UNDERPASS BENEATH TAIPEI INTERNATIONAL AIRPORT

by

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ABSTRACT

A 4-lane highway is to pass underneath a taxiway and a runway of the Taipei International Airport located to the north of the city center of Taipei. The requirement that air traffic shall in no case be interrupted during the construction necessitates the adoption of special construction techniques. Working shafts are constructed and tunneling is carried out between these shafts. The tunnel is sheltered by interlocking steel pipes installed by using the pipe-jacking technique. Under the taxiway and the runway, the so-called Endless Self Advancing Method (ESA Method) is adopted to ensure that the settlements are within tolerances. Furthermore, a comprehensive instrumentation program is implemented for monitoring the performance of the temporary works and the ground response to various construction activities.

INTRODUCTION

As depicted in Fig. 1, to ease the traffic congestion in the northern part of the Taipei City, an underpass is currently being constructed to extend Fuhsing N. Road northward to connect to Tachieh Bridge which crosses the Keelung River. A major portion of this extension is underneath the field of the Taipei International Airport which is a busy airport serving both civilian and military air traffic with more than 300 commercial flights per day. Figure 2 is a layout showing the configurations of the underpass, the taxiway and the runway. As shown in Fig. 3, the underpass has to dive to a depth of 21.37m (road level) at its south end because of the provision of a tunnel box for the Taipei Rapid Transit Systems (TRTS) on the top and also because of the presence of a drainage box culvert. At its northern end, it is to meet the existing Bingjiang Street and therefore has to pass underneath the runway with a very thin cover of only 5.6m in thickness above its roof.

As shown in Fig. 4, the underpass has 2 lanes in each direction and the twin-cell box is 22.20m in width and 7.80m in height. The requirement that the air traffic shall be maintained all the time eliminates the possibility of using the cut-and-cover construction method in the sections where the taxiway and the runway are present. In fact, because construction activities above the surface are limited to the period between 11 pm to 5 pm within the entire boundary of the airport, the cut-and-cover method is used only for constructing five working shafts which are absolutely necessary for the work to be done. Elsewhere, an innovative method is required for work to be carried out with minimum interruptions.

