

BUILDING PROTECTION FOR UNDERGROUND WORKS

by

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ABSTRACT: This paper discusses building protection measures for underground works such as deep excavations and tunneling. More importantly, the limitations and side effects of these measures, if any, are discussed to enable engineers to make sound judgment. Some of the case histories in Taipei and Singapore are used as examples for the purpose of illustration.

1. INTRODUCTION

Excavations in cities usually are carried out in congested areas with buildings of poor conditions present within the zone of influence and, furthermore, in most of the cases, the ground conditions are not favorable for deep excavations, i.e. the soils are poor and/or ground water table is high. One of the major concerns in such cases, of course, is the potential of damaging adjacent buildings due to ground movements. In reality, it is practically impossible to totally eliminate ground movements as a large chunk of earth is removed from the ground, refer to Fig. 1, and the geo-stress is relieved. However, it is possible to reduce ground movements for minimizing potential damages to adjacent buildings.

In the following sections, commonly-adopted building protection measures are discussed. Although emphasis is on deep excavations, it is intended to cover underground works in a broad sense, i.e. a few protection measures related to tunneling are also included. However, because of the limited space available, tunneling operation and performance are specifically excluded.

2. FACTORS AFFECTING BUILDING SAFETY

The first requirement in building protection is obviously the safety of the excavation itself. The responsibility of design of temporary works for excavations usually falls on contractors. Unfortunately, contractors often have difficulties in weighting their profits and the safety of surrounding buildings. Very few general contractors retain competent geotechnical engineers on board and normally "cheapest" advices are sought. It should be noted that design of retaining systems, for example, is by no means a straightforward job and failures are not rare. Building protection shall

therefore start with the engagement of capable geotechnical engineers in the design team. Site conditions shall be fully explored and soil parameters properly interpreted. Of course, it is even more important to have experienced geotechnical engineers in the supervision staff during the construction stage to deal with unforeseen situations.

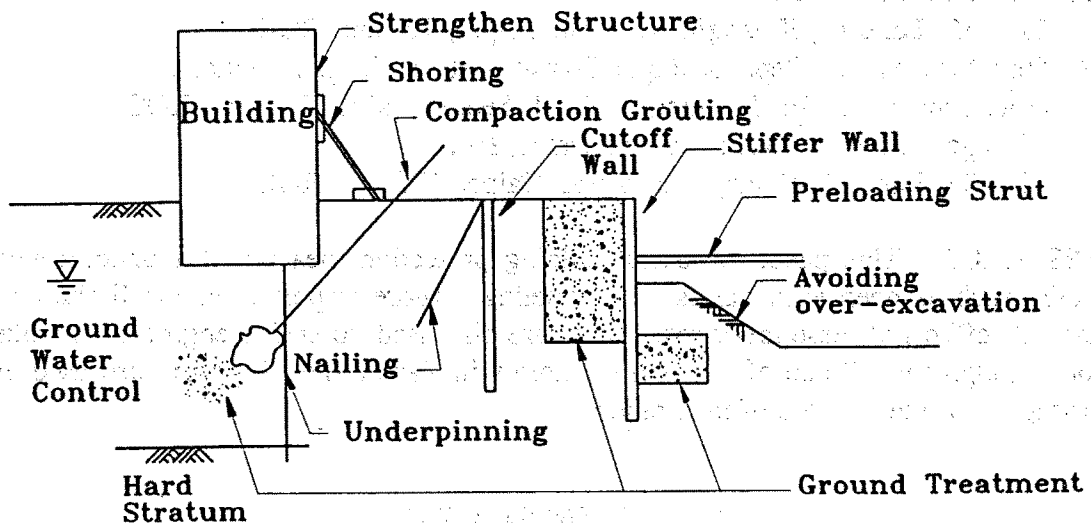


Fig. 1 Concept of Building Protection

Structural failures of wall members of excavations are relatively uncommon. The two most common failure modes of temporary works are: a) heave/piping at the bottom of excavation, and b) failure of the supporting systems, namely, struts and walings. The analysis for heave/piping is quite simple and problems, if any, usually arise because of poor soil investigation leading to wrong strength parameters and/or because of inadequate control of ground water pressure below the bottom of excavation. On the other hand, structural analysis of retaining systems is quite controversial. There are many analytical procedures available and none is suitable for all the situations. This is because of the complicated stress-strain relationship of soils and also because of the fact that many factors cannot be properly accounted for in analysis. Workmanship of the contractor, for example, is the most influential but unfortunately is the least predictable factor. Therefore, the design has to be reasonably conservative to prepare for substandard workmanship.

Earth pressures acting on the active side of the wall reach the active state quickly as excavation proceeds and can be computed with confidence. After all, the reductions of earth pressures from the at-rest state to the active state are small. Besides, the ground water table on the active side is normally assumed to be maintained at its original level but, in reality, there is a good chance for the ground water to be lowered as a result of seepage flow into the pit. Therefore, the active pressures adopted in designs are likely to be greater than what really are. There were cases in which retaining systems failed as a result of rising ground water level during heavy

rains or due to leaking water pipelines, but they can be considered as exceptions rather than rules. Bending moments and shears in walls are insensitive to the distribution of pressures on both sides, therefore, as long as the total active pressure is adequate, the maximum bending moment and shear will be about right.

The active pressures are taken by: a) the passive earth pressures (including water pressures) on the passive side and, b) reaction forces in struts. Strut loads are therefore very sensitive to how passive pressures are computed. Unlike active pressures, passive pressures are strongly displacement-dependent (and time-dependent as well) and are significantly affected by the water heads below the bottom of excavation. The water heads below the bottom of excavation are difficult to predict because of the difficulty in estimating seepage effects. Even the ultimate strengths of soils below the bottom of excavation are difficult to determine because of the difficulty in evaluating the effects of stress relief (i.e., swelling). It is therefore not surprising for two designers to come up with strut loads differing by a factor of two or greater and the same can be said for wall deflection which is the major source of building damages.

It is not the intention of this paper to discuss the design of retaining systems per se, rather, practicing engineers are reminded that there is no reliable analytical procedure for computing strut loads at this stage. To become a competent designer of retaining systems, one shall always pay attention to field data and observations. Soil parameters to be adopted in analyses shall be calibrated to suit local experience. It will not be a surprise to obtain different soil parameters following different analytical procedures and the soil parameters to be adopted shall be the ones back-calculated from the same procedure to be adopted in the predictions.

Even with proper structural design of temporary works, damages to adjacent buildings may still occur as a result of poor workmanship and/or environmental factors. For examples, much ground movements can be induced as a result of over-excavation, delay in strutting, leakage through diaphragm wall joints, etc. For these reasons, engineers must be familiar with general principles of building protection, and more importantly, be aware of the limitations of each protection measure and, if any, the side effects.

3. ZONE OF INFLUENCE

As a geotechnical engineer, it is one of his duties to estimate how far away the ground movements are likely to cause building damages, i.e. the so-called zone of influence. All the buildings, fully or partly, within the zone of influence are subjected to inspection prior to any construction activities. The purpose is to clear the liability of contractors regarding the existing defects of the structures. The so-called dilapidation surveys, or condition surveys, are usually carried out by architects and only surficial evidences, such as cracks and leakages, are recorded. Structural conditions, to the best, are only qualitatively stated because structural members, i.e. beams and columns, are usually covered and are unable to be

inspected. Therefore, the surveys really do not serve the technical purpose they ought to.

An accurate prediction of ground movements is not an easy job because ground movements are governed by many factors which are totally out of the designer's control. To assess the damage potential of ground movements to a certain structure is an even more difficult job because the exact tolerance of the structure to the ground movements is almost impossible to establish. Settlement criteria proposed by Burland and Wroth (1974) and the Institution of Structural Engineers (1978) for a few common types of structures are widely adopted. Table 1 is a compilation of the criteria used by the majority of designers of the Taipei Rapid Transit Systems (TRTS) Project. Criteria of this type fail to include the conditions of structures into consideration. For these reasons, zones of influence are usually established by past experience and judgment (the synonym of "gut feeling"). After all, they merely serve the simple purpose of defining the extents of dilapidation surveys and do not have to be determined scientifically.

