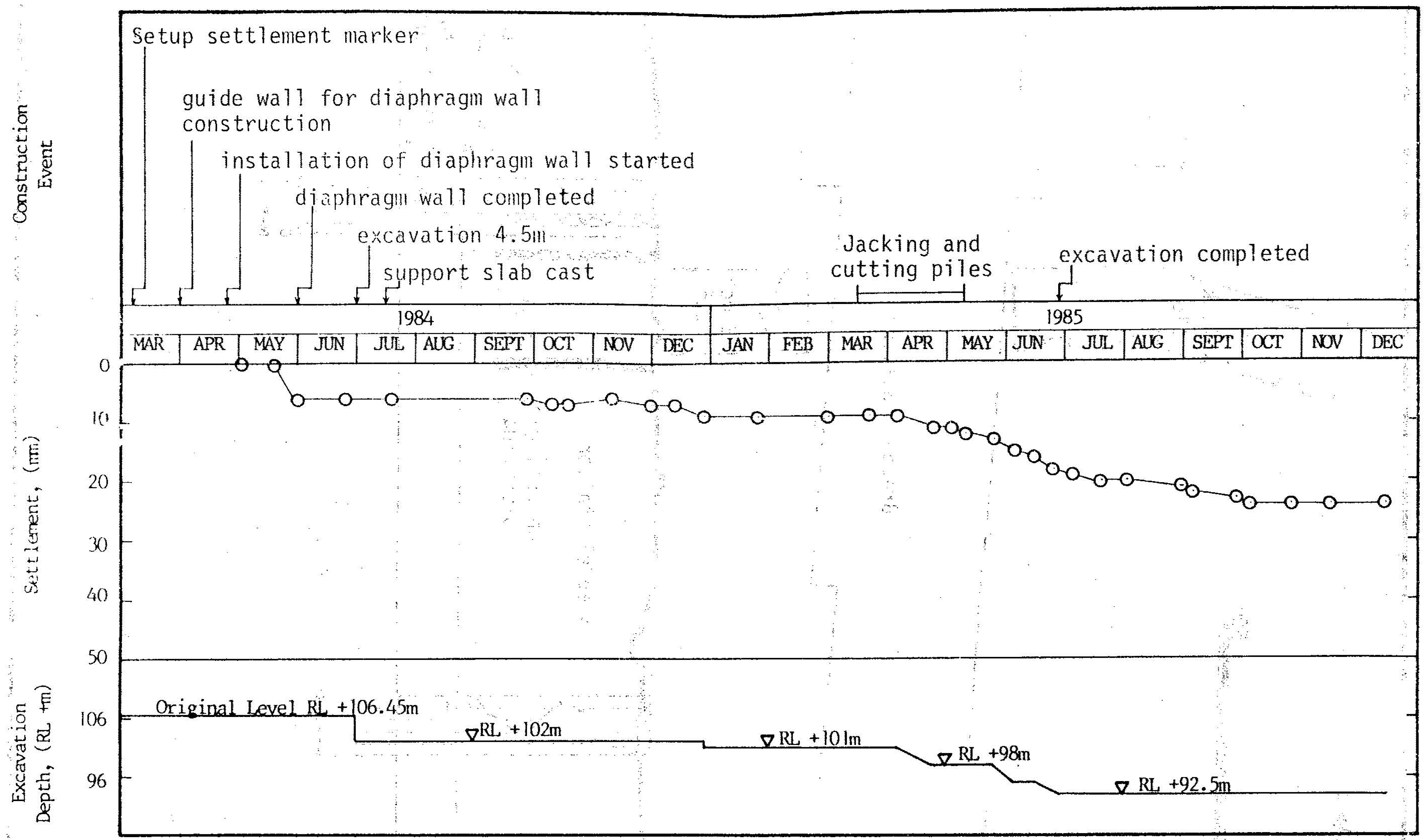

Figure 3 Settlement at Marker 15 at Block 206

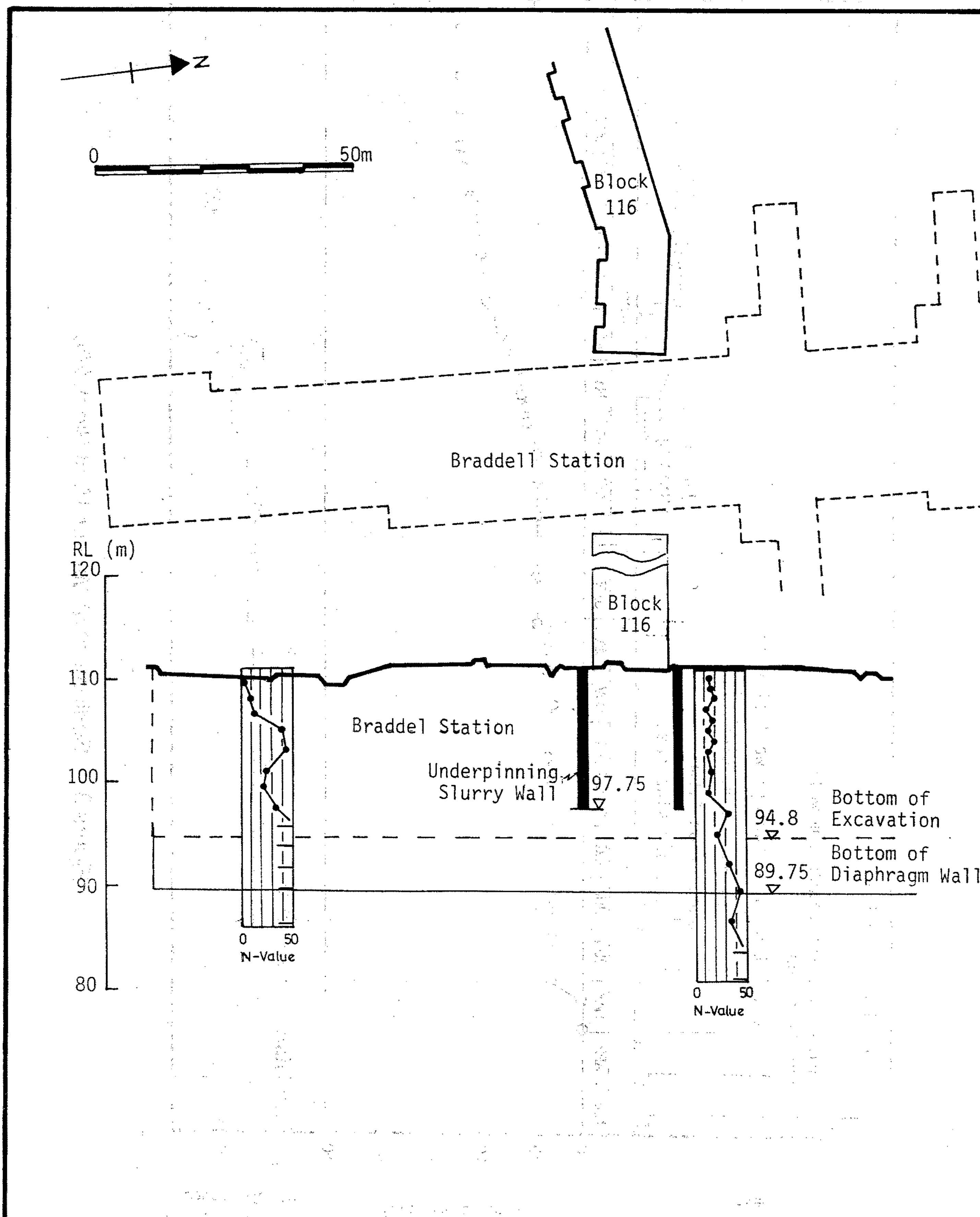