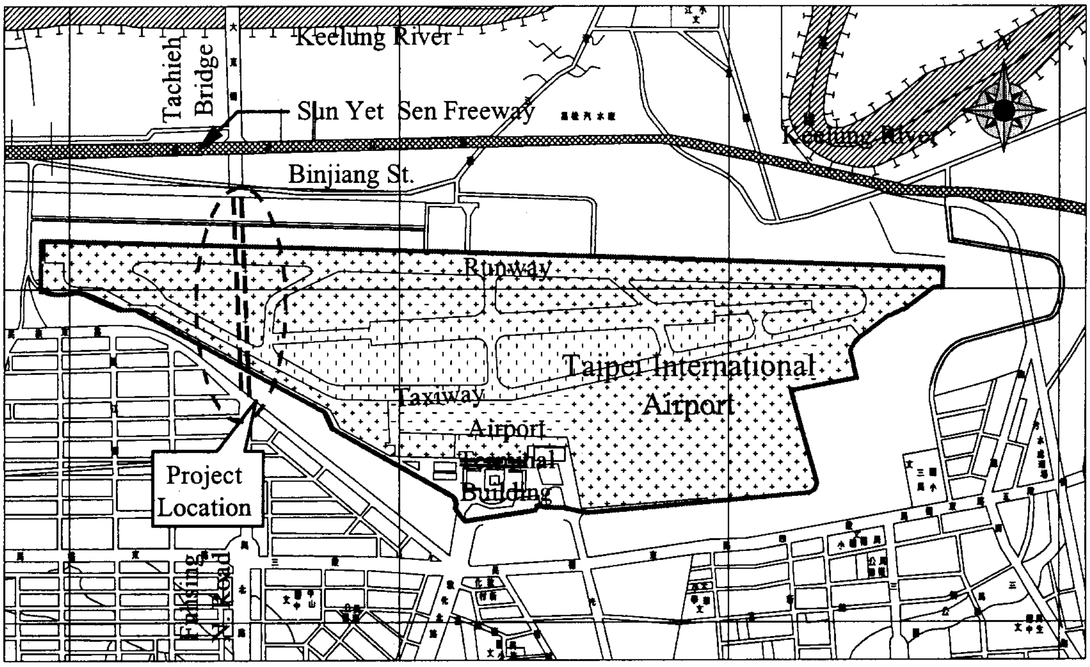


Fig. 1 General Layout

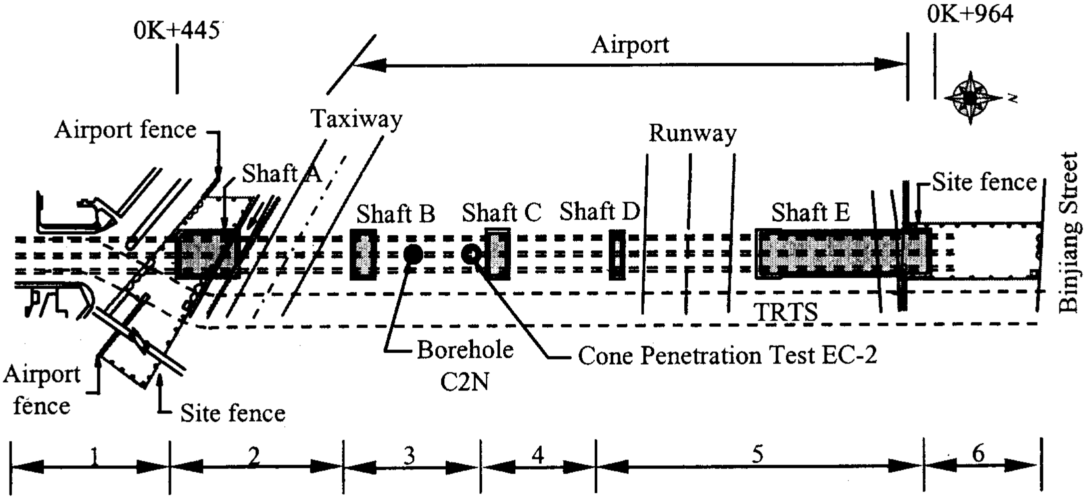


Fig. 2 Site Plan

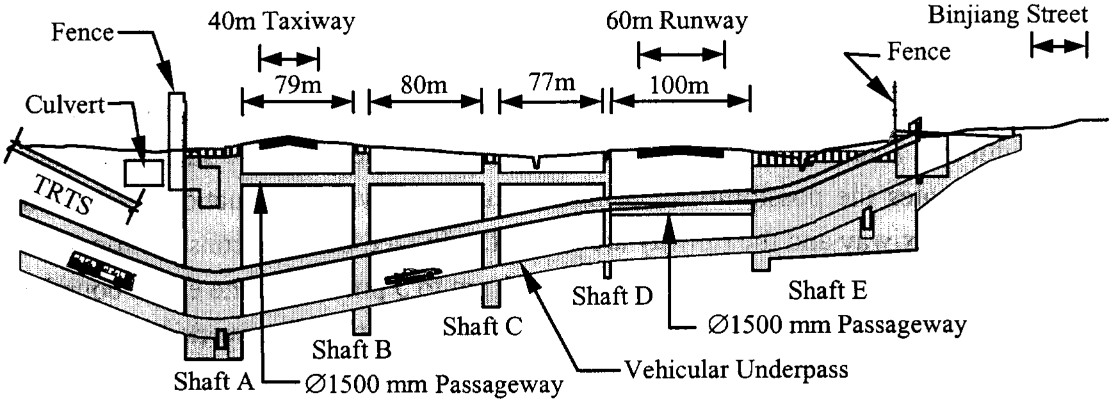


Fig. 3 Longitudinal Section

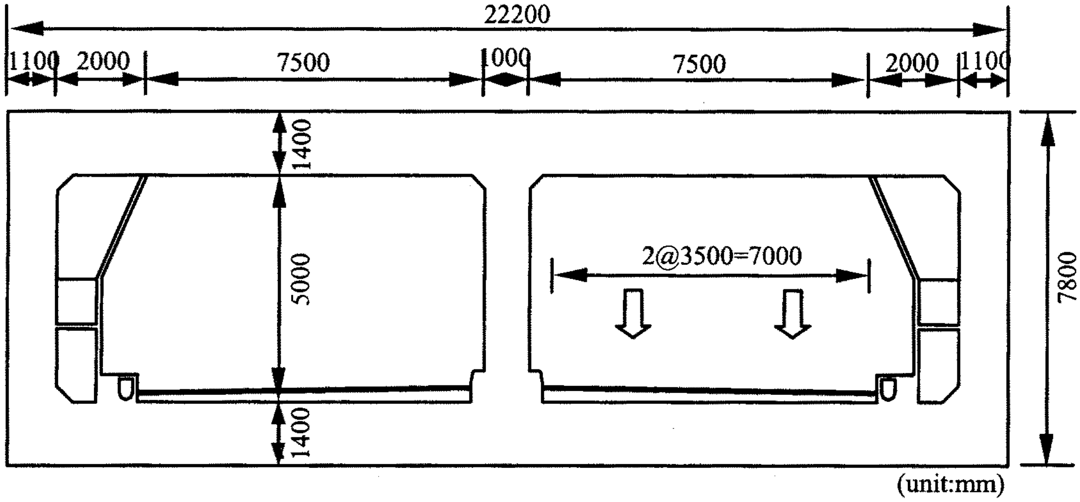


Fig. 4 Typical Tunnel Section

If circular tunnels were to be adopted, they both would have to be 11m in diameter. Tunnels of this size are impossible to be constructed at this site in consideration of the shallow depth of embedment and the poor ground conditions. Even if they were possible, the ground settlement would have been enormous and would endanger the safety of the flights. One of the critical criteria imposed is that settlements of the runway must be maintained within 25mm. If settlements exceed this tolerance, the runway must be resurfaced.

After a thorough study and extensive evaluation of all the options, it was decided that the sections of the underpass within the boundary of the airport be constructed by tunneling in a protective shelter formed by interlocked pipes. Furthermore, for sections directly underneath the taxiway and the runway, the so-called Endless Self Advancing (ESA) method will be adopted (Hsiung, 1997; Continental Engineering/Tekken JV, 1997, 1998) to construct the tunnel box.

The owner of the project is the Division of New Construction Projects, Bureau of Public Works of the Taipei Municipal Government. Moh and Associates, Inc. is the consulting engineer responsible for the design and construction supervision.

GROUND CONDITIONS

A total of 18 boreholes, of which 5 are located within the airport, were sunk to a maximum depth of 75m. As depicted in Figs. 5 and 6, at the surface is a thick layer of silty clay (CL) with a sandy silt (ML) layer present at depths varying from 3 to 10m. The blow counts obtained from standard penetration tests vary from 2 to 5 within a depth of 25m or so. As shown in Table 1, the natural water content of the clay is very close to the liquid limit indicating how soft the clay is. The undrained shearing strengths of this clay layer obtained from triaxial compression tests increase linearly with depth with an average of 100 kPa at a depth of 40m. The sensitivity of the clay varies from 4 to 10. Table 1 also lists the design parameters adopted.