Table 1 Criteria for Building Movements Commonly Adopted by TRTS Designers

Type of Structure	Total Settlement (mm)	Tilt	Angular Distortion	Deflection Ratio
Load-bearing Wall (Brick or Masonry)	25	1 / 500	1 / 500	1 / 2000
Timber Structures	25	1 / 500	1 / 500	1 / 1000
Frame Building on Spread Footings	50	1 / 500	1 / 500	
Frame Buildings on Mat or Piles	50	1 / 300	1 / 300	

It is obvious that the zone of influence is a function of ground condition and depth of excavation. Fig. 2 was adopted in the construction of Singapore Mass Rapid Transit Systems (SMRT). It was found to be adequate in general, and except in a

couple of occasions in which groundwater drawdown was excessive, none of structures outside the zones of influence so defined were damaged. For the Taipei Rapid Transit Systems (TRTS), a much simpler figure, Fig. 3 is used. Figs. 2 and 3 are in fact consistent with each other because the subsoils in the Taipei Basin, the so-called Sungshan Formation are in-between the stiff and the soft ground in Singapore.

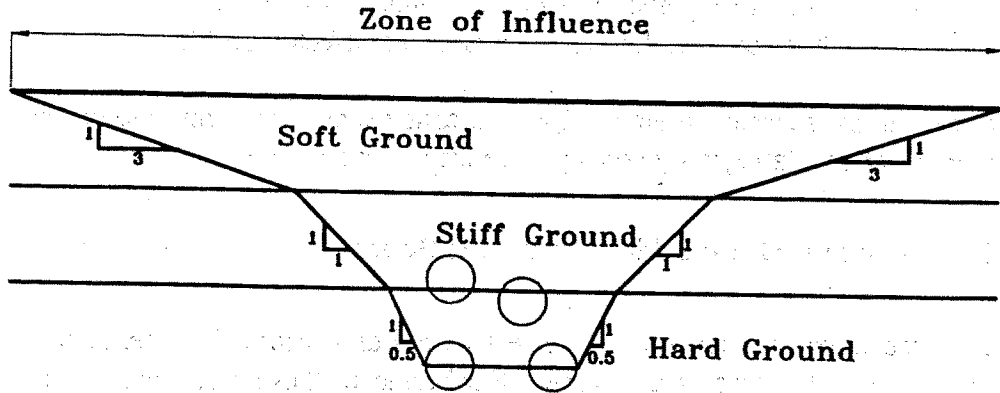


Fig. 2 Zone of Influence for Construction of SMRT

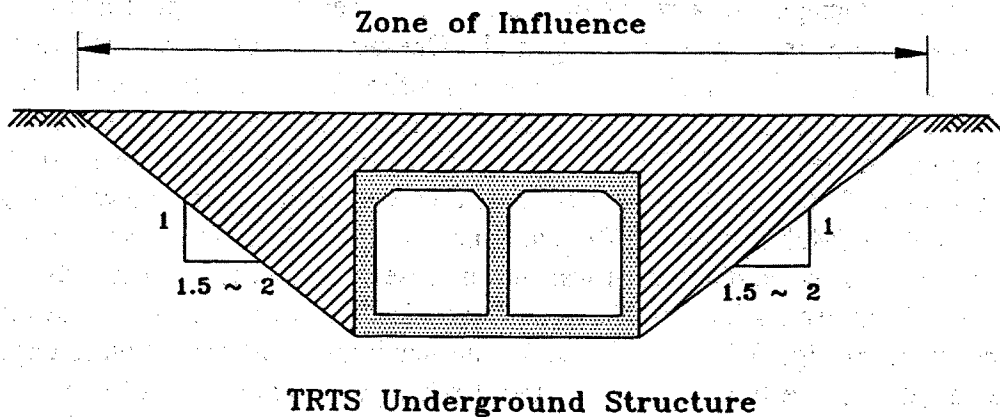


Fig. 3 Zone of Influence for Construction of TRTS

4. BUILDING PROTECTION MEASURES

Buildings within the zone of influence have to be protected beforehand if they are likely to be damaged by the ground movements. A few protection measures commonly adopted are depicted in Fig. 1. Basically they can be classified into the following four categories:

- a. those reduce ground movements at source
- b. those limit the influence of ground movements
- c. those strengthen the structures and/or foundations
- d. those correct the movements of the affected buildings

The measures discussed herein are by no means exhaustive. Besides, because of the limited space available, only concepts are introduced without details.

4.1 Reducing Ground Movements at Source

Experience indicates that the most effective building protection measures are those reduce ground movements at source. Furthermore, these measures are carried out within the site boundaries and can be executed without interference from outside parties. Therefore, they shall be the first ones to consider.

4.1.1 Stiffer Retaining System

Retaining structures are conventionally designed on the principle of force-equilibrium, i.e., balancing active pressures by passive pressures and reactions in struts, and only bending moments and shears in the wall and the strut loads are of primary interest. The deflection of the wall has not received sufficient attention. With more and more deep excavations carried out in cities and more and more buildings damaged as a result of ground movements, the importance of limiting wall deflections is now being recognized. One way to reduce wall deflections is to preload struts. Fig. 4 shows a typical profile for wall deflections obtained in constructing R12 Station of Contract CH218 of the TRTS Hsintein Line. The maximum deflection of 25mm corresponds to only 0.15% of the final depth of excavation of 16.3m. This ratio falls far below the data points shown in Fig. 5 for the T2 Zone (Moh and Ou, 1979; Woo and Moh, 1990) in which the site is located. The thickness of the diaphragm wall in this case is 1m which corresponds to 6% of the depth of excavation and the ground consists an alternation of sand and clay. According to Fig. 6 (Ou, et al, 1988), the maximum wall deflection is expected to be something like 0.5 to 0.8% of the depth of excavation. It is believed that the previous data shown in Figs. 5 and 6 are for cases without preloading of struts because, in the past, struts were seldom preloaded. The observed low value of 0.15% is thus a proof of the effectiveness of preloading.

Nearly all the struts in the TRTS Project are preloaded to 50%, or greater, of their design loads and Fig. 4 is typical for the T2 Zones. However, there are cases in

which wall deflections are 2 to 3 times of what is shown. The larger deflections are found to be a result of: a) over-excavation below the strut levels, and b) prolonged delay in placing and preloading struts. It is therefore very important to have tight site supervision to avoid these from happening.