Figure 4 Plan and Soil Profile around Block 116

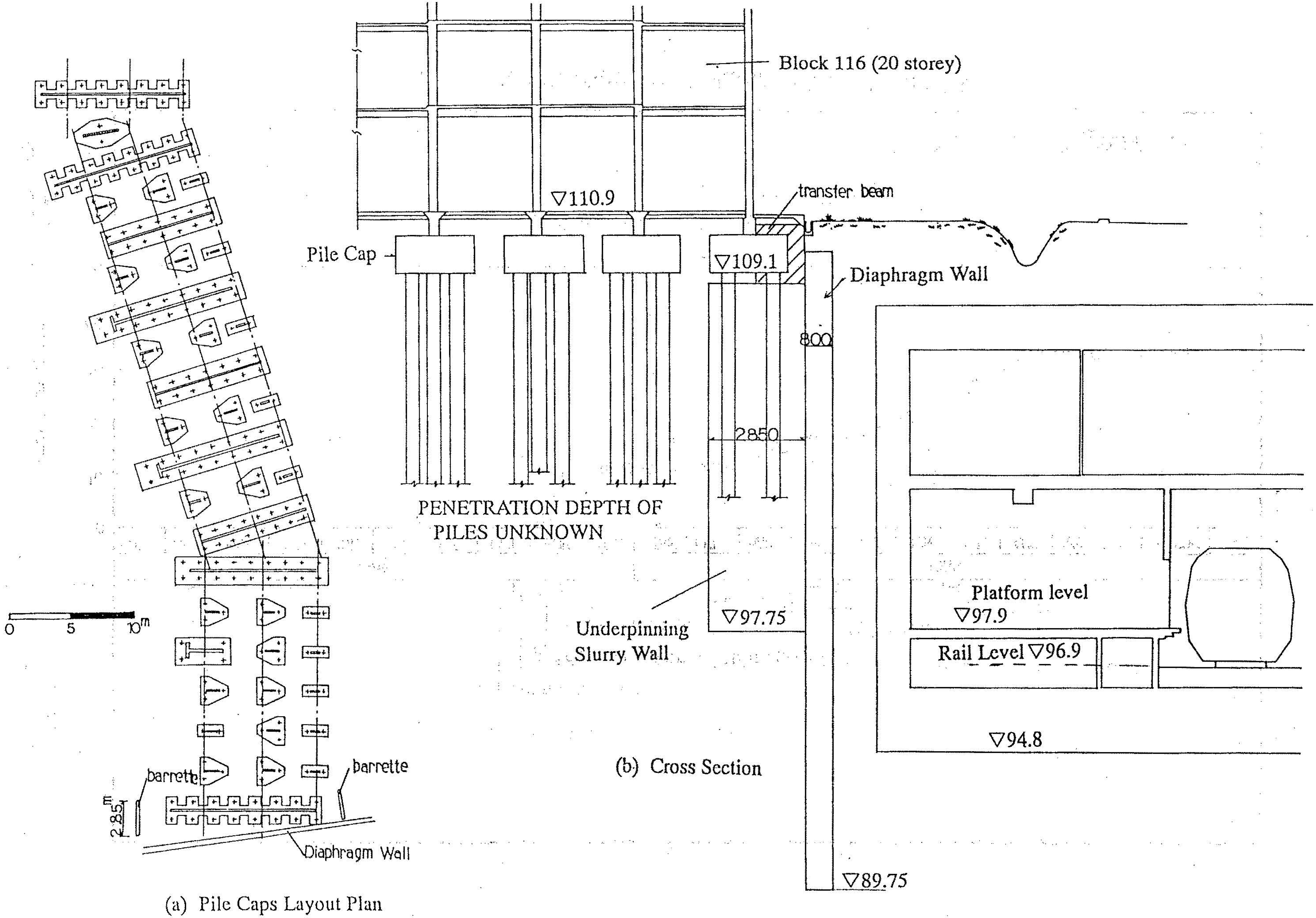

Figure 5 Concept of Underpinning at Block 116