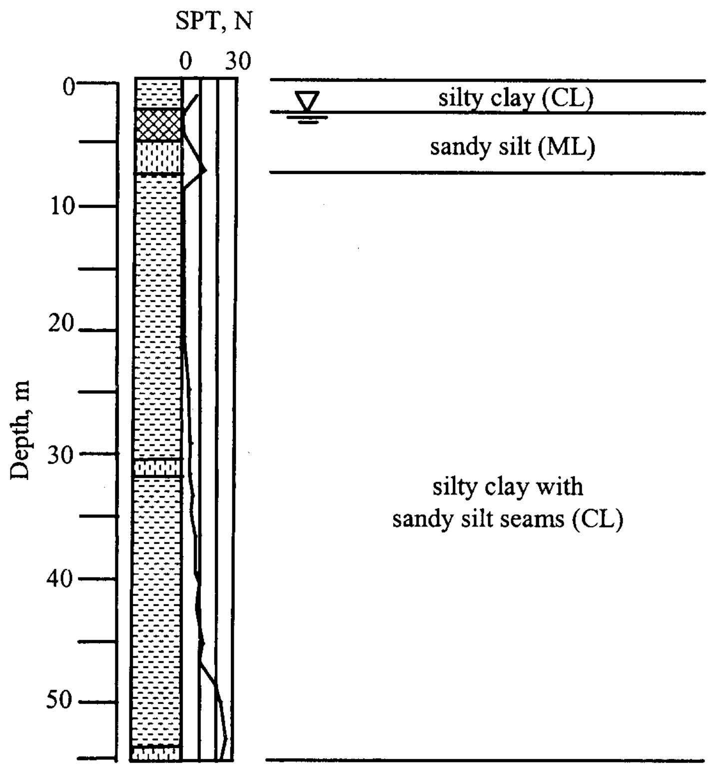


Fig. 5 Log of Borehole C2N and Results of SPT

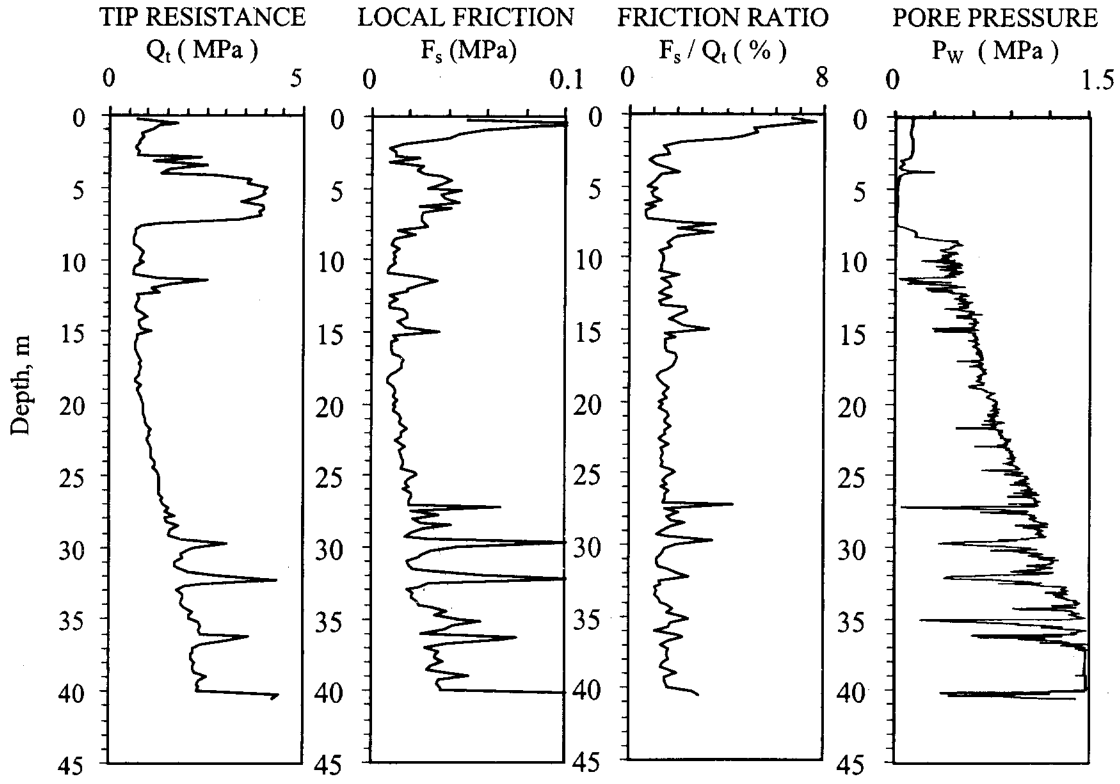


Fig. 6 Results of Piezocone Test EC-2

Table 1 Design Parameters

0k+450 to 0k+740

Depth (m)	**Soil Type**	**N (blows)**	γ_t **(kN/m^3)**	w_n **(%)**	w_l **(%)**	I_p **(%)**	**c' (kPa)**	**ϕ' (deg)**	s_u **(kPa)**	**E (MPa)**
0~3	**CL**	**4**	**18.2**	**28**	**28**	**8**	**0**	**33.5**	**26**	**26**
3~8	**SM**	**7**	**19.2**	**28**			**0**	**32**		**28**
8~24	**CL**	**4**	**18.6**	**34**	**34**	**10**	**0**	**32.5**	**38**	**38**
24~41	**CL**	**8**	**19.0**	**29**	**29**	**9**	**0**	**33**	**70**	**70**
41~56	**CL**	**17**	**20.0**	**23**	**30**	**10**	**0**	**34**	**128**	**128**
56~60	**CL**	**>50**	**19.0**	**25**			**0**	**34**		**200**

0k+740 to 1k+200

Depth (m)	**Soil Type**	**N (blows)**	γ_t **(kN/m^3)**	w_n **(%)**	w_l **(%)**	I_p **(%)**	**c' (kPa)**	**ϕ' (deg)**	s_u **(kPa)**	**E (MPa)**
0~9	**CL**	**4**	**18.5**	**31**	**32**	**12**	**0**	**31.5**	**28**	**28**
9~13	**ML**	**2**	**18.9**	**31**			**0**	**32**		**8**
13~22	**CL**	**3**	**18.5**	**34**	**35**	**12**	**0**	**33**	**39**	**39**
22~32	**CL**	**6**	**19.0**	**32**	**33**	**12**	**0**	**33**	**60**	**60**
32~34	**ML**	**11**	**19.2**	**24**			**0**	**33**		**44**
34~40	**CL**	**13**	**19.6**	**26**	**26**	**8**	**0**	**33.5**	**87**	**87**

Piezocone penetration tests were carried out at 5 locations within the airport to a maximum depth of 40m and 9 dissipation tests were performed. The results of one of the piezocone tests are given in Fig. 6 and, as can be noted, thin seams of sandy soil are clearly identifiable. This piezocone test was carried out at a location of 50m north to the borehole of which the log is shown in Fig. 5. The two sets of results obtained are quite compatible.

Because the site is very close to the Keelung River and is protected from flooding by a levee located only a couple hundred meters away, the groundwater table at the site is high and is affected by the water level in the river. Normally, the groundwater table is at depth of a couple meters, or even less, below the ground surface. However, whenever the river was flooded in a typhoon season, the groundwater table rose to a level very near the surface. Therefore, the groundwater table is assumed to be at the surface in the design.

METHODS OF CONSTRUCTION

As depicted in Fig. 2, five working shafts are sunk and the underpass is to be constructed in 6 sections. For Sections 1 and 6, spaces are available for these two sections to be constructed by using the cut-and-cover method. Other sections have to be constructed by tunneling. As discussed above, the ground conditions are very poor and tunneling could not be carried out without auxiliary measures. Various options have been evaluated and the pipe-roof technique was opted to be the most favorable method in consideration of the safety of the tunneling operation. Furthermore, instead of just providing a roof, excavation is to be carried out in a protective shelter enclosed by interlocked steel pipes in Sections 2 to 5.

The five shafts, in the sequence of A to E, are 40m, 12m, 12m, 5m and 116m in length, respectively. Shaft D is used only as an arrival shaft and is therefore shorter than others. Shaft A has the greatest depth of 26.5m. Within the boundary of the airport, work is allowed to be carried out only between 11pm to 5am, diaphragm wall panels cannot be completed in such a short time. Secant piles of 1,500mm in diameter are used as retaining walls. Similarly, Shafts B and C are retained by secant piles. Shafts D and E which are relatively shallow in depth are retained by soil-mixing-wall (SMW) of 600mm in thickness. Because each pile cannot be completed in one go, these SMW piles were fully cased to prevent the bored holes from collapsing during the intermission. Casings were then withdrawn during concreting.

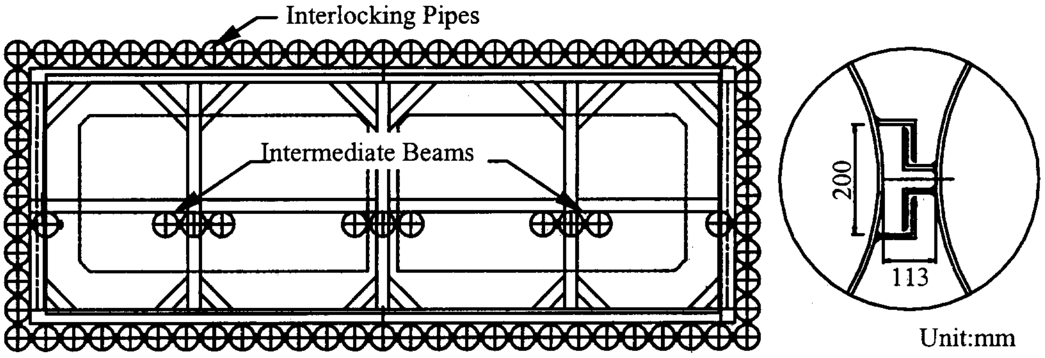
Excavation is first carried out inside each shaft to the bottom level of the roof pipes and the roof pipes are installed by using the pipe jacking technique. Subsequently, excavation is carried out in three stages and in each stage, three pipes on each side are installed. Finally, excavation is completed and the bottom pipes are installed. In addition to the pipes which form the shelter, there are 11 pipes to be installed in Sections 3 and 4 to serve as intermediate beams during tunneling as shown in Fig. 7, and 12 pipes to be installed in Sections 2 and 5 to serve as cable ducts, of which the locations are indicated in Fig. 8. The latter are to be used to house cables which are to be used to jack segments to their positions as shown in Fig. 9. All these additional pipes are of the same size as those forming the shelter and they are installed as excavation reaches appropriate depths.