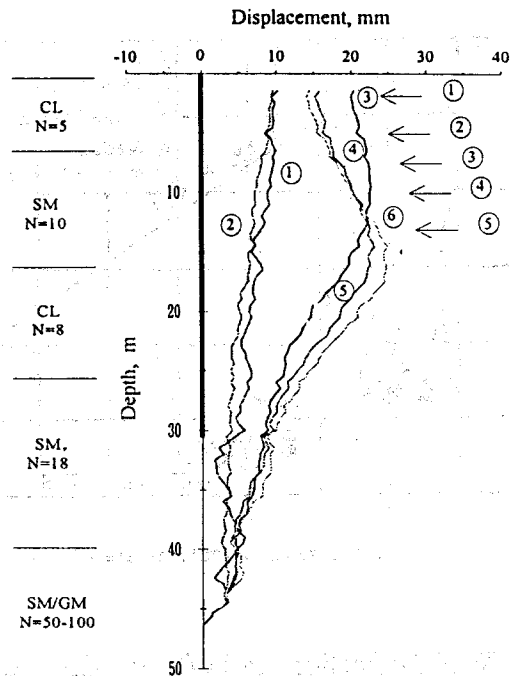


Fig. 4 Diaphragm Wall Deflections at TRTS R12 Station

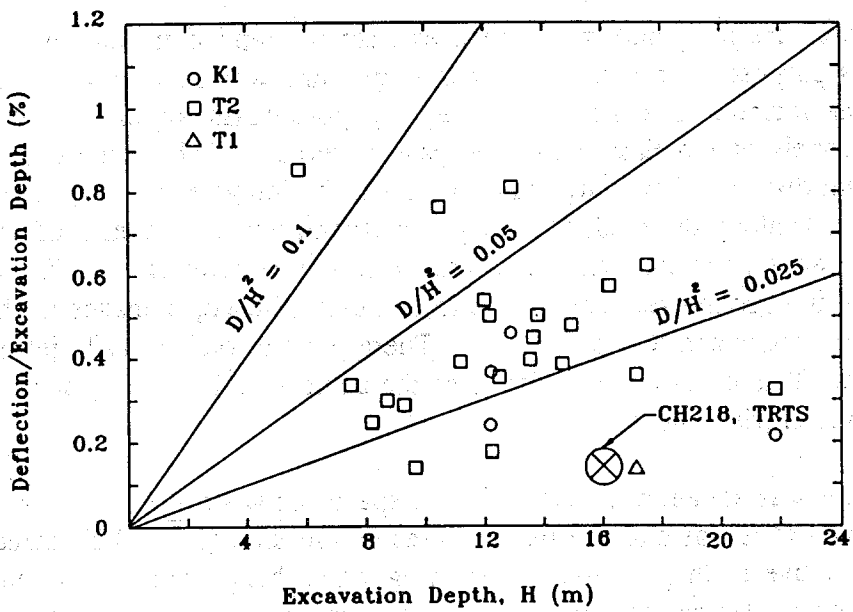


Fig. 5 Wall Deflections in Different Zones in Taipei Basin

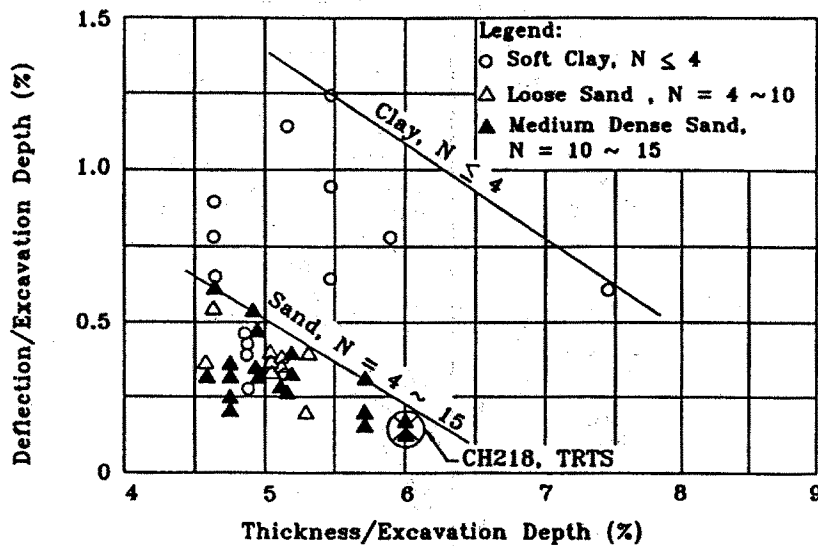


Fig. 6 Wall Deflections in Different Ground Conditions

4.1.2 Ground Improvement

High-pressure jet grouting has been extensively applied in underground works for various purposes. In most of the cases, grouting was used in small areas with few columns formed. In constructing the Singapore Mass Rapid Transit Systems, the twin tunnels of the East-West Line pass underneath Robinson Road in the central financial district. There are many important buildings in a very close proximity of the tunnels along the road. Grouting was carried out for a stretch of 950m in length to form annuli surrounding the two tunnels, as illustrated in Fig. 7, for the purpose of reducing ground settlements due to tunneling, hence, damages to these buildings (Hulme, Potter and Shirlaw, 1989). There were a total of 4700 jet grout columns formed. This is, in the knowledge of the authors, still the largest operation of this kind ever carried out.

Grouting was sometimes applied in the spaces between the retaining walls and the building and it was claimed that the greater soil strength in the treated zone would reduce active earth pressures on retaining walls, hence wall deflections and ground settlements. Unless the treated zone is wide enough to behave as a gravity wall providing resistance to ground movements, the effectiveness of such a measure is questionable. There have been cases in which one or two rows of grouted columns were installed immediately outside the diaphragm walls and instrument readings show that ground settlements in areas with treatment were practically the same as those in areas without treatment.

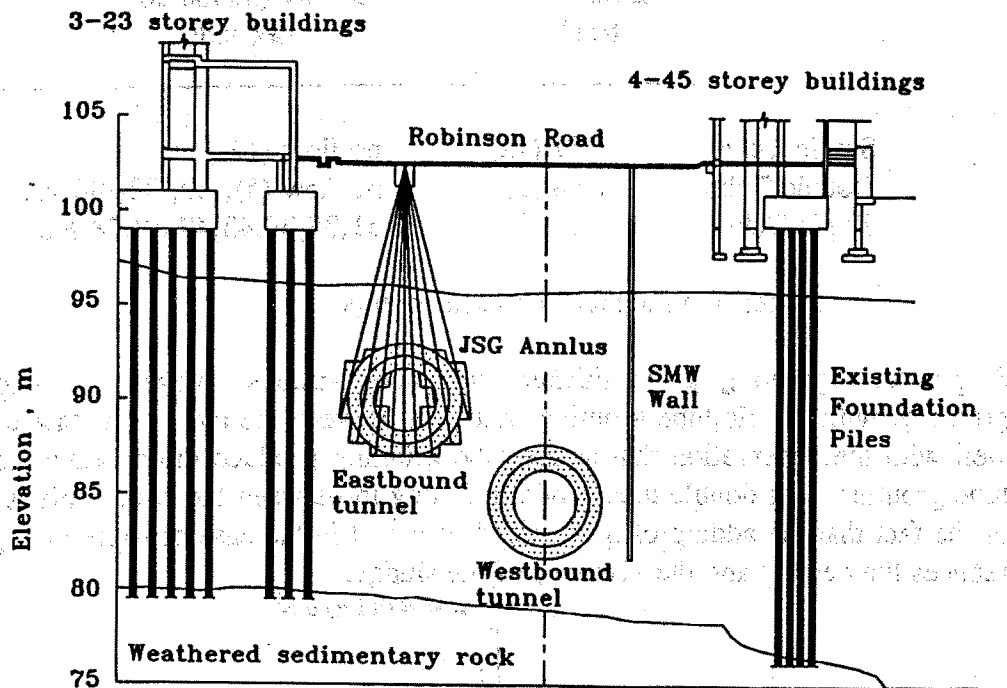


Fig. 7 Building Protection Along Robinson Road (SMRT)

The major problem with high pressure jet grouting outside the excavation is the associated ground heave which may cause considerable building damages if not properly controlled. The heave mechanism is illustrated in Fig. 8. First of all, as the sludge is forced out of the ground, the drags along the rod and the side wall make the escape difficult and, as a result, the pressure in the bulb at the bottom of the hole builds up. The pressure in the bulb is directly related to the density and the viscosity of the sludge and the length of passageway of the flow, i.e. the length of the grouting hole. Secondly, the grouting hole may collapse and totally block the passageway of the sludge. Once the pressure exceeds that required for cavity expansion, the bulb will expand just like a balloon causing the ground to heave.

In the case mentioned above, heaves typically of 200 to 400 mm were observed (Hulme, Potter and Shirlaw, 1989) and considerable utility damages were reported. Therefore, care must be exercised if a large quantity of grout is to be injected in a limited area, particularly if injection is to be carried out in inclined holes which are more likely to collapse and have longer passageway for the sludge to escape. It should be noted that the dissipation of excess porewater pressures in clay could in some cases lead to significant consolidation settlement which could last for weeks after the end of operation.

A trial was recently carried out for the construction of TRTS (Shirlaw, 1993) in which grout columns were formed by using single, double and triple tubes under a pressure of 400 bars. A comparison of the data obtained is as follows:

	Density t/m ³	Viscosity (marsh cone) seconds
Single Tube	1.57 (12)	no flow (12)
Double Tube	1.48 (8)	no flow (5), 30, 33, 80 sec
Triple Tube	1.35 (9)	31,35,36,43,47,50,58 sec

Note: () number of measurements

Single tube grouting gives thicker and more viscous sludge than triple tube grouting, with double tube grouting falling in-between the two. This fact correlates well with the observation that single tube grouting produce more heave than triple tube grouting with double tube grouting falling in-between the two. This is because of the fact that the adding of pressurized water jet in the case of triple tube grouting reduces the density and the viscosity of the sludge.

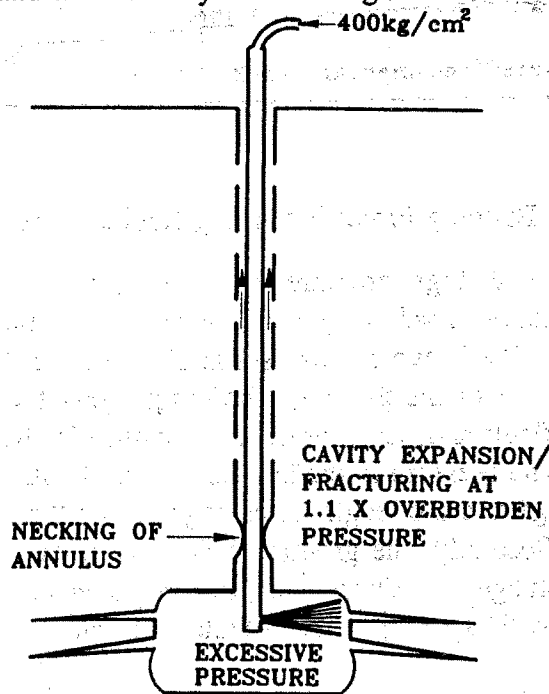


Fig. 8 Heave Mechanism of Jet Grouting

Grouting is being used to form a slab below the bottom of excavation of City Hall (BL13) Station of the TRTS Nankang Line, see Fig. 9. The slab essentially behaves as a strut resisting the inward movements of the retaining walls at all the stages of excavation. The same principle is used in protecting a historical monument, the South Gate of the Old Taipei City, see Fig. 10, in front of which TRTS twin tunnels are to be constructed by using the cut-and-cover method, but instead a slab, three transverse panels are used. At the time this paper was prepared, the excavation had reached a depth of 14.7m and the maximum deflection of the diaphragm wall was only 7mm as depicted in Fig. 11. Comparing Fig. 11 with Fig. 4, the deflections shown in the former figure are only a quarter of those

shown in the latter while both sites are located in the T2 Zone and the excavations have about the same depths. This proves the effectiveness of the transverse panels in reducing wall deflections. In this particular case, the panels were installed by using the diaphragm walling technique because the machine was readily available at the site. Sometimes, diaphragm wall panels can not be installed due to obstructions from underground utilities or due to traffic requirements, jet grouting can be used instead to achieve the same purpose.