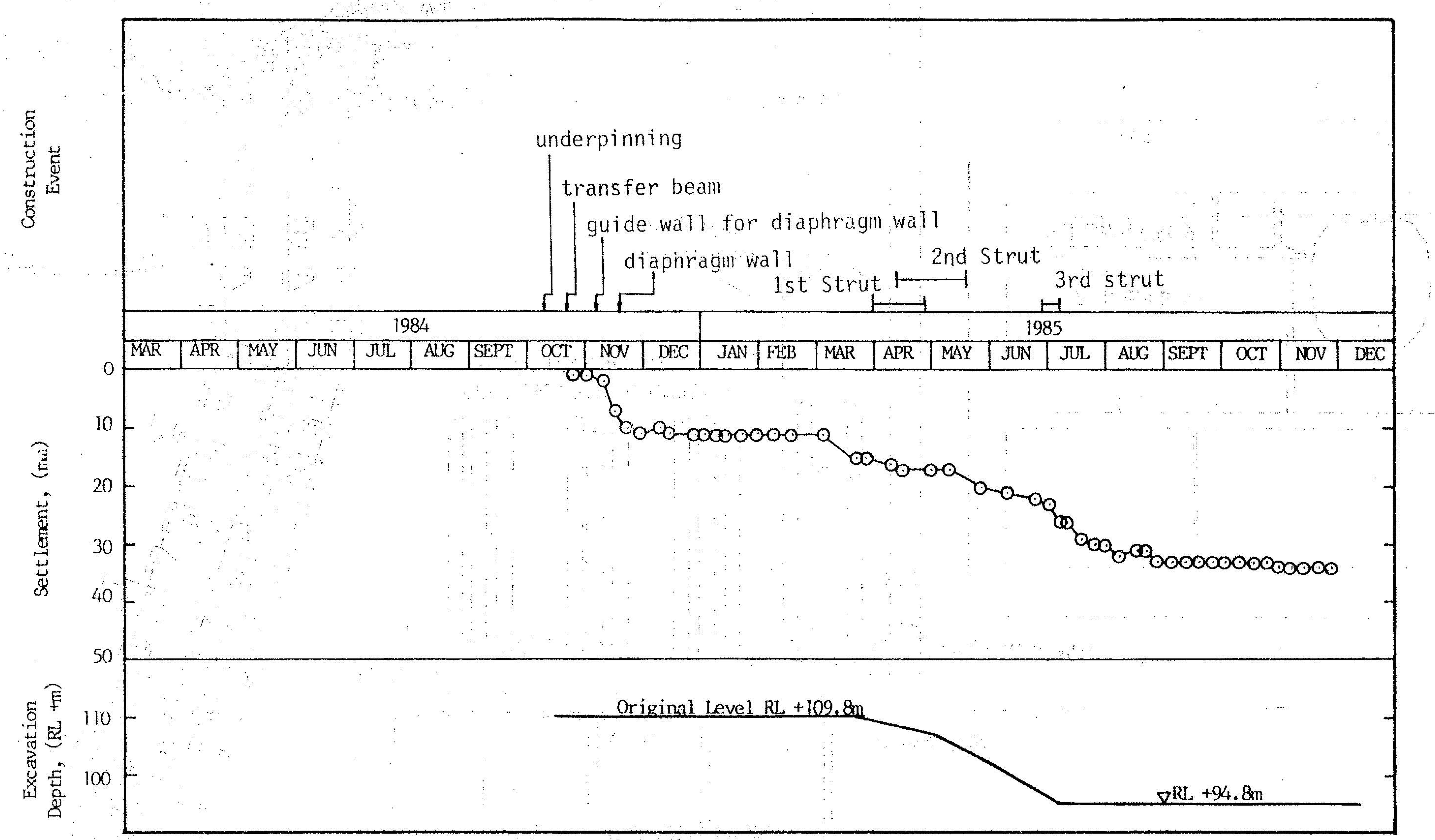

Figure 6 Settlement at Marker 13 at Block 116

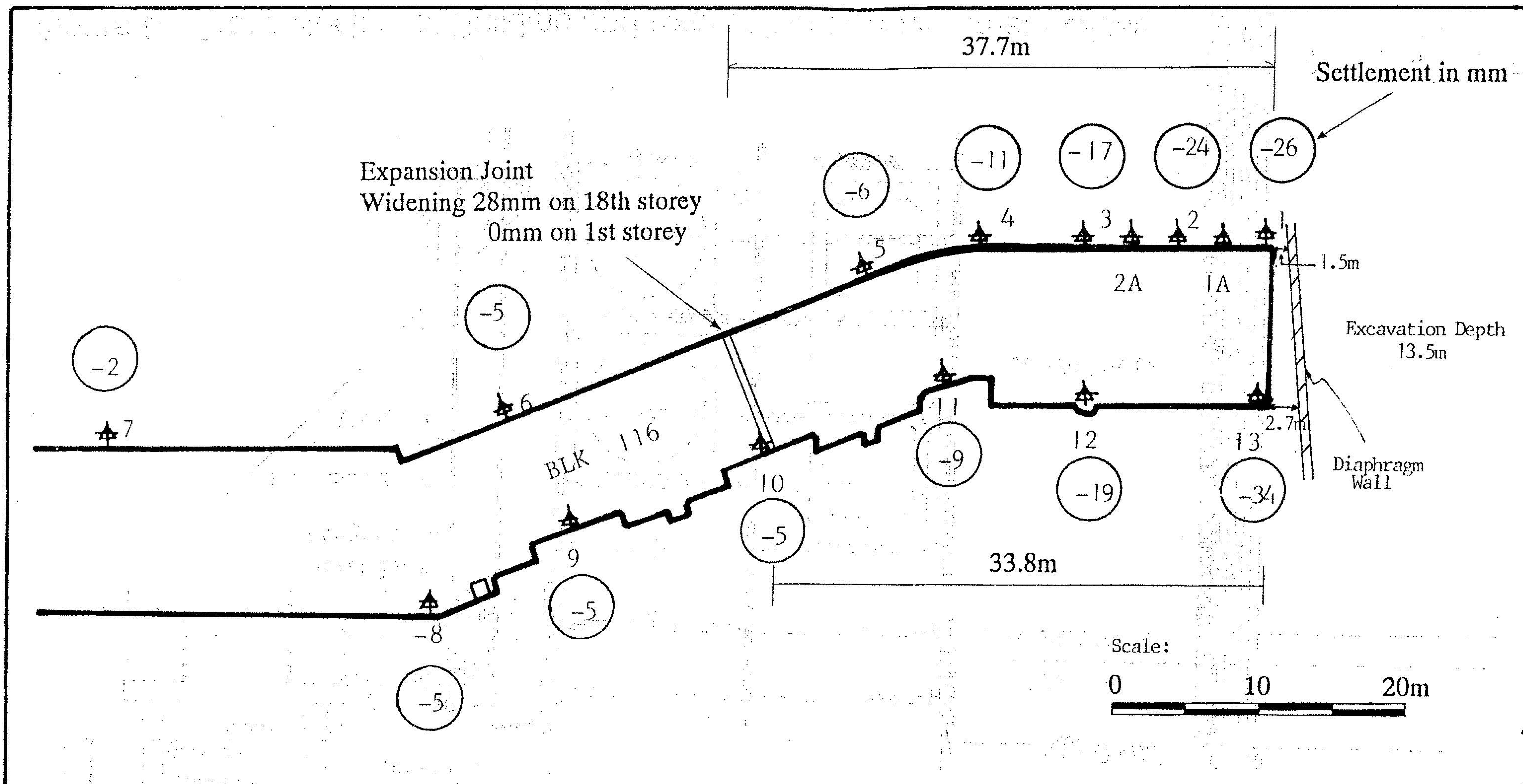

