Analysis of cycle excavation and productivity of large-scale rock tunnel projects — lesson learned in Taiwan

Sy-Jye Guo

Abstract: Tunnel construction has become a major part of infrastructure development in Taiwan in the 1990s. This study compares and analyzes the productivity difference in the construction of two large-scale long rock tunnels, i.e., the Pengshan and Nangkang No. 2 tunnels. These two tunnels, which are 3.8 and 2.7 km in length, respectively, are part of the Taipei–Ilan Expressway. The cross section, construction method, and contract type are all similar. Both projects utilized multi-skilled working crews for improving productivity. However, essential differences in productivity and monthly progress were recorded. This study analyzes the key factors for these differences regarding the geological condition, working crews, equipment and facilities, and management approach. Based on the productivity data analysis of the two tunnels, the key points for productivity improvement of large-scale rock tunnel projects are then pinpointed.

Key words: cycle excavation, productivity, rock tunnel, Taiwan.

Résumé : La construction de tunnels est devenue une part majeure du développement d’infrastructures à Taiwan dans les années 90. Cette étude compare et analyse la différence de productivité entre la construction de deux long tunnels sous le roc à grande échelle, soit les tunnels de Pengshan et Nangkang no. 2. Ces deux tunnels sont respectivement d’une longueur de 3,8 et 2,7 km et font tous deux partie du projet de voies rapides de Taipei–Ilan. La section transversale, la méthode de construction, et le type de contrat sont tous similaires. Les deux projets utilisent des équipes de travail à compétences multiples pour une productivité améliorée. Cependant, des différences essentielles dans la productivité et les progrès mensuels ont été enregistrées. Cette étude analyse les facteurs clés de ces différences par rapport aux conditions géologiques, aux équipes de travail, aux équipements et installations, et à l’approche de gestion. Basé sur l’analyse des données de productivité pour les deux tunnels, les points clés pour l’amélioration de la productivité de projets de tunnels sous le roc à grande échelle sont donc identifiés.

Mots clés : cycle d’excavation, productivité, tunnel sous le roc, Taiwan.

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Introduction

In Taiwan, highway construction has always been a major part of infrastructure developments in order to meet the traffic demand. To build a highway network and improve the traffic connection between the western and eastern coasts of Taiwan, which are separated by the Central Mountain Range, a lot of major rock tunnel construction projects are critical and essential. The Taipei–Ilan Expressway, which connects the Taipei metropolis to the Lan-Young plain, is one of the major infrastructure developments currently undertaken in Taiwan. Several tunnel construction projects are included in this project. To improve the productivity of the tunnel construction, the Taiwan Area National Expressway Engineering Bureau requires that each local contractor must joint venture with a foreign contractor for transferring construction techniques, skilled labor, and management experience. Many foreign contractors, consultants, and workers from Japan, Switzerland, and South America have been involved in these tunnel projects, but their performance in terms of productivity has been quite different.

Few studies have focused on productivity performance of rock tunnel excavation. Oglesby et al. (1989) discussed technical development and human factors for productivity improvement. Wong et al. (1997) analyzed the performance of deep excavation in mixed-soil profiles for the Central Expressway in Singapore. Henderson (1982) studied the labor issues in tunneling in the 1980s. Ahrens (1991) focused on the management of underground works. Burleson et al. (1998) presented multi-skilled labor utilization strategies in construction in U.S.A. Most previous studies were either on general labor management in construction or on the soil properties of excavation. However, in rock tunnel construction, the most critical factor for project success is how fast the excavation can be safely completed. In other words, the focus is generally on the excavation productivity. The sooner the tunnel is completed, the sooner the highway can be opened to traffic.

The purpose of this study is to analyze the key factors that may affect the productivity of rock tunnel construction through comparison of the productivity and progress of two large-scale projects: the Nangkang No. 2 and Pengshan tun-

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S.-J. Guo. Department of Civil Engineering, National Taiwan University, Taipei, Taiwan 106.

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Table 1. Basic information on the Pengshan and Nangkang No. 2 tunnels.