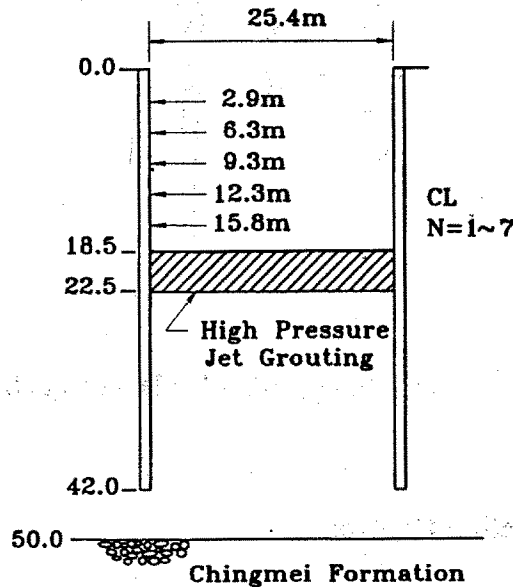


Fig. 9 Grouted Slab at City Hall Station (TRTS)

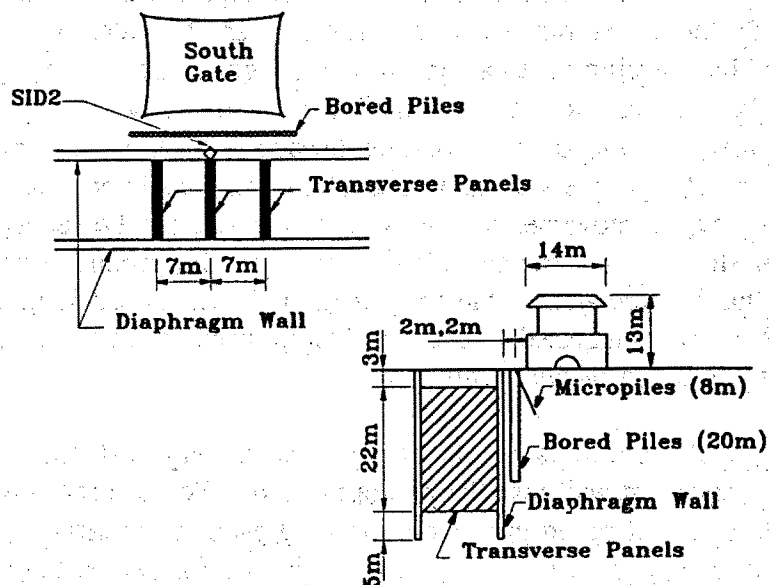


Fig. 10 Protection of South Gate (TRTS)

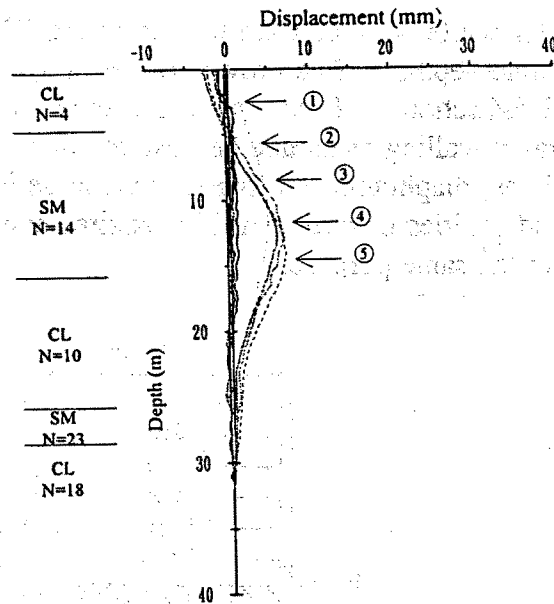


Fig. 11 Diaphragm Wall Deflections at South Gate (TRTS)

4.1.3 Construction Control

As more data become available, it has been found that the installation of diaphragm walls caused more ground settlements than what was previously believed. The problem is more serious at locations where the effects of several diaphragm wall panels accumulate. For example, Fig. 12 shows that ground settlements of an order of 30 mm were induced merely due to the installation of diaphragm wall panels for a TRTS station, entrance and a launching shaft. Ideally, the problem can be lessened by installing the panels which are right in front of buildings first to cut off the influence due to the installation of subsequent panels. However, such arrangement is not always possible because of other constraints such as traffic diversion, utility diversion and schedule. The settlement mentioned is associated with the inward movements of very soft clay and can be reduced by maintaining a level of slurry in the trench much higher than the ground water table. However, unless this is stipulated in the specification, it will be difficult to implement at the site. It is thus suggested to include this requirement in the specification whenever there is likelihood of the problem.

Collapses of side walls of slurry trenches in very soft clays and/or loose sands during diaphragm wall installation are not rare. To protect the South Gate shown in Fig. 10, a row of bored piles were installed prior to diaphragm walling. Moreover, the piles are anchored to micropiles at their tops for better stability. The diaphragm wall panels were successfully installed without incidents.

During excavation, it is important not to over-excavate below the design strut levels. Struts shall be installed as soon as practical. As mentioned in Section

4.1.1 that wall deflections for apparently similar excavations, i.e., similar excavation depth, wall thickness, levels of struts, preloading procedure, etc., differ by factors up to 3, and the differences can be attributed to over-excavation and delay in strutting and preloading.

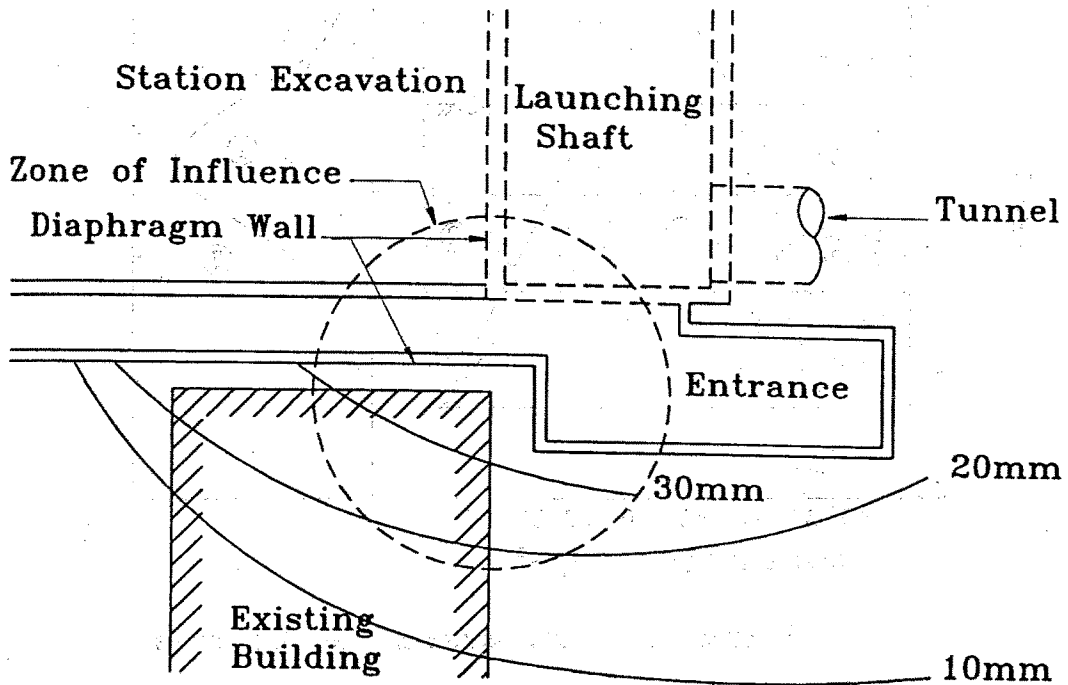


Fig. 12 Settlements Due to Diaphragm Walling

In sands, wall deflections can be much reduced by lowering the water level below the bottom of excavation resulting in drastic increase in the passive resistance of soils as the effective stresses increase. Fig. 13 shows that a comparison of wall deflections for two profiles of water pressure (Moh, Crooks and Shirlaw, 1989). This, however, can only be done if the walls are sufficiently deep to cut off the seepage flow and thus ground water table outside the pit is unaffected, or the lowering of ground water table will not cause intolerable ground settlements outside the pit.