Figure 7 Settlement Readings on 28 November, 1985

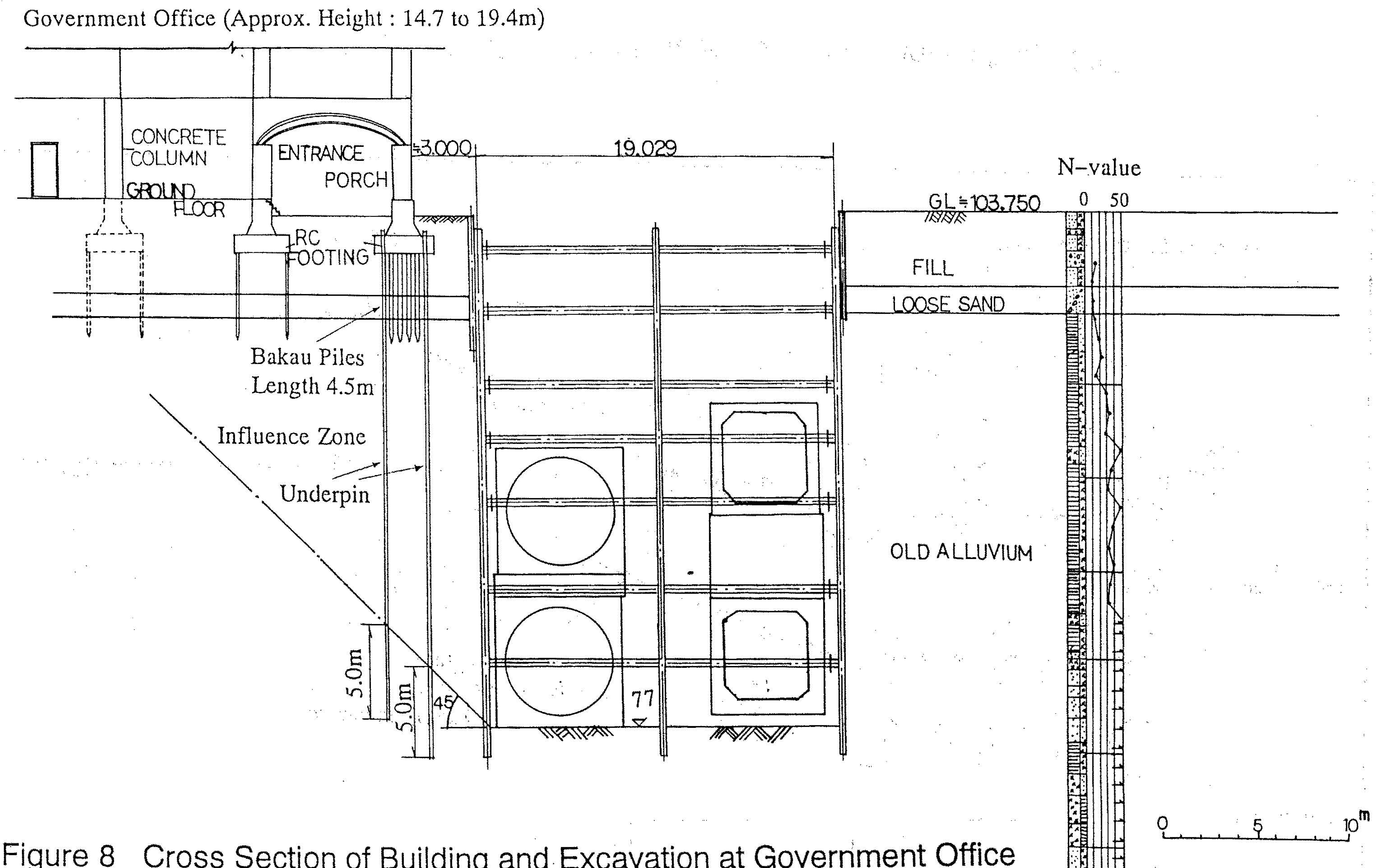

Figure 8 Cross Section of Building and Excavation at Government Office