	Nangkang Tunnel project	Pengshan Tunnel project
Contractor	Kong-Hsin Construction (Taiwan) joint venture with Mitsui (Japan)	Shan-Tai Construction (Taiwan) joint venture with Yi-Tai (Italy)
Contract work	Nangkang No. 1 and No. 2 tunnels bridge and pavement construction	Pengshan Tunnel bridge and pavement construction
Project start date	1994-09-16	1993-08-14
Duration	1730 calendar days	2190 calendar days
Total contract price	3 210 000 000 NT*	4 558 888 000 NT
Length of tunnel (m)		
Eastbound	2698 (No. 2)	3861
Westbound	2720 (No. 2)	3806
Cross section	Two-lane	Two-lane
Contract price of major tunnel	1 587 054 000 NT	2 240 839 000 NT
Major tunnel price/contract price	49.44%	49.39%

*31 NT = US $1 in 1999.

Table 2. Average monthly excavation progress in Taiwan.

Year	Total length of tunnels (m)	Average length of tunnels (m)	Number of tunnels	Average cross-sectional area (m^2)	Average excavation progress (m/month)
1972–1981	29 198	912	33	29.8	68.3
1982–1986	38 797	485	79	23.7	50.3
1987–1991	39 999	800	50	39.7	32.5
1992–	129 443	2353	116	63.4	58.0

nels. Both tunnels are part of the Taipei–Ilan Expressway project. The cross section, construction method, and contract type are similar, but the productivity of the two tunnels has been quite different. The average monthly progress of the Pengshan Tunnel was about 75 m, whereas that of the Nangkang No. 2 Tunnel was only about 56 m. Four major aspects — geological condition, working crew, equipment and facilities, and management approach — are examined in this paper to determine the key factors accounting for such differences. Based on the productivity analyses of the two projects, essential differences and key factors are identified to improve productivity in rock tunnel construction.

Project background

Table 1 summarizes the basic contract information for the Pengshan and Nangkang No. 2 tunnels. Both contracts include a major tunnel construction and some bridge and highway pavement works. The Nangkang No. 1 Tunnel, which is 456 m long, is shorter than these two tunnels and therefore is not included in this study.

The owner of these projects, the Taiwan Area National Expressway Engineering Bureau, required that the joint venture approach be adopted for contract procurement in these projects. Also, for productivity improvement, multi-skilled working crews were specified in both contracts. The architects/engineers of these projects, Sinotech Engineering Consultants Inc., designed a similar cross section for both tunnels. Both tunnels adopted the new Austrian tunneling method (NATM) for construction. Also, the contract price of each tunnel accounts for about 50% of the total contract price. Because of the similarities in construction of the two tunnels, it was possible to compare the monthly progress for productivity improvement.

Monthly excavation progress

The NATM has been applied in tunnel construction in Taiwan since the 1970s. The average excavation progress (AEP) for rock tunnel construction is summarized in Table 2 (Huang et al. 1998). To show the overall productivity of tunnel construction, the average excavation progress (in metres per month) in a period is calculated as follows:

$$[1] \qquad \mathrm{AEP} = \Sigma\,[(L_i/\mathrm{TL})\mathrm{MP}_i]$$

where L_i is the length of tunnel i, TL is the total length of the tunnels constructed during the period, and MP_i is the monthly progress of tunnel i.

Prior to 1991, most tunnels in Taiwan were designed for one-lane traffic, and thus the cross-sectional area was normally less than 40 m^2. The average monthly excavation progress in the 1970s appears to be better than in other periods. Two main reasons contributed to this result: (*i*) the involvement of Japanese consultants in the 1970s in assisting the contractors in the NATM techniques and (*ii*) the use of a bonus system for motivating the productivity of workers. In the 1980s, the average excavation progress declined. Although the complex geological conditions encountered on the sites may partly account for the slower progress, the declining productivity of the Taiwanese workers is undoubtedly another factor to be considered. Moreover, in the 1990s, tunnels of larger cross section were constructed; some tun-