Once all the shafts are completed, they will be covered by steel decks so works can proceed underground during the day time. The shafts at the two ends will be the only accesses for workers and materials. It will then no longer be necessary for workers and machines to enter the airport except for taking instrument readings.

Sections 3 and 4 are in an open field and settlement is of less concern. Excavation is therefore carried out in a conventional way in which two headings are made and the pipe-shelter is propped by steel members as depicted in Fig. 7. The loads on the roof pipes are temporarily transferred to pre-installed intermediate beams resting on the soil bench. These intermediate beams are to be removed as the bench is excavated and the loads are transferred to the bottom pipes. The tunnel box is to be cast-in-situ after the completion of mining.

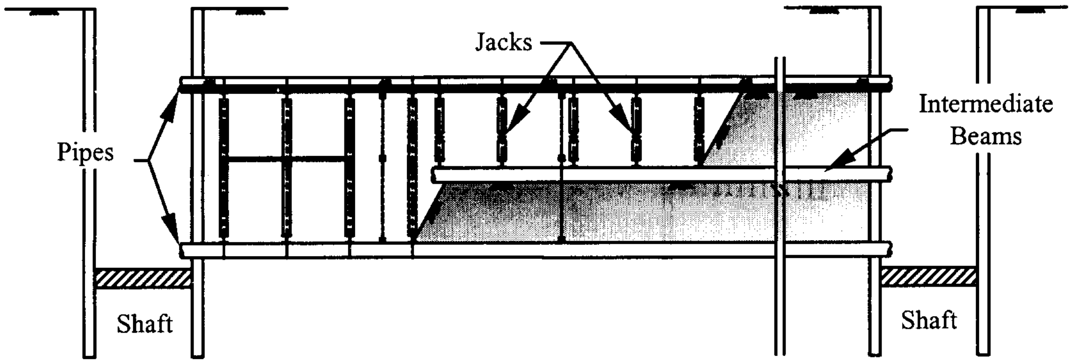
For Sections 2 and 5, settlement of the taxiway and the runway is of primary concern. It is envisaged that settlements would exceed the tolerance if the above-mentioned approach is adopted without additional measures. Therefore, these two sections are to be completed by using the so-called endless-self-advancing method (ESA method) in which, as illustrated in Fig. 9, the tunnel boxes are advanced segment by segment in a manner resembling the movement of centipedes. This method is patterned by Uemura Engineering Co., Ltd of Japan.

For these tunnel boxes to be properly positioned, refer to Fig. 8, five guide tunnels are to be manually dug and guide rails are to be installed. These guide tunnels are in two types: Type A at the two lower corners and Type B at the intermediate spans. They are in a shape of shield and are supported on ribs formed by steel tubes. Wood planks are used as laggings behind these ribs. Type A tunnels are roughly 2,360mm in height and Type B tunnels are roughly 2,100mm in height. Three guide rails are provided in each tunnel. These guide tunnels serve as pilot tunnels for the purpose of unveiling ground conditions along the path and also serve as drains.



(a) Cross-Section

(C) Details of Interlocks



(b) Longitudinal Section

Fig. 7 Tunneling in Sections 3 and 4

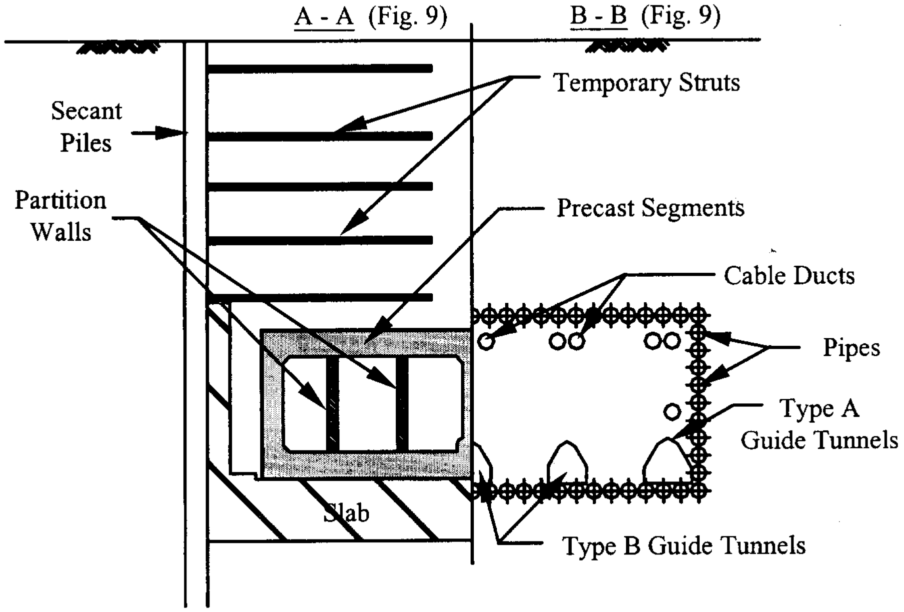
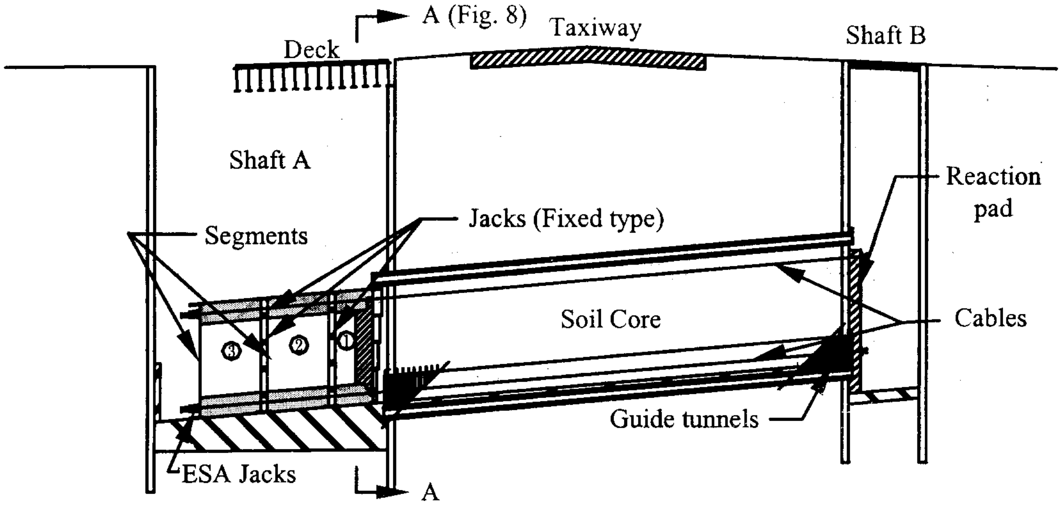
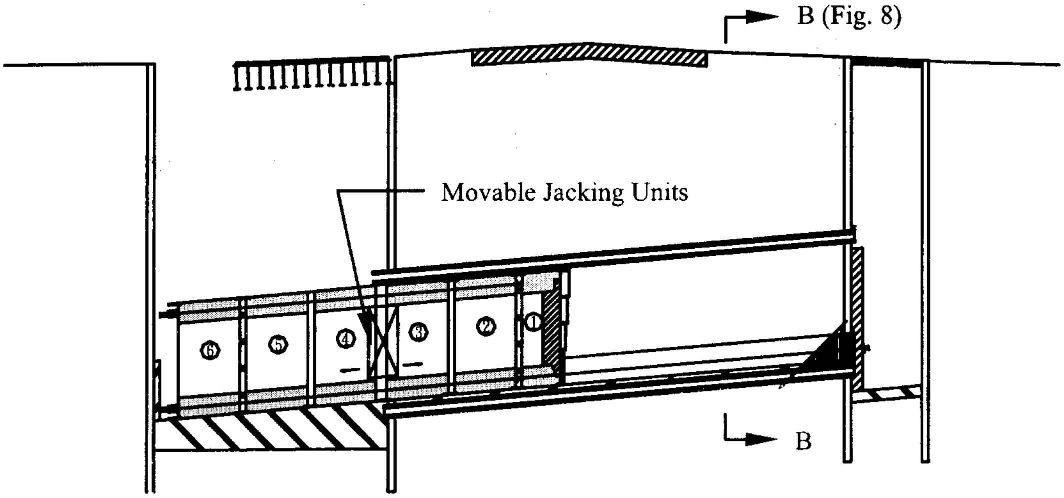