In very soft clays, wall deflections and ground settlements can be reduced by partitioning the site into several compartments and carrying out excavation one by one. This may become the only way of completing the job if the soft clay is too thick and the retaining wall have to be excessively deep to gain anchorage.

4.2 Limiting the Influence of Ground Movements

This category includes measures which are taken between the excavation and the building to reduce ground displacements at the building.

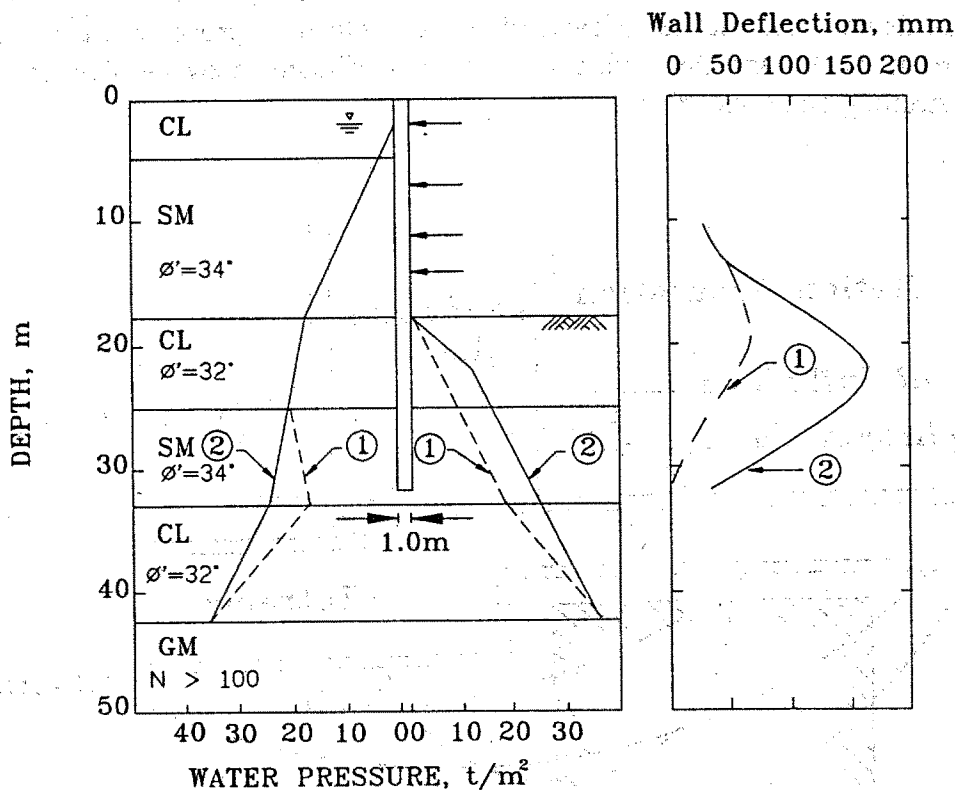


Fig. 13 Effects of Water Pressure on Wall Deflections

4.2.1 Resisting Ground Movements

Piles have often been installed outside the retaining walls and were claimed to be effective in reducing ground movements. However, in the opinion of the authors, unless they can resist ground movements themselves, they will simply move together with soils and do not serve the intended purpose. To be able to resist ground movements, the piles shall be anchored at the top, or shall extend far below the active zone and act as cantilevers. In either case, the piles shall be structurally strong enough to take the earth pressures. Ou et al (1991) shows a case, refer to Fig. 14, in which the use of two rows of soil nails reduced wall deflections to a half. It should be noted that, however, the installation of nails might induce ground settlements which, in some cases, could totally offset the benefits gained.

The soil-mix-wall (SMW) shown in Fig. 7 was installed for the purpose of protecting foundation piles of adjacent buildings during tunneling. Some of these piles are within a couple of meters from the outer edge of the tunnel lining. Although the SMW wall was not anchored in a stiff layer, the continuity in the longitudinal direction of tunnel effectively stopped the ground movements from affecting these foundation piles.

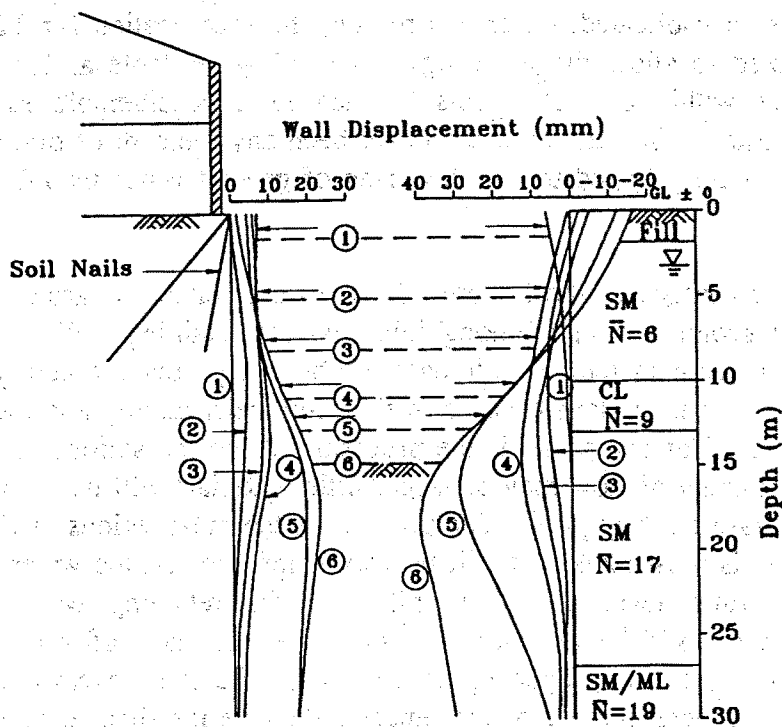


Fig. 14 Reducing Wall Deflections by Soil Nailing (redrawn from Ou et al, 1991)

4.2.2 Maintaining Ground Water Table

Seeping of ground water into the pit is likely to cause two problems : a) consolidation of clay leading to ground settlement, and b) erosion of fine particles leading to cavities. Sand layers are relatively incompressible and will have very small settlements even if the water table is lowered. Clay layers are impermeable and the ground water table is unlikely to be lowered. Therefore, the problem of consolidation settlement will not be serious if the ground consists of sand only or clay only. The problem will be more serious for sites with normally consolidated clay layers sandwiched between sandy layers. In such cases, the loss of water through sandy layers is likely to cause consolidation settlement of the clay.

Consolidation settlements may reach a distance of, say, 100m or beyond if ground water table is significantly lowered. Therefore, it is important for retaining walls to be watertight and to be sufficiently long to cut off seepage flow below the toes if seepage is likely to result in excessive ground settlements. On the other hand, for over-consolidated clays, a minor drawdown of ground water will not be harmful because the associated ground settlements are expected to be small. In the Taipei Basin, the ground water levels in Sublayer 1 and Sublayer 3 of the Sungshan Formation were once lowered by as much as 20m and 40m, respectively, in the central city areas due to excessive use of ground water as supply (Moh and Chin, 1991). The water levels have gradually recovered since the government banned the

use of ground water in mid-70's and, as a result, the clays in Sublayers 2 and 4 are now much over-consolidated. For this reason, the specification for TRTS Project has been relaxed to allow the lowering of ground water table as long as ground settlements are within control. This has led to a considerable saving in the construction costs. So far, there has never been any incident of building damage which can be directly linked to the lowering of ground water in Sublayers 4 and below.

A very high percentage of the building damages are related to ground subsidence due to loss of ground through leaking joints on the retaining walls. Cavities of several tens of cubic meters in volume have been reported frequently. Leakage usually will not occur in clays because of their low permeability and their ability to seal the fissures. For coarse sand, the problem will not be serious either because, although the quantity of flow may be large, little materials will pass through unless the joint is extra-ordinarily poor. The problem is the most serious in silts in which internal erosion is most likely. It will be very helpful to test the water tightness by lowering the water level inside the pit once the retaining walls are closed. However, a successful test does not guarantee the lack of problem because diaphragm wall joints may open up as the wall deflects as excavation proceeds. Therefore, a sufficient number of piezometers shall be installed to closely monitor the ground water table and grouting shall be applied to seal off the crack if found. It has become popular nowadays in areas where buildings are in a very close proximity to grout the diaphragm wall joints beforehand regardless whether there are cracks or not.