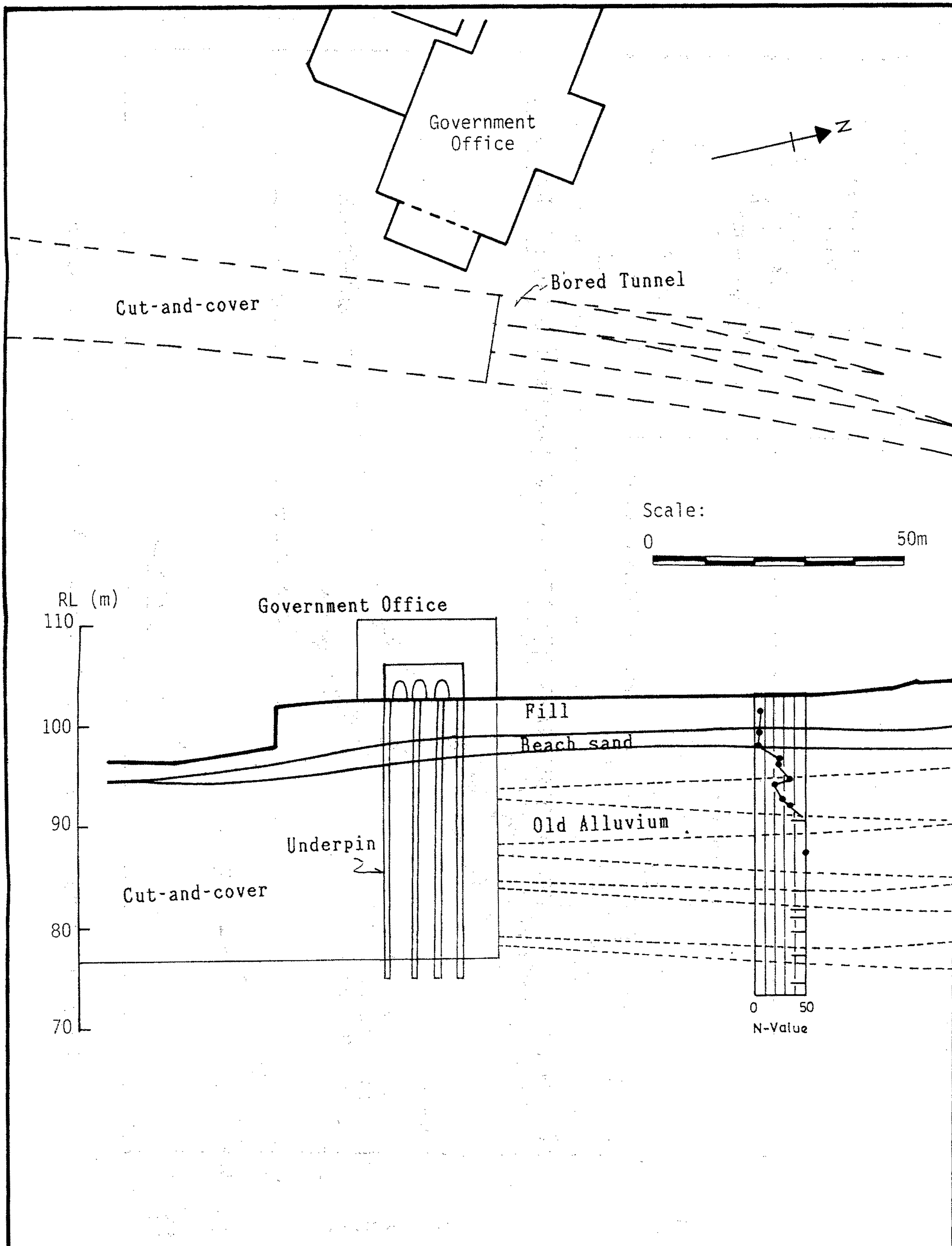

Figure 9 Plan and Soil Profile around Government Office

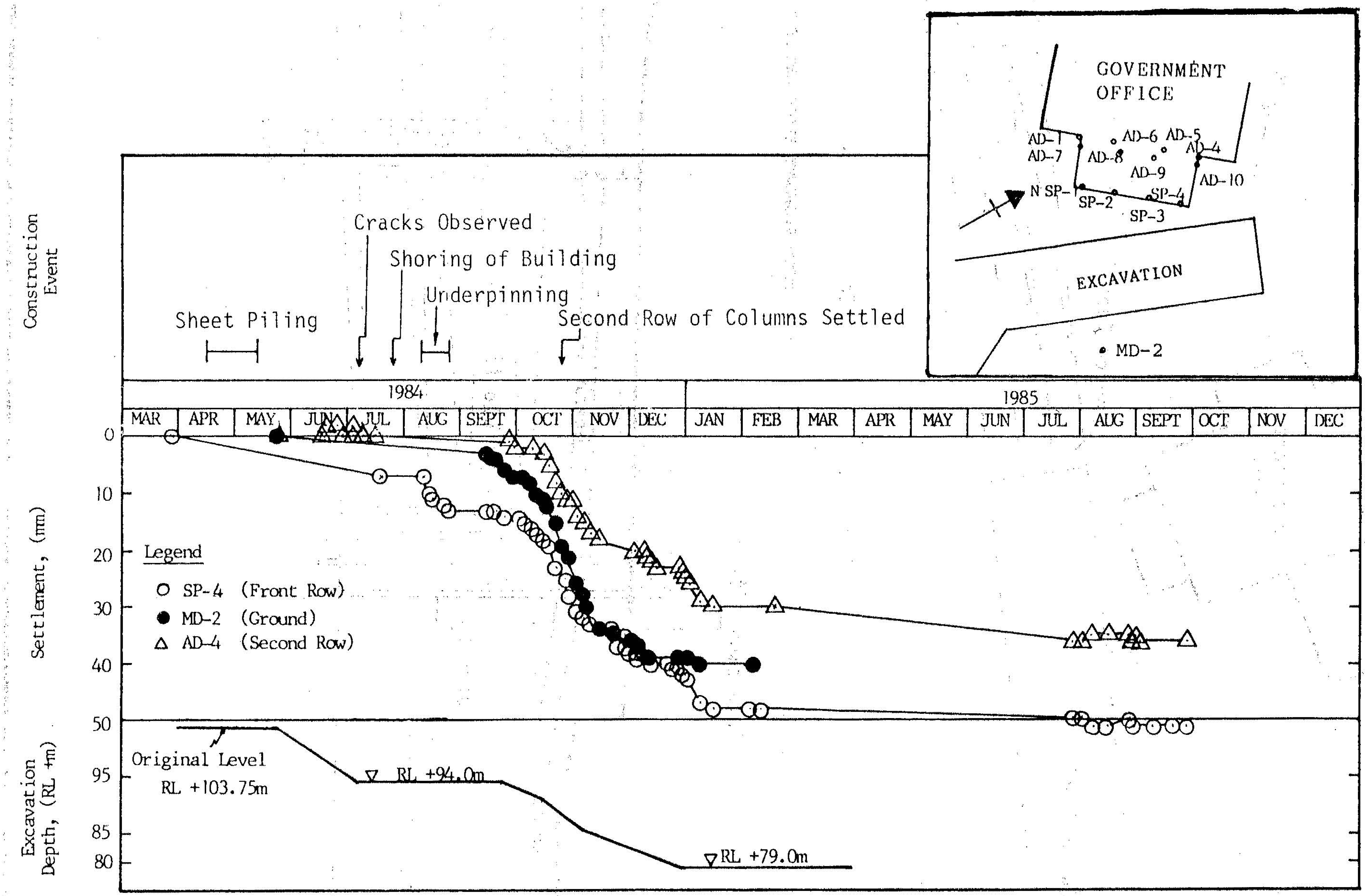