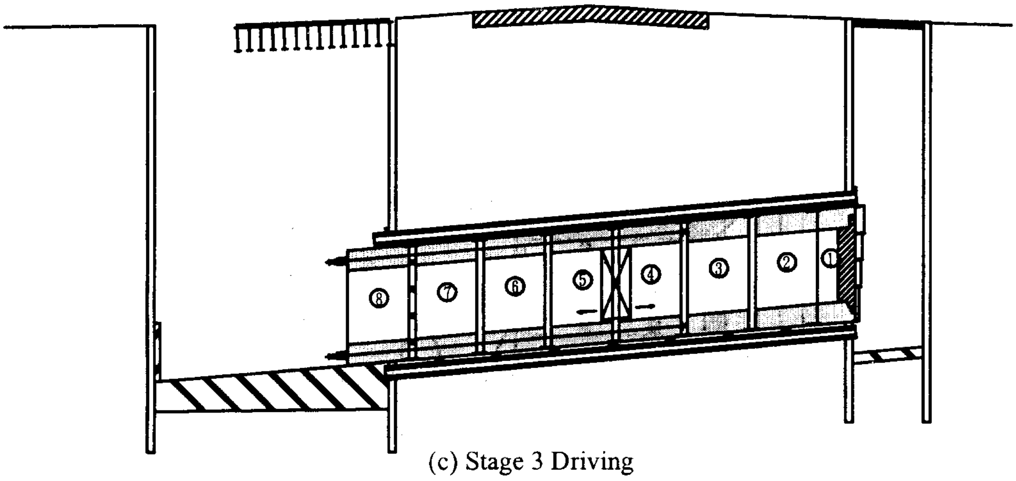
Fig. 8 Cross-section of ESA Layout



(a) Stage 1 Driving



(b) Stage 2 Driving



(c) Stage 3 Driving

Fig. 9 Tunneling in Section 2

Once the guide tunnels are completed, the soil core inside the pipe-shelter is excavated and the tunnel box is jacked into the shelter in full-section segments of 10.5m each, except the first segments which are 6.5m in length. At each time, only one segment is moving and the remaining segments provide reactions required. The tunnel box under the taxiway, i.e., Section 2, is divided into 8 segments and is driven in 3 stages as illustrated in Fig. 9. In front of this segment is a cutting edge made of steel plates. This cutting edge is partitioned into 24 chambers arranged in 4 rows. Excavation is carried out chamber by chamber and the face is braced by breast jacks, 4 in each chamber.

The basic idea of the ESA method is that each time a segment is being driven, the majority of the reaction comes from the frictional resistance acting on the rest of segments. For example, when Segment 3 is being driven by jacking against Segment 4, refer to Fig. 9(b), part of the jacking force is taken by the frictional resistance acting on Segments 4, 5 and 6, and the remaining force goes to the end of Segment 6 and is taken by cables. The force taken by the cables which run through the guide tunnels is transmitted to the reaction pad in Shaft B. The force taken by the cables which run through cable ducts is transmitted to Segment 2 and is resisted by the frictional resistance acting on Segment 2. This way, the size and the rigidity of the reaction pad required are much reduced. The tunnel boxes are surrounded by soil on their sides and on their roofs all the time. During jacking, lubricant will be injected from grouting holes on the segments to reduce frictional resistance. In theory, the forces taken by the cables are not affected by the length of the tunnel box and the tunnel box can be as long as desired. In addition to the jacks which are fixed to segments at the joints, four movable jacking units are used to provide extra driving forces and each unit is equipped with 15 jacks with a capacity of 150 tons per jack. Shaft E is long enough for all the 10 segments to be cast at one time and jacked consecutively toward Shaft D.

DESIGN CONSIDERATIONS

Ground settlement is the primary concern in the design. Settlements may occur as a result of excavation or as a result of lowering of groundwater table. It is therefore important for the retaining systems for shafts to have sufficient rigidity and watertightness. It is even more important for the pipe-shelter to satisfy these requirements. As an auxiliary measure, extensive ground improvement work was carried out to strengthen subsoils and to cut off seepage paths.

The shafts are rectangular in shape and the design of shafts is conventional, except that it is necessary to include the loading from airplanes into consideration. It has been found that lateral pressure on walls from airplanes is rather small in comparison with that from the surcharge due to construction activities. The surcharge was increased by 5 kPa to simulate the loading from airplanes wherever necessary.

Since this is the first time for the ESA method to be used in Taiwan, there are a lot to be learned. Furthermore, the ground conditions encountered at this site and the fact that the tunnel is to be driven underneath a busy runway are unprecedented. Therefore, a comprehensive instrumentation program is desirable for maintaining the safety of construction, enhancing construction procedures and documenting experience.