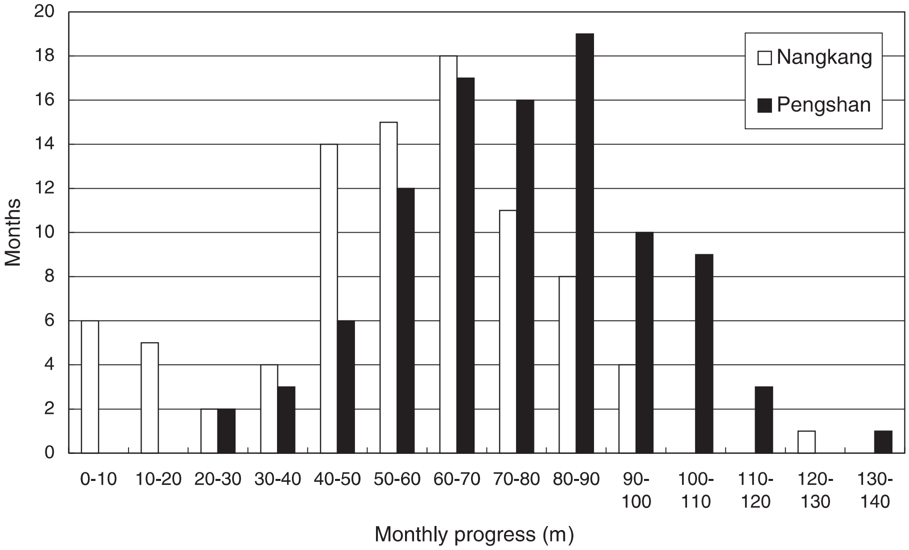


Fig. 1. Distribution of monthly excavation progress of the Pengshan and Nangkang tunnels.

Table 3. Average monthly excavation progress.

	Monthly excavation progress (m)				Overall progress (m)
	West exit		East exit		
	Eastbound	Westbound	Eastbound	Westbound	
Pengshan					
Average	69	75	86	77	75
Std. dev.	23	23	20	14	22
Nangkang No. 2					
Average	58	62	49	56	56
Std. dev.	22	26	24	27	25

nels were even required to accommodate three- or four-lane traffic. However, the development of automated excavation equipment greatly eases the difficulty for rock tunnel excavation. The average excavation progress for rock tunnels climbed to about 58 m per month.

Table 3 summarizes the average monthly excavation progress for the Pengshan and Nangkang No. 2 tunnels. A total of 98 monthly progress data (49 months) for the Pengshan Tunnel and 88 data (44 months) for the Nangkang No. 2 Tunnel have been collected. The excavation progress, which is usually considered as an indication of productivity performance, is the most important factor for tunnel construction. The data in Table 3 correspond to the excavation progress for the upper half section only. It should be noted that, in tunnel construction, once the upper half section is completed, the lower half section can easily be excavated with little safety concern. Therefore, the excavation progress of the upper half section is a critical factor in controlling the overall schedule and related management issues in tunnel construction.

There is a significant difference in the average monthly excavation progress of the two tunnels. The average monthly progress, over the past four years, of the Pengshan Tunnel is about 75 m, whereas that of the Nangkang No. 2 Tunnel is only about 56 m; this represents a distinct difference in productivity of 34% (75 vs. 56). Figure 1 shows the distribution of monthly excavation progress for the two tunnels. Using the chi-square (χ^2) test ($\alpha = 0.01$), it is observed that normal distribution governs the monthly excavation progress of both tunnels.

Compared with the average monthly excavation progress of 116 tunnels in Taiwan since 1992 (Table 2), the productivity performance of the Nangkang No. 2 Tunnel is approximately the average rate. However, the productivity performance of the Pengshan Tunnel is significantly better than that of the Nangkang No. 2 and other tunnels constructed in Taiwan since 1992. Although the NATM approach for rock tunnel excavation in Europe may yield a progress of about 100 m per month, it is difficult to achieve the same progress rate in Taiwan because of the complex geological conditions. The overall progress of the Pengshan Tunnel was about 25% ahead of the planned schedule in 1998. On the contrary, the Nangkang No. 2 Tunnel was about 14% behind the planned schedule. As a result of its outstanding productivity performance, the Pengshan Tunnel project was granted the Excellent Construction Project Award in 1998.

In addition to the aforementioned project background for the two rock tunnels, the geological condition of the Nangkang No. 2 Tunnel appears to be slightly better than the Pengshan Tunnel. Based on the rock mass rating (RMR) method (Bieniawski et al. 1993), Type VII, which usually consists of soft rocks with continuous joint and abundant underground water, is the most difficult type of rocks from the

Table 4. Percentages of various types of rocks.