One way to maintain the ground water table is to replenish water from recharging wells. However, experience shows that recharging of water is ineffective once consolidation has started. One of the reasons is that the wells are easy to be clogged. Some success was achieved for protecting the gas works along the East-West Line of the SMRT. In this case, recharging wells were closely spaced and were installed beforehand. A high water head was always kept in the wells. The ground water table was successfully maintained and no ground settlements have been observed.

4.3 Strengthening Structures/Foundations

Ground movements are time-dependent. The final settlement profiles may not be the most critical ones as far as the safety of building is concerned, and intermediate stages may even be more critical. Therefore, it will be helpful to strengthen the structures so temporary stresses can be taken care of by the shoring members which will be removed once ground movements cease. If necessary, permanent structural members can be added to, or can be used to replace, the existing members.

Underpinning was frequently adopted as a method of building protection and figures similar to that shown in Fig. 15 are frequently included in design manuals and handbooks. It should be recognized that the installation of underpinning piles may lead to settlements of considerable magnitudes which may be of the same order or even greater than the ground movements without underpinning. Fig. 16 shows a

case in which diaphragm walls were used for replacing the existing foundation piles of an apartment under which SMRT tunnels were to be constructed by using the cut-and-cover method (Todo, Hwang and Hulme, 1992). The weight of the structure was transferred to the diaphragm walls by jacking against the slab across the diaphragm walls before cutting the piles. At the end, the maximum settlement reading is 25mm, including:

- a) 6mm due to diaphragm wall installation
- b) 6mm due to excavation above the transfer slab
- c) 6mm due to excavation below the transfer slab
- d) 6mm due to construction of permanent structure and backfilling the space between the roof and the transfer slab

It is apparent that the remove of excavation reduced side friction on the diaphragm walls and caused the diaphragm walls to sink. During load transferring process, i.e., jacking the structure against the transfer slab and cutting the piles, the settlements were kept minimal. However, the transfer slab settled by 20 to 30mm, part of which was due to the sinking of diaphragm walls. It is necessary for the diaphragm walls to settle so sufficient friction can develop to support the structure. That means, if the load had not been transferred to the slab by jacking, the final settlement of the building could have been 20 to 30mm greater than what was observed.

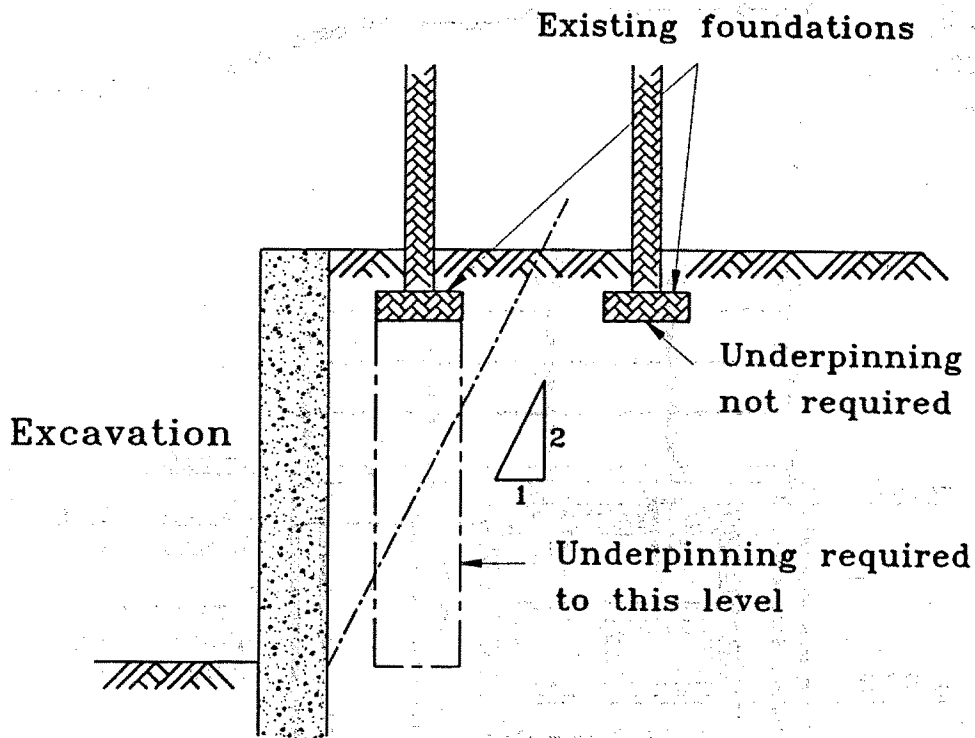


Fig. 15 Underpinning for Building Protection
(not recommended for use by the authors)

The ground for the case shown in Fig. 16 consists of silty clay and sandy clay with N-values varying from 5 at surface to 50 at a depth of 25m. The installation of diaphragm walls induced 6mm settlements. In soft clay and loose sand, installation of underpinning piles may cause the ground to settle by 20 to 30 mm. Even in stiff clay and dense sand, ground settlements of this magnitude are not uncommon. Subsequently, ground has to settle by a certain amount, say, 20 to 30mm, before the shaft friction on the underpinning members can develop for taking the loads. Therefore, little is gained if a building is expected to settle by, say, 50 mm or less without underpinning.

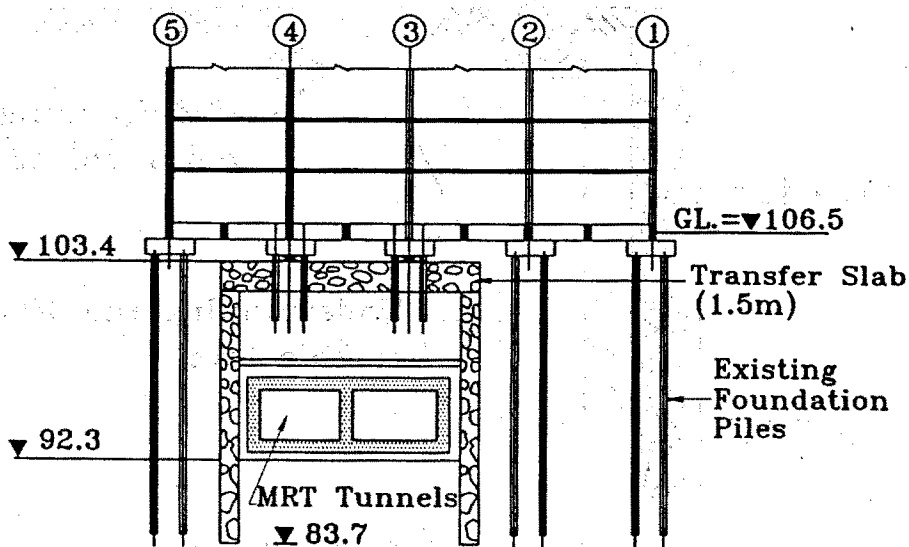
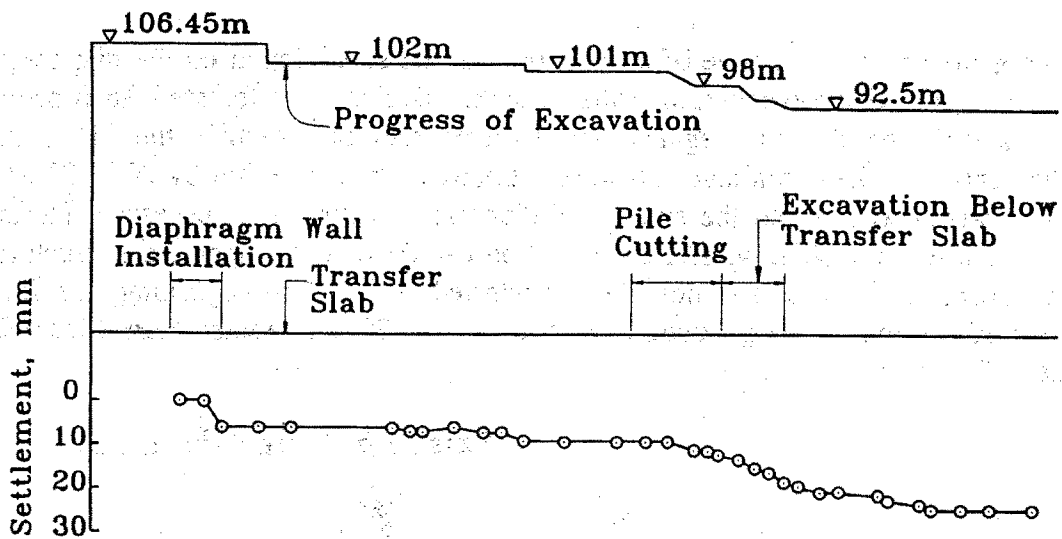


Fig. 16 Underpinning of Block 206 (SMRT)

Instead of underpinning structures directly, foundation soils underneath the building can be hardened to reduce their deformability. There are many ways to do the job, for examples, chemical grouting, jet grouting, lime column, and compaction grouting, etc. Each has its merits and limitations. Grouting from the inside of the premises is often not possible/practical and has to be carried out through inclined grout holes from adjacent open space. Disturbance and loosening effects due to drilling might induce settlements of intolerable magnitudes. The situation could be aggravated when the grout holes are closely spaced. It has been observed in several cases along the Nankang Line of the TRTS that settlements of 30 to 40 mm occurred during the installation of tubes for chemical grouting.