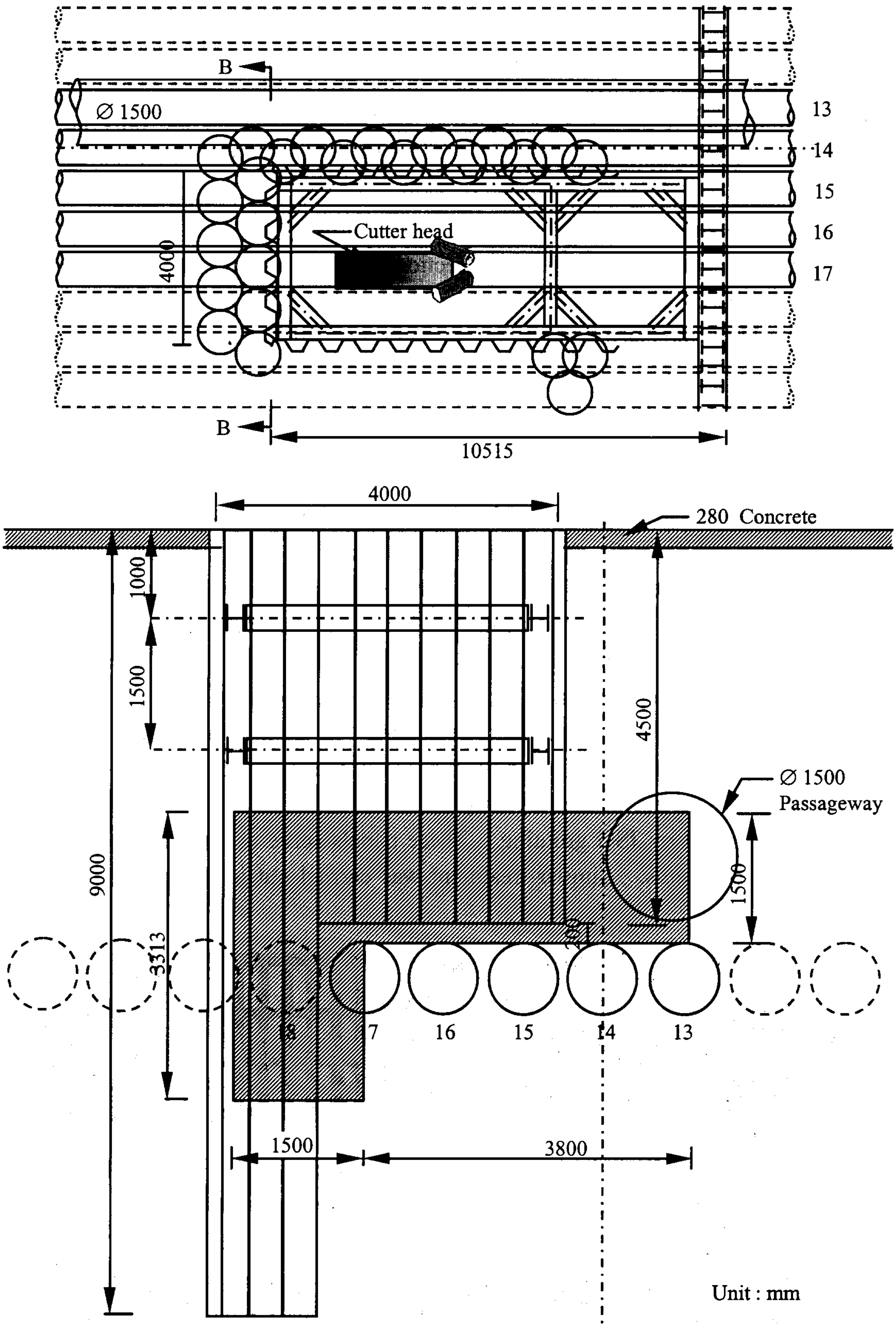
PIPE JACKING

As of August 1999, roof pipes in all the sections have been completed and jacking is continued for installing the rest of pipes. The pipe-shelter running from Shaft E to Shaft D will be completed in October and advancement of the tunnel box is to be commenced in August, 2000. Jacking is being carried out from Shafts A to B, B to C, C to D and E to D. These pipes are 812.8mm in their outer diameter and are interlocked, as illustrated in Fig. 7, for better watertightness and better alignment of pipes. At the location of the runway, the top of the pipes is only about 4.5m below the runway. As depicted in Figs. 5 and 6, there exists a sandy silt layer at depths varying from 3m to 10m, seepage could become a problem if pipes were not interlocked. These interlocks are filled with styrofoam so they will not become water paths. The openings made on the retaining walls for launching pipes and for receiving pipes are sealed by sealant and rubber gaskets.

In Sections 2 and 3, two units of earthpressure balancing type Iron-Mole manufactured by Komatsu Ltd. are used. The bearing of the cutter head can be adjusted by 3 degrees in any direction for correcting the alignment of pipes. In Sections 4 and 5, four units of slurry type Uncle-Moles manufactured by Iseki Poly-Tech, Inc. are used. The bearing of the cutter head can be adjusted by 1.7 degree in the vertical direction and 1.2 degree in the horizontal direction. For both types of machines, the cutter heads are 830mm in diameter giving a theoretical clearance of 9mm between the ground and the pipes. During jacking, lubricating fluid is injected to fill up this void for reducing frictional resistance acting on pipes. Four jacks, each with a capacity of 150 tons, are employed and for most of the pipes which have already been completed the jacking forces were generally below 200 tons. However, a peak force of 280 tons was occasionally required.

Pipes are kept open so compensation grouting can be carried out from the grouting holes in the pipes to rectify ground settlement should it exceed tolerance and will be filled with concrete upon the completion of tunneling. In some of the pipes, instruments are installed for monitoring the deformations of these pipes and the stresses induced.

Large pieces of timber were encountered at depth of roughly 6m during jacking of roof pipe No. CU17 between Shafts C and D and jacking force exceeded 800 tons. A temporary shaft was sunk for the purpose of removing these obstacles. It was retained by sheet piles as illustrated in Fig. 10. The sheet piles on the western side of the shaft were obstructed by roof pipes which had already been installed and ground improvement was carried out at their toes to prevent water from seeping into the shaft. Several pieces of timber were discovered and removed. Two of them were about a half meter in length and 200mm in diameter. Pipe No. CU17 was extended all the way to Shaft D and the shaft was backfilled after the completion of the remedial work.



Section B-B

Fig. 10 Temporary Shaft for Removing Timber

MATERIAL PASSAGEWAY

As depicted in Fig. 3, a passageway of 1,500mm in diameter is installed for transporting material between shafts. This passageway allows works to be carried out underground in the day time and is a key element in speeding up the work. For more than two-third of the construction period, it serves as a walkway for workers and is the only access/exit for materials and light equipment/machines required for works to be carried out in Shafts B, C and D.

This passageway is installed between shafts by using the pipe jacking technique in a similar manner as described above. The section of the passageway between Shafts D and E has to be lowered by 5m or so to stay away from the pipe-roof. Even so, it still conflicts with the tunnel box and has to be removed during tunneling.