Figure 10 Settlement at Marker SP-4, MD-2 & AD-4 at Government Office

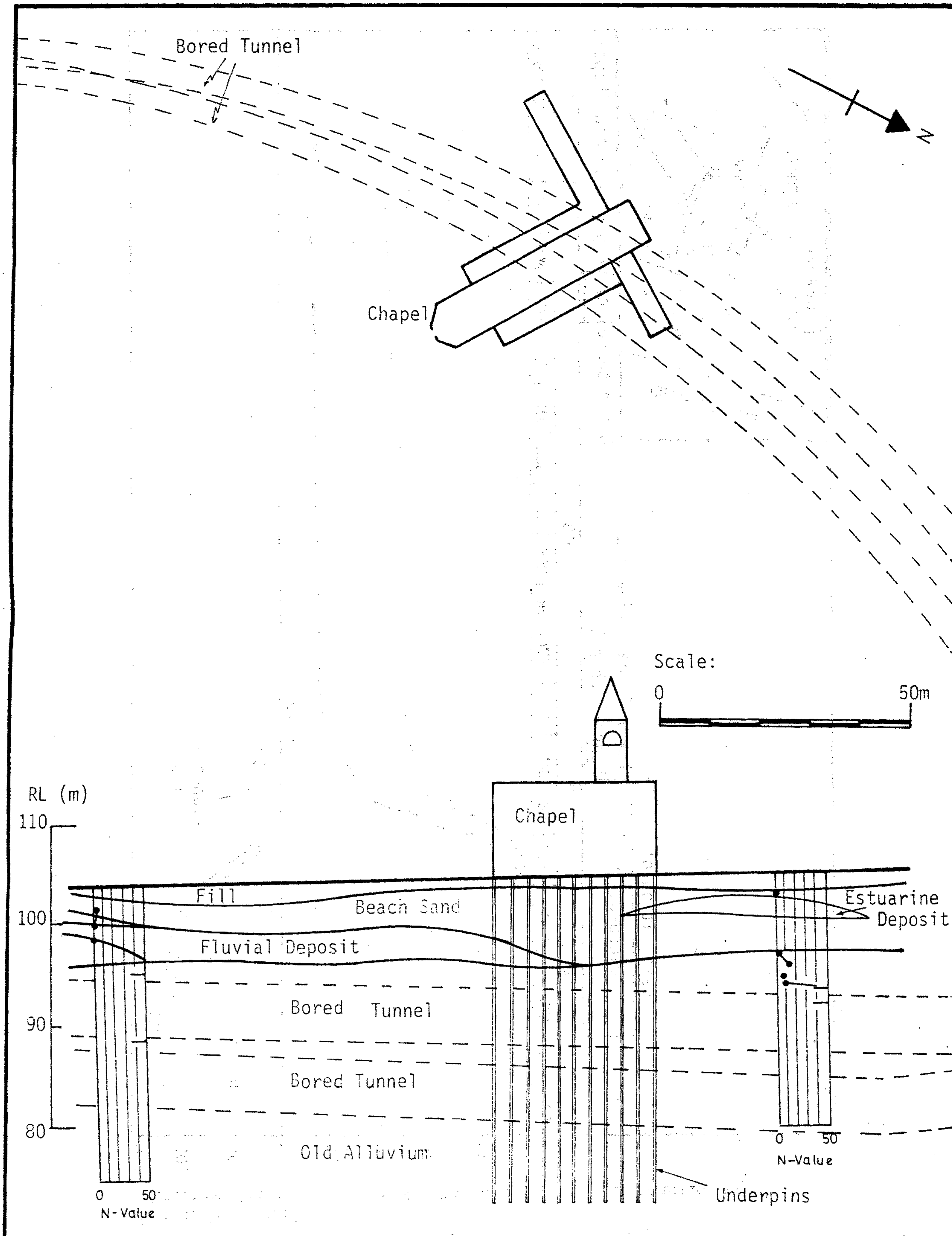