In the TRTS Project, compaction grouting has been used in several contracts and trials have been carried out. Grouted columns of about 0.8m in diameter and 12m to 18m in length were formed by injecting cement-sand-gravel mixture and cone penetration tests were performed in adjacent ground to compare the soil strengths before and after grouting. So far, test results are not encouraging. The increases in soil strength are insignificant and the influence of grouting does not go beyond a distance of 1m away from the edges of the columns.

4.4 Correcting Movements of Buildings

Once the movements of a building have become excessive, an extremely difficult situation is faced. The leaning Tower of Pisa is a classical example and is a perfect case history for illustrating the point. It was built in three stages, i.e. between the years of 1173-1178, 1272-1278 and 1360-1370 (Ground Engineering, 1993). The tilt of the tower reached 5.5° , toward the south, in 1991 with a slightly increasing rate of 6 seconds per year. The settlements of the tower have been extensively studied by many researchers and a full investigation was conducted by a special Commission of the Italian Ministry of Public Works (1971) and yet the cause of tilt is still under debate. Hypotheses range from bearing capacity failure (Leonards, 1979), differential consolidation (Mitchell, Vivatrat and Lambe, 1977), to effects of solar energy (Ground Engineering, 1993). This illustrates how experts can differ in opinions even with full facts presented.

Alerted by the collapse of the civic Tower Pavia Cathedral in 1989, the Italian Government set up an International Committee, the 15th commission of this kind in this century, composing of renowned experts for safeguarding the Tower to figure out schemes to safeguard the tower. As a first precaution, lightly prestressed steel strands were applied in the vicinity of the first cornice to arrest the tendency for buckling of the external facing stones thereby ensuring its structural integrity. Major modification of the structure has been ruled out to preserve the historical value of the tower. Underpinning is not favored because of the fear of causing more damages (Mitchell, 1991, ISSMFE, 1993). Neither is dewatering considered appropriate because of the lack of controlling its performance.

Modifications of structures and/or foundations are considered to be "hard solutions" and "soft solutions", as illustrated in Fig. 17, include :

- a. counterweight
- b. electro-osmosis
- c. under-excavation

All of these measures are aiming at inducing controlled consolidation settlements on the north side which has settled by "only" 0.8m as compared to the 2.8m settlement on the south side. A load of 600 tons was placed on the north side in a gradual manner between June and September, 1993 and it was anticipated to reduce the tilt by 5 to 10 seconds (ISSMFE, 1993). Readings taken at the end of February, 1994 indicated that a reduction of tilt of 37 seconds had been achieved (ISSMFE, 1994)

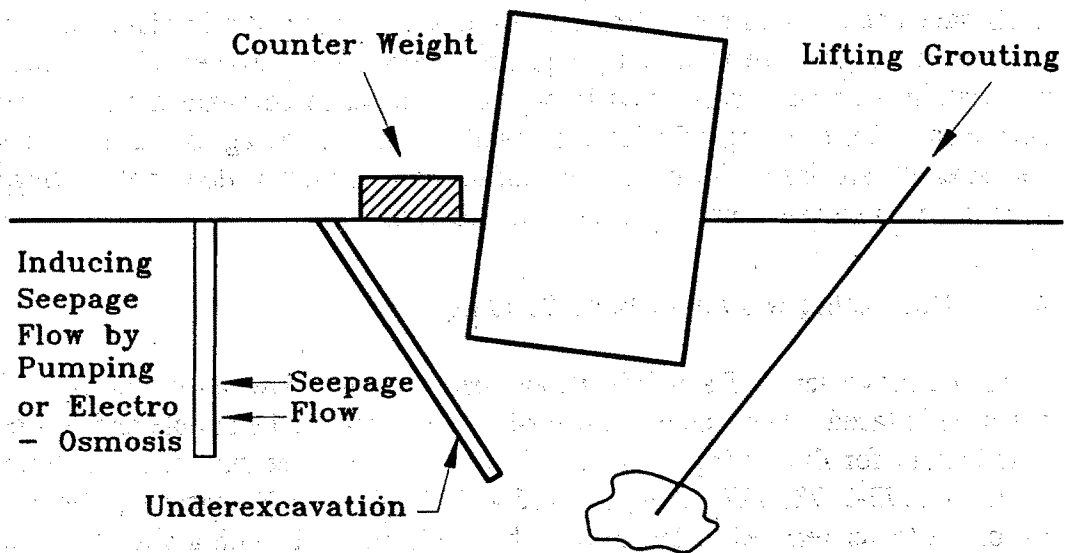


Fig. 17 Correcting Building Tilt

The use of electro-osmosis to induce seepage flow, hence, consolidation settlement, to the knowledge of the authors, has never been applied in practice previously. Electrodes, 20m in length, were installed at this site to prepare for the trial. The aim is to induce settlement in Pancone clay between depths of 10 to 20m, therefore, the electrodes are sheathed over their top 10m. At the time this paper was prepared, the trial was yet to be carried out and no data were available regarding its performance.

Under-excavation has been favorably considered but so far no work has been carried out. It involves removing a certain amount of soil from inclined drilled holes underneath the foundation to cause controlled settlements. An interesting case is reported by Amirsoleymani (1991) that, refer to Fig. 18, a prism of 24m x 8m x 0.24m of soil beneath the mat foundation of a building was removed to correct the tilt. The operation was executed in 5 steps by pulling a steel chain and, as a result, the tilt was reduced by 0.011 radians.

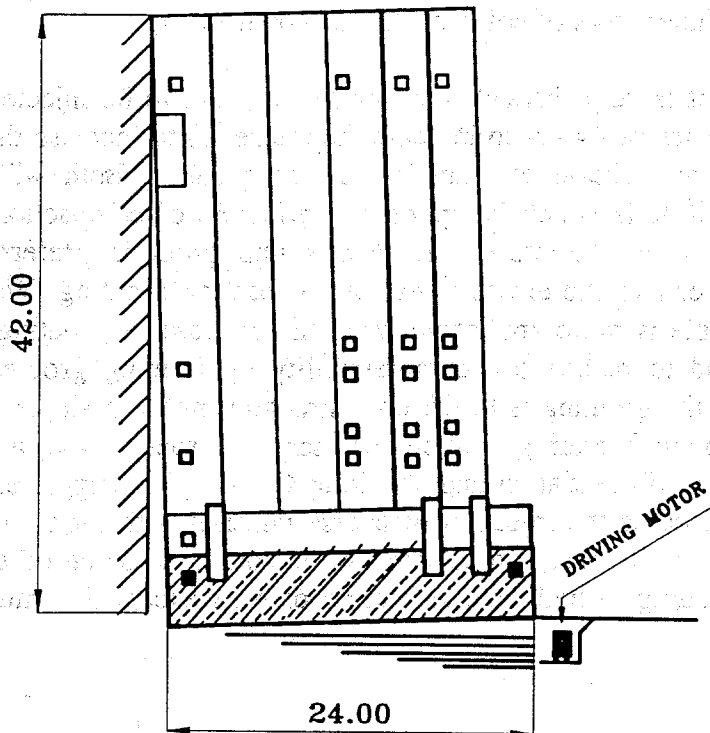


Fig. 18 Correcting Tilt by Under-excavation
(redrawn from Amirsoleymani, 1991)

Instead of lowering the opposite side, the tilt of a building can also be corrected by lifting up the depressed side. It can be achieved by directly jacking up the foundation against the ground or heaving up the foundation by injecting materials into the underlying ground. Lifting up buildings by injection is an old concept but is a relatively new technique. Little experience is available to guide the design. For TRTS, the compaction grouting mentioned at the end of Section 4.3 produced minimal ground heaves. It has been found that in soft clays, because of the slow rate of dissipation of porewater pressure, ground heaved quickly. However, the subsequent dissipation of excess porewater pressures led to ground settlement which in some cases were even larger than the heave produced previously. Since the up-and-down movements will be very damaging to structures, grout in soft clay is not encouraged.