	Type I	Type II	Type III	Type IV	Type V	Type VI	Type VII
Pengshan	0	1.08	9.65	32.73	38.13	18.41	0
Nangkang No. 2	0	0	0.2	62.86	25.45	11.19	0.3

construction point of view. On the other hand, Type I is the easiest one for excavation. The percentages of each type of rocks for the two tunnels are given in Table 4. Although a small portion of Type VII exists in the Nangkang No. 2 Tunnel, there is a larger portion of Type VI existing in the Pengshan Tunnel. Further investigation of the underlying causes for the progress difference of the two tunnels should prove valuable for productivity improvement in tunnel construction.

Cycle excavation and productivity

In tunnel construction, excavation process can be stopped as a result of unfavorable geological conditions or accidents. Under such circumstances, the monthly excavation progress will decrease significantly until the difficulties or damages are overcome. A productivity time analysis for cycle excavation can be utilized to reveal the efficiency for each task involved in each cycle. In such an analysis, those stoppages caused by unfavorable geological conditions and accidents are not included and only normal progress are collected and recorded. The length of each cycle excavation depends on the type of rocks being excavated.

In this study, the cycle time for each individual cycle excavation has been collected from the daily job site records, based on which the average cycle time for each task can be calculated. The average cycle times for each task of the two tunnels for types IV, V, and VI rocks are listed in Tables 5, 6, and 7, respectively. Since these three types of rocks account for about 90% of the composites of both tunnels, the other types of rocks are simply neglected in this study.

The average cycle length varies according to the type of rocks. For soft rocks such as Type VI, the average cycle length is usually shorter than the cycle length for Type IV or V because of safety concerns. To compare the average time spent of a cycle (ATC) for 1 m of progress, the total time of a cycle given in Tables 5–7 can be divided by the average cycle length:

[2] $$\mathrm{ATC} = \mathrm{TTC}/\mathrm{ACL}$$

where TTC is the total time of a cycle and ACL is the average cycle length.

The results are given in Table 8 and Fig. 2. As can be seen, for Type IV rocks, there is basically no difference in the productivity performance for the two tunnels. However, for types V and VI rocks, a significant productivity difference exists. The Pengshan Tunnel required about 7 to 8 h to complete 1 m of progress, whereas the Nangkang No. 2 Tunnel took about 11 h.

Table 5. Average cycle time for each task for Type IV rocks.

	Nangkang No. 2		Pengshan	
Task	Time (min)	(%)	Time (min)	(%)
Preparing and clearing	31.5	4.64	22.5	3.90
Drilling and blasting	127.3	18.73	95.0	16.49
Ventilating and muck out	134.5	19.80	150.0	26.03
Wire mesh setting	66.4	9.78	32.5	5.64
Steel rib setting	33.1	4.87	32.5	5.64
Shotcrete	144.5	21.27	115.0	19.96
Support tube setting	62.8	9.24	50.0	8.68
Rock bolt setting	79.4	11.69	78.8	13.67
Total time for a cycle	679.4	100	576.3	100
Average cycle length (m)	1.66	—	1.50	—

Table 6. Average cycle time for each task for Type V rocks.

	Nangkang No. 2		Pengshan	
Task	Time (min)	(%)	Time (min)	(%)
Preparing and clearing	55.0	5.3	15.9	3.2
Drilling and blasting	127.5	12.2	72.5	14.7
Ventilating and muck out	210.0	20.1	125.0	25.4
Wire mesh setting	75.0	7.2	31.4	6.4
Steel rib setting	62.5	6.0	35.0	7.1
Shotcrete	200.0	19.1	66.8	13.6
Support tube setting	95.0	9.1	22.0	4.4
Rock bolt setting	220.0	21.0	124.3	25.2
Total time for a cycle	1045	100	492.9	100
Average cycle length (m)	1.50	—	1.03	—

Table 7. Average cycle time for each task for Type VI rocks.