Figure 11 Plan and Soil Profile around Chapel

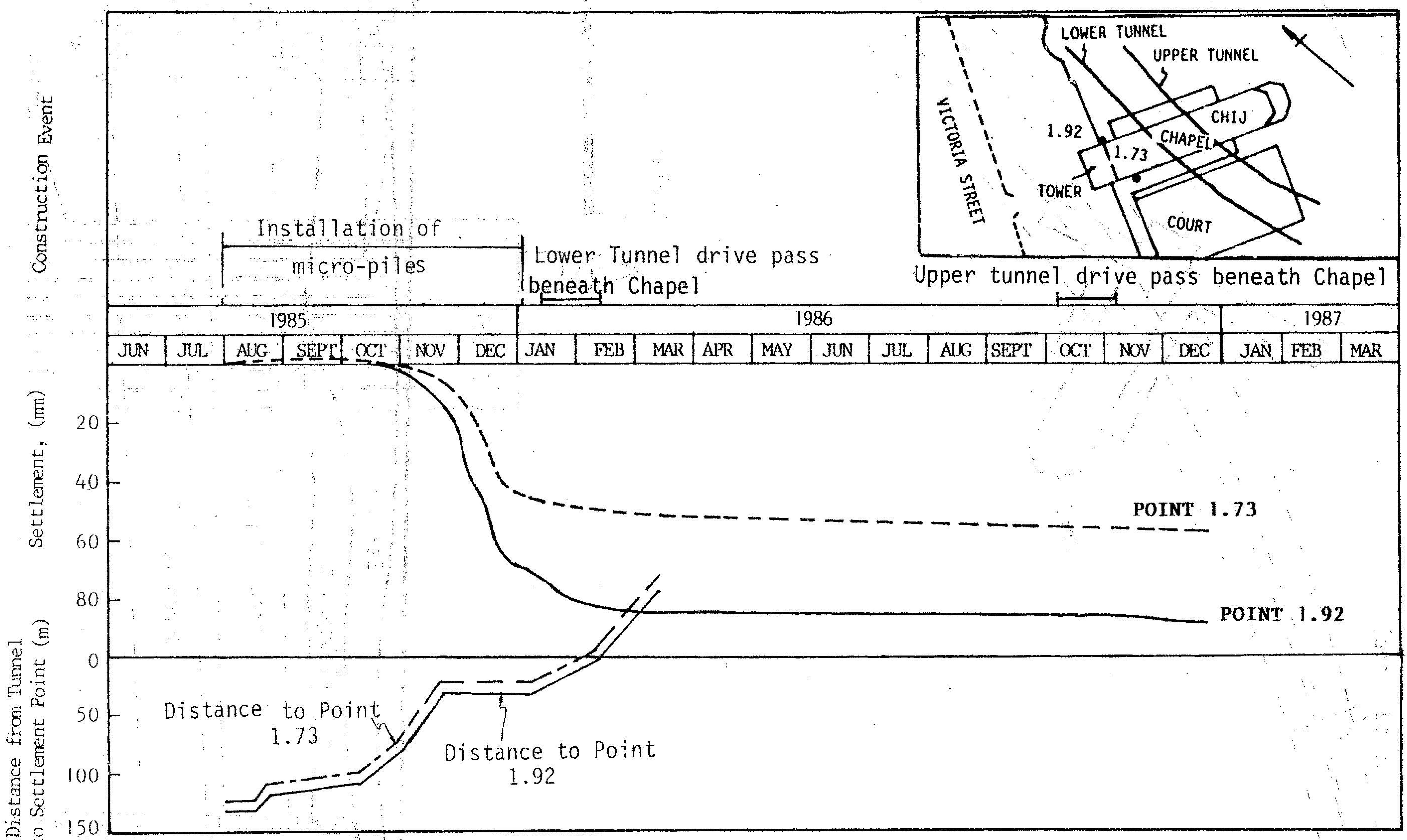

Figure 12 Settlement at Points 1.73 and 1.92 at Chapel