GROUND IMPROVEMENT

As mentioned above, the ground is very soft and it is therefore necessary to perform ground improvement to ensure the safety of construction and to limit ground movements. Figure 11 shows, for example, the improvement works carried out at Shaft E. Grouting was carried out by using the JMM (Jumbo Mini Max) method at the south end to solidify the subsoil all the way from surface to a depth of 6.7m below the final depth of excavation. This will help reducing ground movements, and hence, settlement of the runway. Outside the south end wall, treatment was carried out by using the Jumbo Special Grout (JSG) method to prepare for launching of pipes and tunnel segments. In the middle section of the shaft, JSG grouting was carried out to form 4 panels, running in the longitudinal direction. Across the shaft, there are 21 panels formed by using the JMM method and one panel, i.e., the very southern one, formed by JSG grouting. These panels serve as bracings for the purpose of limiting wall movements. Similar treatment was carried out in the northern end with one

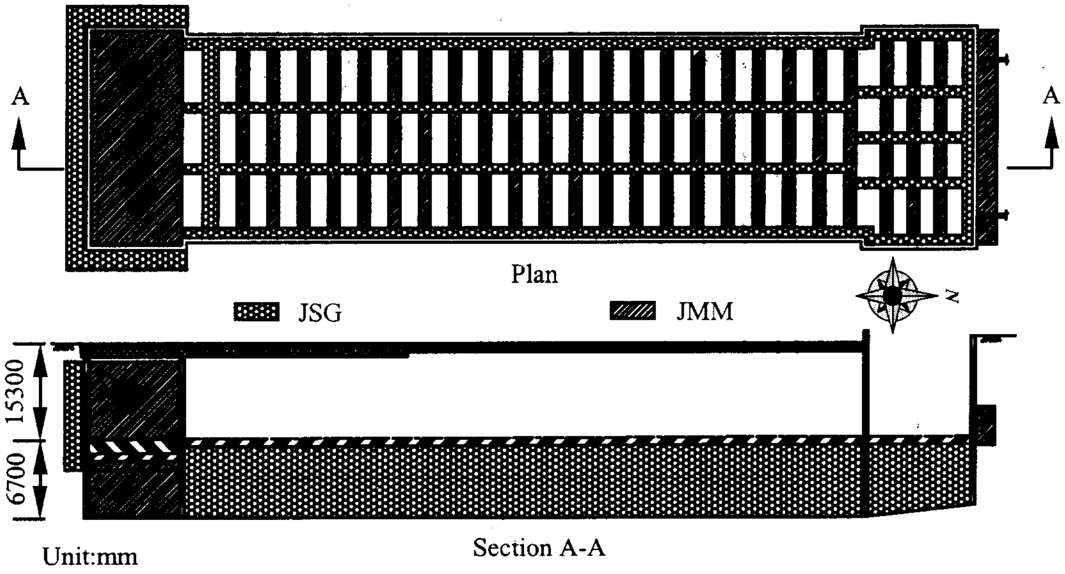


Fig. 11 Ground Improvement at Shaft E

row of JSG grouting along the perimeter, 3 panels in the longitudinal direction by JSG grouting and 3 panels across the shaft using the JMM method. Outside the northern wall, a block of subsoil was treated by using the JMM method to back the reaction pad which is to be used to drive tunnel segments.

In the JMM method, a blade of 800mm in width is rotated to disturb subsoil and grout is injected from nozzles on the edges of the blade at pressures of 180 bars to 300 bars to form columns of 2m in diameter. Columns have an overlap of 300mm to ensure continuity. In comparison with high pressure jet grouting, the JMM method offers better quality of the products. However, alongside the perimeter and at places where the operation is obstructed by struts and pin posts, high pressure jet grouting, such as JSG method, will be easier to carry out. This is the reason that both types of grouting are adopted herein.

Similarly, ground treatment was also carried out at other shafts but to a much less extent. Considerable treatment is to be carried out inside the pipe-shelter, but the program is yet to be finalized after the ground conditions are better confirmed during the installation of pipes. In principle, the soil core is to be solidified by cement-bentonite-water mix to improve the stability of the face and to reduce water flow, if any. The soil surrounding the guide tunnels, refer to Fig. 12, will be treated by using the double-packer grouting method to yield a minimum unconfined compressive strength of treated ground of 160 kPa while the unipack method will be used elsewhere to yield a minimum unconfined compressive strength of 80 kPa.

INSTRUMENTATION

Because of the utmost importance of the safety of air traffic, a comprehensive instrumentation program has been implemented at the site. In addition to temporary works, some navigation facilities, such as radar towers, are also being monitored to ensure that their movements will not affect their performance. The most important item to be monitored

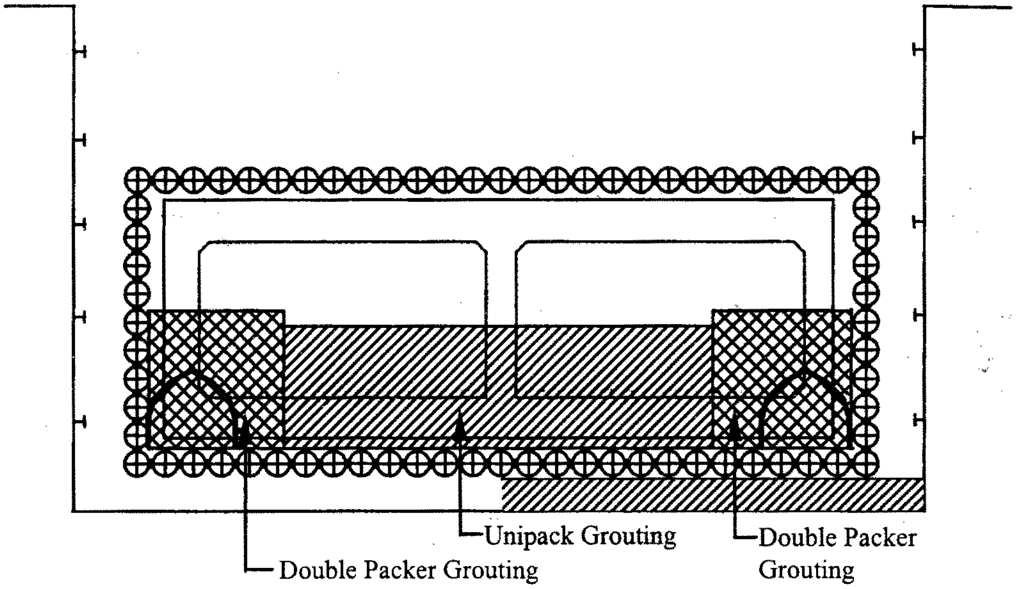


Fig. 12 Ground Improvement for ESA Work

among all is certainly the settlements of the runway and the taxiway. Settlement points are arranged in a 7 by 23 grid in the primary area above the tunnel on the pavement of the taxiway and in a 13 by 15 grid above the runway. They are spaced at 5m intervals. Intermediate points will be added as needs arise. Since survey is not allowed to be carried out on either the taxiway or the runway during the period in which the airport is open to services, inclinometer casings are installed in two of the roof-pipes under the taxiway and two of the roof-pipes under the runway and deflections of these pipes are monitored by using horizontal inclinometer probes. Deflections of pipes are measured at 1m intervals every morning and every night during ESA works.