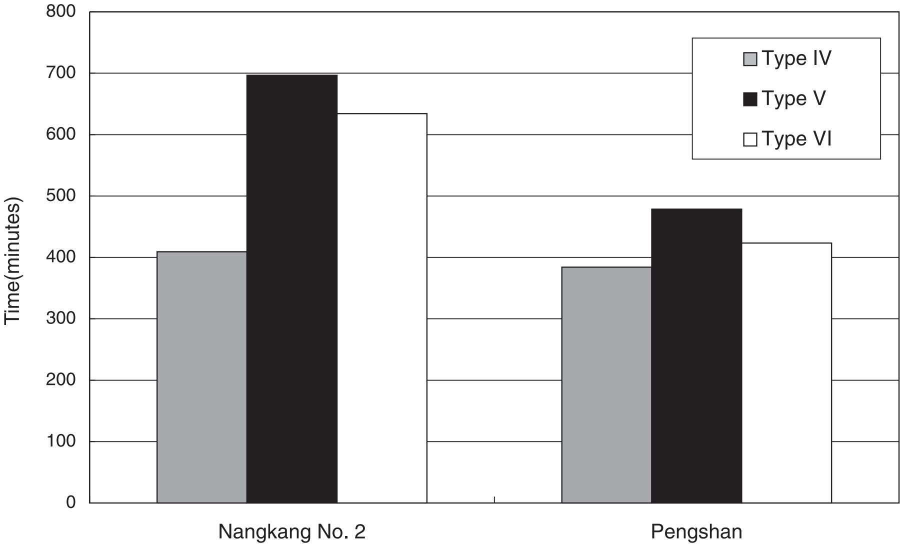
	Nangkang No. 2		Pengshan	
Task	Time (min)	(%)	Time (min)	(%)
Preparing and clearing	13.1	2.20	15.8	3.59
Drilling and blasting	100.9	16.93	65.5	14.87
Ventilating and muck out	95.6	16.04	147.9	33.61
Wire mesh setting	40.0	6.71	31.8	7.22
Steel rib setting	89.7	15.04	51.7	11.75
Shotcrete	134.1	22.48	65.3	14.83
Support tube setting	77.5	13.00	11.2	2.54
Rock bolt setting	45.3	7.60	51.0	11.59
Total time for a cycle	596.2	100	440.2	100
Average cycle length (m)	0.94	—	1.04	—

From the analysis of the results given above, three aspects of concern should be discussed. First, the average time needed per metre of cycle progress in the Pengshan Tunnel is significantly less than that in the Nangkang No. 2 Tunnel regardless of the type of rocks being excavated. This fact correlates well with the observation that the excavation productivity in the Pengshan Tunnel was better than in the Nangkang No. 2 Tunnel. Second, as can be seen from Table 8, for Type IV rocks, a difference of only about 25 min was recorded, but for types V and VI rocks, the Nangkang

Table 8. Cycle time per metre for each task (min).

	Type IV rocks		Type V rocks		Type VI rocks	
Task	Nangkang	Pengshan	Nangkang	Pengshan	Nangkang	Pengshan
Preparing and clearing	19.0	15.0	36.7	15.4	14.0	15.2
Drilling and blasting	76.7	63.3	85.0	70.4	107.4	62.9
Ventilating and muck out	81.0	100.0	140.0	121.3	101.7	142.2
Wire mesh setting	40.0	21.7	50.0	30.5	42.6	30.6
Steel rib setting	19.9	21.7	41.7	34.0	95.4	49.7
Shotcrete	87.0	76.7	133.3	64.9	142.6	62.8
Support tube setting	37.8	33.3	63.3	21.3	82.4	10.8
Rock bolt setting	47.8	52.5	146.7	120.7	48.2	49.0
Total time for a cycle	409.3	384.2	696.7	478.5	634.3	423.3

Fig. 2. Comparison of progress time per metre for the upper section.



No. 2 Tunnel needed about 3½ h (210 min) longer to complete one meter of cycle progress. In other words, only about two thirds of the time was needed in the Pengshan Tunnel for types V and VI rocks. Such a difference in productivity is the main reason for the difference in monthly progress performance. Third, for all the tasks involved in a cycle excavation, the shotcrete accounts for the primary time difference for the two tunnels. Other tasks such as rock bolt setting and muck out can also result in essential time difference, especially for Type V rocks. From the data analysis and comparison in Table 8, it is crucial that the causes of productivity difference be further investigated for productivity improvement.