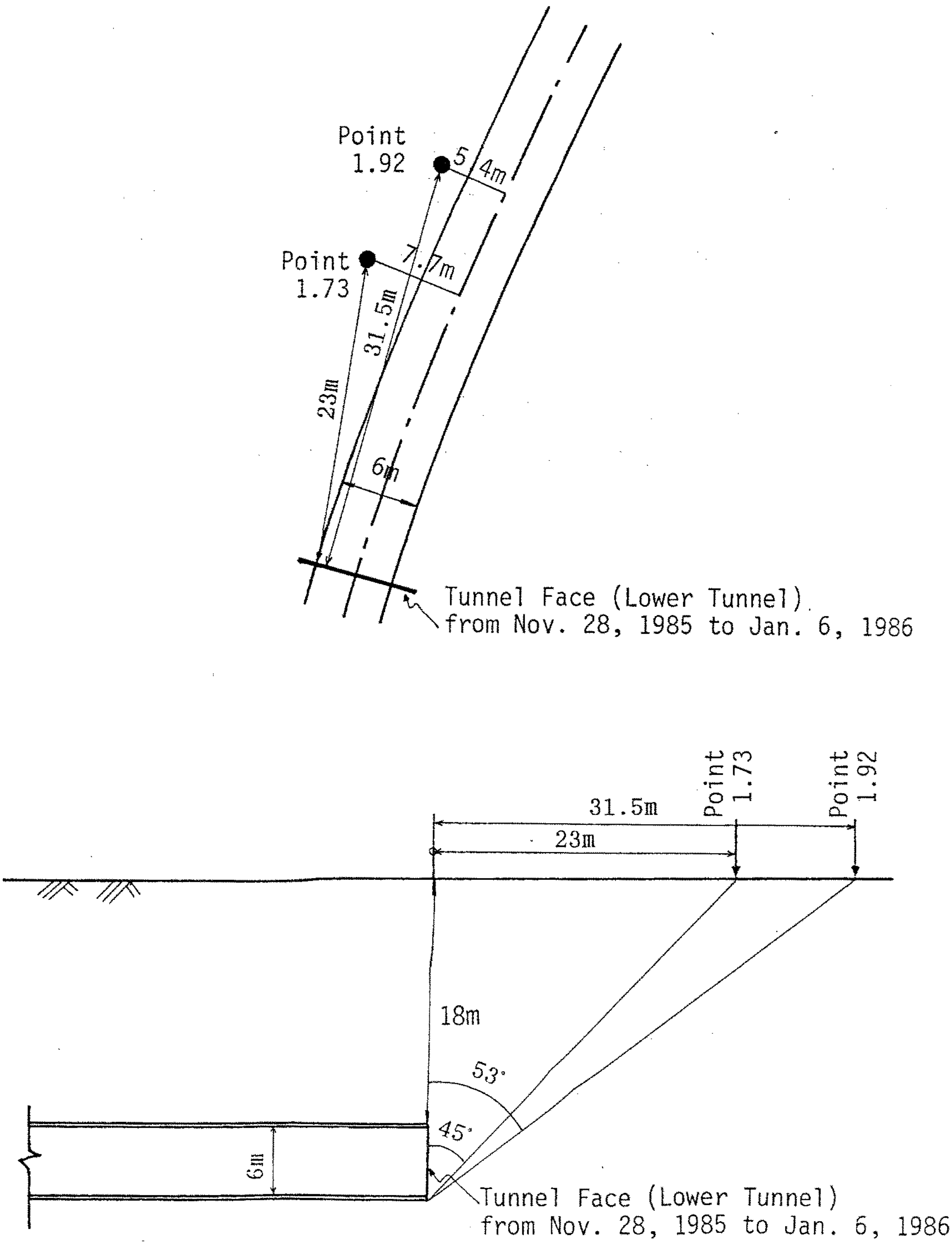

Figure 13 Location of Tunnel Face Relative to Settlement Point 1.73 and 1.92 at Chapel during Underpinning Work