In sands, post-operation settlement is not a problem. However, it has been found that a very large quantity of grout is required for the heave to be significant. Unless access is available for the operation to be carried out inside the premises, which is very unlikely to be the case, grouting is usually conducted from inclined holes and is conducted in the limited space between the building, which is to be lifted up, and the retaining walls of the excavation. It is preferable to apply grouting at as deep as possible, refer to Fig. 19, so that

- a) the point of injection can be farther away from the retaining wall to minimize the pressures on the wall and

- b) the inner rows of columns can also be lifted up

However, it is very difficult for low-slump grout to be injected below a depth of 8m. There are two ways to increase the intake: a) to increase the grouting pressure and/or, b) to increase the mobility of the grout. Both will lead to hydraulic fracturing of soils which is against the principle of compaction grouting. It is claimed in many literatures that low slump grout is preferred and hydraulic fracturing reduces the effectiveness of compaction grouting (Warner, et al, 1992). This principle is more applicable when the purpose of grouting is to improve soil strength and to reduce soil compressibility by forming grouted columns. If the purpose of the grouting is to lift up a structure, not at a single point but in a large area, hydraulic fracturing may be necessary. In such a case, a new terminology is required for differentiation and "Lifting Grouting" is suggested. Lifting grouting can be defined as the injection of coarse material with high mobility under a very high pressure. In fact, lifting grouting is similar to some other types of pressure grouting leading to hydraulic fracturing of soils except that much coarse materials are used.

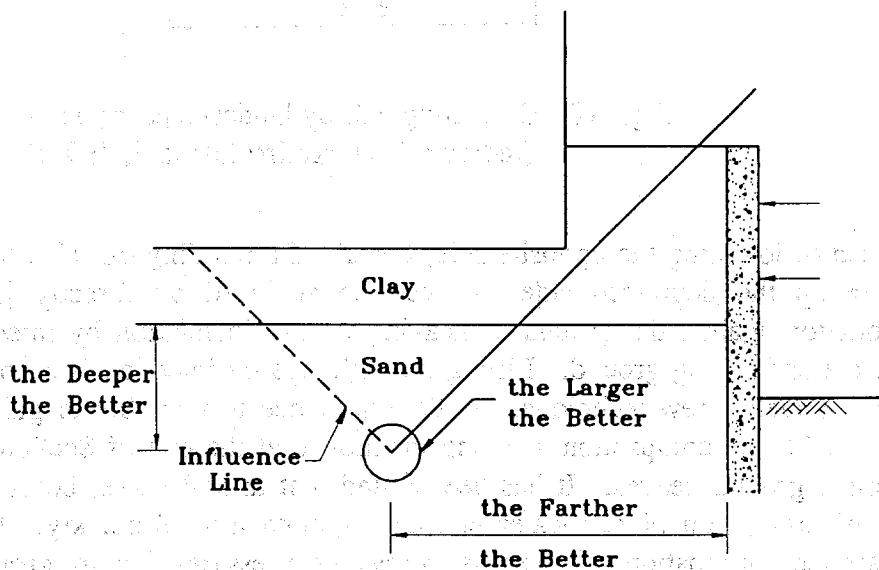


Fig. 19 Optimum Pattern of Compaction Grouting

There is a common fear among engineers of damaging structures due to hydraulic fracturing. A series of trials on lifting grouting are undergoing in Taipei in an attempt to understand the mechanism better and to provide guidances on field control. So far there are sufficient evidences to indicate that, because the grout consists mainly of coarse materials, it will not travel very far horizontally. Secondly, it is not difficult at all to control the rate of heave by controlling the rate of injection, therefore, the risk of damaging structures is avoidable. A question remaining to be answered is how hydraulic fracturing would affect the bearing capacity of the foundation soils. On one hand, grouting densify the foundation soils thus increase their strengths and bearing capacity. On the other, hydraulic

fracturing may produce cracks, at the temporary stage, infilled with relatively weaker materials. The net effects of the two mechanisms are unclear at this moment. For mat foundations, this is unlikely to be a problem because cracks will be fully contained in the triangular wedge beneath the mat. But for small size footings, there is a potential danger of loosing bearing capacity if cracks are in an unfavorable pattern. One thing for sure is that because of the rapid dissipation of excess porewater pressures, consolidation, if any, will complete during the operation and will not be a problem afterward. For the same reason, it is expected that the materials infilling the cracks will be sufficiently densified (and hardened if cement is present) and their strengths could even be higher than the original strengths, even they were weak to start with.

5. INSTRUMENTATION AND ALERT SYSTEM

With growing awareness of its importance, instrumentation has become a necessity for underground works. The use of personal computers makes full automation possible. To the authors' knowledge, the instrumentation program adopted in the construction of TRTS is the most extensive one which has been implemented and the computerized alert system may also be the first one of this kind (Moh and Chin, 1991). In brief, as shown in the flowchart in Fig. 20, contractors are responsible for taking readings and transmitting, in a specified format, the data through modems and telephone lines to GESC's (Geotechnical Engineering Specialty Consultant) employed by the project owner, the Department of Rapid Transit Systems of Taipei Municipal Government, monitoring stations where the data are immediately verified by computer for mistakes. If a certain reading, such as strut load, tilting of building, exceed the pre-set alert level, a notice will be faxed automatically to the Resident Engineer supervising the contract of concern. The process takes less than an hour. The contractor will be requested to provide explanations and, if necessary, to prepare contingency measures. In the meanwhile, Quality Assurance Officer will also be informed and will follow up with the issue to ensure that proper actions are taken and are taken in time.

All the instrument readings are stored in the Integrated Data Storage Center managed by GESC. The handling of tens of millions records calls for a powerful retrieval system. Several packages have been developed and data of individual or groups of instruments can be plotted in a matter of seconds. The database has been very useful for back-analyses for correlating field data with analytical procedures.

6. CONCLUSIONS

As demonstrated hereinbefore that the several protection measures adopted in the construction of the Singapore Mass Rapid Transit Systems and the Taipei Rapid Transit Systems have effectively reduced ground movements and, hence, damages to adjacent structures. As often said, "An ounce of prevention is worth of a pound

of cure". It is essential to have a proper design of temporary works and tight construction control to avoid problem in the first place. A full understanding of the usages and limitations of remedial measures is important for selecting the most proper one to suit the particular situation encountered if problem does occur. It should always be remembered that inadequate measures will do more harm than good.

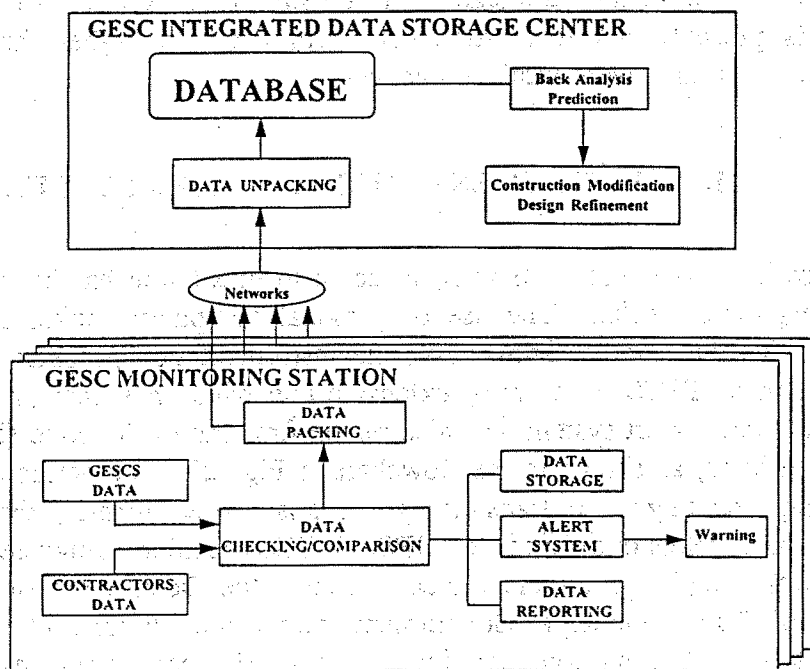


Fig. 20 Monitoring and Alert System (TRTS)

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