Analysis of idle time

The average idle time for each metre of excavation progress can also be calculated from the daily excavation records for the two tunnel construction projects. The causes for idle time are classified as equipment breakdown, utility breakdown, wait for material, wait for equipment, blockout of access, cleaning the rebound, and handling of squeezing deformation. The idle times for each cause in various types of rocks are summarized in Tables 9–11. Other work stoppages caused by design/engineering and weather/rains have been excluded. It can be observed that for Type IV rocks, the difference in the idle time for the two tunnels is considered small. However, for types V and VI rocks, the idle time in the Nangkang No. 2 Tunnel appears to be about 40 min longer than in the Pengshan Tunnel. The major causes of the idle time include handling of squeezing deformation, equipment breakdown, and wait for material. The handling of squeezing deformation requires technical expertise and experience in rock tunnel construction. The contractors of the Nangkang No. 2 Tunnel did not perform as well as those of the Pengshan Tunnel.

Equipment breakdown is another essential factor for the idle time. Periodic maintenance and regular checks can insure the workability of excavation equipment, thereby reducing the idle time caused by equipment breakdown. Shortage of materials may be encountered in using shotcrete in tunnel construction. Insufficient supply of shotcrete in the Nangkang No. 2 Tunnel has resulted in a significant idle time and delayed the excavation schedule. The management of the facilities and equipment for the two tunnel projects will be discussed further in the next section.

Key points for productivity difference

To further investigate the causes of productivity difference in the construction of the two tunnels, field observation and expert interviews were conducted at both job sites. Based on

Table 9. Average idle time per metre of progress for Type IV rocks (min).

Cause of idle	Nangkang No. 2	Pengshan
Equipment breakdown	9.29	1.13
Utility breakdown	4.73	3.70
Wait for material	1.30	0.82
Wait for equipment	0.49	3.17
Blockout of access	0.98	0.29
Cleaning the rebound	0.00	0.00
Handling of squeezing deformation	8.48	9.69
Total	25.27	18.80
Idle time/cycle time	6.17%	4.89%

Table 10. Average idle time per metre of progress for Type V rocks (min).

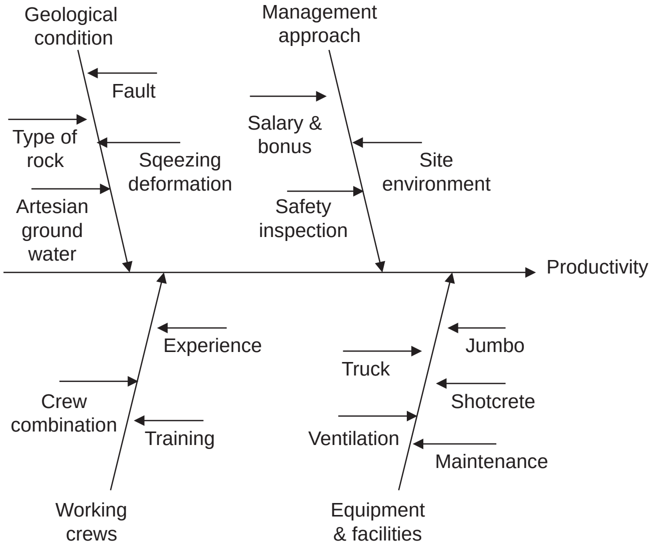
Cause of idle	Nangkang No. 2	Pengshan
Equipment breakdown	19.84	1.92
Utility breakdown	2.86	2.10
Wait for material	14.02	0.14
Wait for equipment	0.90	2.57
Blockout of access	0.00	0.78
Cleaning the rebound	0.00	0.21
Handling of squeezing deformation	15.62	3.94
Total	53.24	11.66
Idle time/cycle time	7.64%	2.44%

daily reports, meeting records, and other related documents of tunnel construction, four major causes for the productivity difference are identified: geological condition, working crews, equipment and facilities, and management approach (Fig. 3).

Table 11. Average idle time per metre of progress for Type VI rocks (min).

Cause of idle	Nangkang No. 2	Pengshan
Equipment breakdown	15.23	1.80
Utility breakdown	1.42	1.61
Wait for material	13.08	0.00
Wait for equipment	2.98	5.98
Blockout of access	0.00	0.00
Cleaning the rebound	0.00	0.00
Handling of squeezing deformation	12.68	5.08
Total	45.40	14.47
Idle time/cycle time	7.16%	3.42%

Fig. 3. Characteristics diagram for productivity difference of two tunnels.