What is worthy of mentioning is the automatic alert system adopted at the site. There are more than a thousand pieces of instruments which can be read automatically at any desirable frequencies. As illustrated in Fig. 13, a total of 14 data loggers are located in shafts and data are transmitted to a control room located at the site office where data are processed and analyzed. In addition, there are more than 500 settlement points and many other instruments of which readings must be taken manually and keyed in to the databases. For each instrument, two trigger values are defined and the current reading is compared with these trigger values. Once the first-level trigger value is exceeded, the contractor is alerted of potential risk and is urged to prepare contingency measures. Once the second-level trigger value is exceeded, contingency measures shall be taken unless it is proved that the situation posts no immediate danger.

The status of instruments is displayed on three panels, one at the site office, one at the office of the project owner, i.e., the Division of New Construction Projects of Bureau of Public Works of the Taipei Municipal Government and the third at the office of the Airport Authority. A green light will indicate that the current reading of the corresponding instrument is within the first-level trigger value and a yellow light will indicate that the reading has exceeded the first-level trigger value but is still within the second-level trigger value. A red light will indicate that the second-level trigger value has been exceeded.

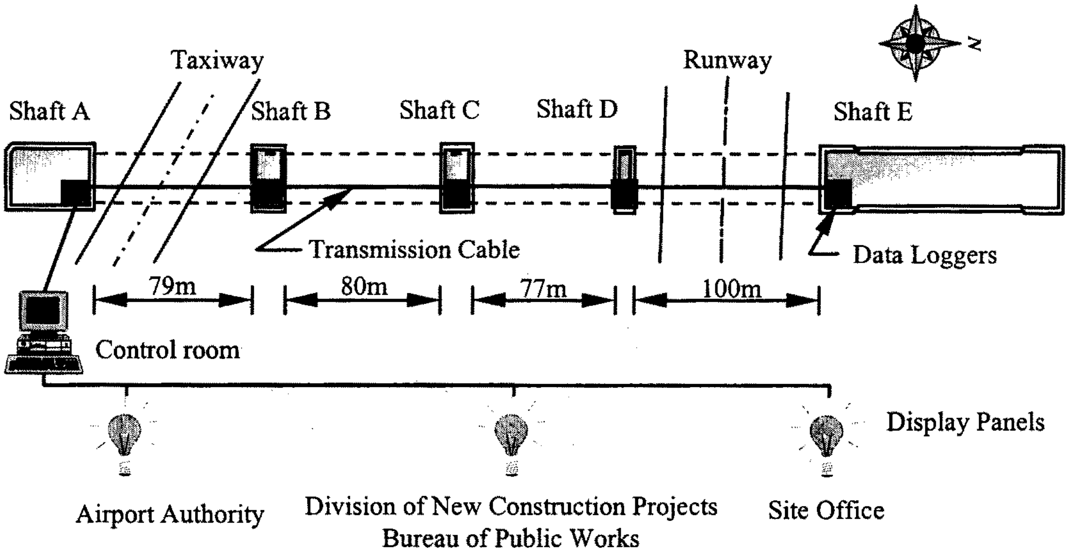


Fig. 13 Transmission of Instrument Readings

Upon the completion of all the pipes running from Shaft E to Shaft D, including the passageway, the settlement of the runway was within 10mm as illustrated in Fig. 14. This magnitude of settlement is remarkably small in consideration of the poor ground conditions encountered and was achieved by back grouting and compensation grouting carried out from the passageway and the roof pipes.

SUMMARY

Although the ESA method has been adopted in quite many occasions in Japan and, presumably, elsewhere, the situation faced at this particular site is believed to be unprecedented in consideration of the extremely poor ground conditions and the risk involved in underpassing the runway of a very busy airport with a thin cover. Considerable thoughts have been given on how constructions can be carried out safely without affecting air traffic and how ground settlements can be minimized. It is believed that the methods of construction chosen are among the best for the purposes.

ACKNOWLEDGEMENTS

The authors are grateful to the Department of New Constructions of Taipei Municipal Government for the permission of publishing the information contained herein. They are indebted to the main contractor, Continental Engineering and Tekken Joint Venture, and its

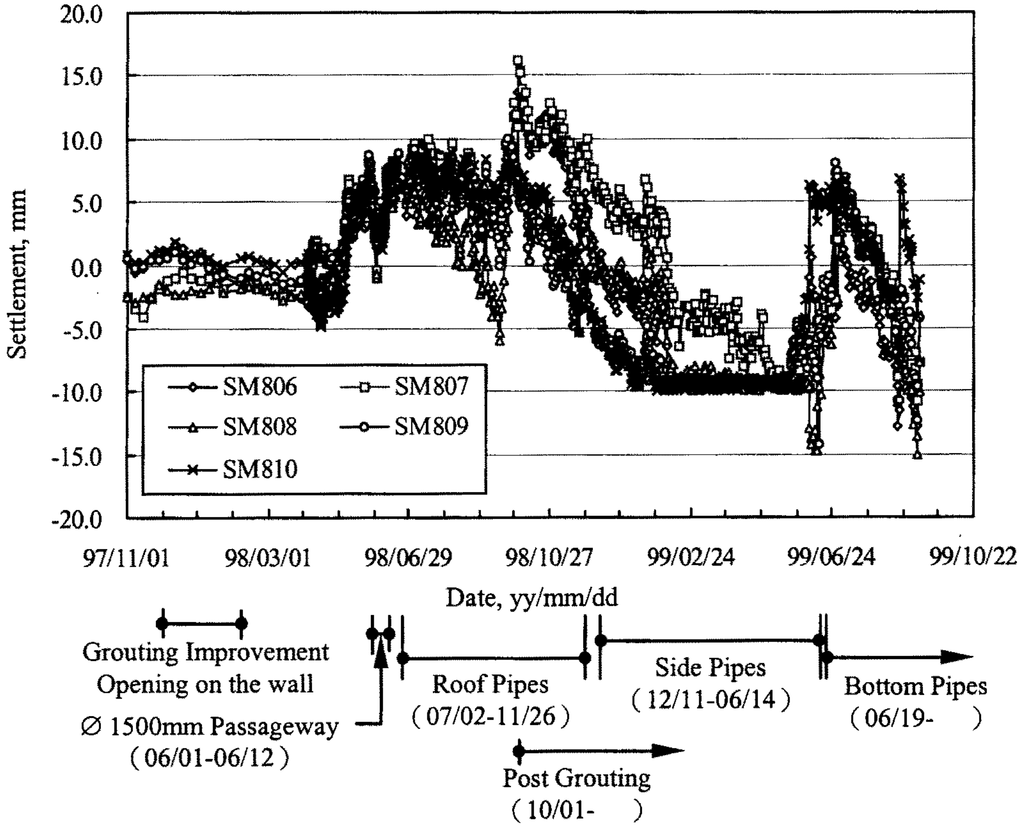


Fig. 14 Settlements of the Runway during Pipe Jacking

specialist subcontractors Komatsu Ltd and Iseke Poly-Tech, Inc of the project for providing the detailed working procedures. Many of the figures were either reproduced or modified from the figures presented in their method statements. Appreciation is due to Uemura Engineering Co., Ltd for the many motivative suggestions made in the design.

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