Geological condition

Geological condition is a major cause of productivity difference in tunnel construction. Four key factors are identified in this regard: type of rocks, fault, artesian groundwater, and squeezing deformation. All these factors could significantly influence the productivity and speed of rock excavation. The distribution of various types of rocks for the two tunnels is shown in Table 4. In Nangkang No. 2 Tunnel, Type IV accounts for about 63%, Type V for about 25%, and Type VI for 11%. On the other hand, in Pengshan Tunnel, there are about 33% of Type IV, 38% of Type V, 18% of Type VI, and less than 10% of Type III. Although a small amount of Type VII exists in the Nangkang No. 2 Tunnel, the distribution of rock mass in this tunnel is comparatively better than that in the Pengshan Tunnel. Moreover, there are three faults existing in the Pengshan Tunnel. These faults need to be carefully handled to prevent accidents and work stoppage. Artesian groundwater and squeezing deformation are two other essential factors in tunnel construction, both of which can result in severe damage to excavation and to the safety of workers. Fortunately, these two factors did not cause much problems in the two construction projects.

Working crews

Tunnel excavation involves multi-tasks in each cycle progress. Typical tasks include preparing and clearing, drilling and blasting, muck-out, wire mesh setting, steel rib setting, shotcrete, support tube setting, and rock bolt setting, etc. Most of the workers in Taiwan specialize only in one or two tasks. Thus, a cycle progress requires several working crews to finish the jobs sequentially. A large amount of time may be wasted in waiting for the next crew to switch over. On the contrary, a multi-skilled crew can do all the tasks in a cycle. Thus, the excavation work can be continuously executed without the constraint of the workers' skill. The advantages of multi-skilled crews have been demonstrated in several previous tunnel construction projects. This is the main reason why the Taiwan Area National Expressway Engineering Bureau required multi-skilled crews for the two tunnels. In the Pengshan Tunnel project, multi-skilled workers from Columbia were employed. These workers and equipment operators with many years of experience had been working on tunnel excavation in various countries. On the contrary, in the Nangkang No. 2 Tunnel project, although the foreman from Japan was also multi-skilled with sufficient experience

Table 12. Crews of operators and workers.

	Foreman	Equipment operator	Operator assistant	Laborer	Total
Pengshan	1 (Columbia)	3 (Columbia)	1 (Thailand)	3 (Thailand)	8
Nangkang No. 2	1 (Japan)	2 (Thailand)	1 (Philippines)	4 (Thailand)	8

Table 13. Major differences of the equipment and facilities in two tunnels.

Equipment/facility	Pengshan Tunnel	Nangkang No. 2 Tunnel
Shotcrete	Wet shotcrete/jumbo arm	Dry shotcrete/human worker
	Capacity 6–8 m^3/s	Capacity 4–5 m^3/s
	Rebound amount 10–20%	Rebound amount 25–30%
Truck for muck out	Capacity 18 m^3 in tunnel	Capacity 12 m^3 in tunnel
	Capacity 12 m^3 to dump site	Capacity 12 m^3 to dump site
Ventilation	Capacity 42 m^3/s	Capacity 25 m^3/s
	1.8 m ventilating pipe	1.2 m ventilating pipe
Equipment maintenance	Regular maintenance in maintenance yard	Irregular maintenance in tunnel

in tunnel construction, the work force was mainly from Thailand and the Philippines and had little experience in multi-tasks operation.

The working crews for both tunnels are shown in Table 12. Both contractors did not employ formal training program in these two projects. The foreign workers with less experience need to improve their skills by working on the job site. From the case studies, it is observed that the Columbia workers are more experienced than the Thai workers. Although the owner did specify the requirement of multi-skilled crews for both contracts, the contractor of the Nangkang No. 2 Tunnel may have chosen to fulfill it only for the level of “foreman” rather than for “equipment operator” for cost-saving consideration. A valuable lesson learned from this study is that it is necessary to specify “experienced operator” in the muti-skilled crew for productivity improvement in future bidding of tunnel construction. A formal training program may also help to increase the productivity of foreign workers, especially Thai and Philippine laborers.

For both tunnels, two shifts of workers are arranged. The day shift worked from 7 a.m. to 7 p.m., and the night shift worked the remaining 12 h. The working hours are shifted every two weeks so that the two shifts can work on an equal basis. On the weekend of shift-changing, the day shift stops working at 7 p.m. on Saturday and is off until 7 p.m. on Sunday to continue the job as the night shift. The previous night shift stops excavation at 7 a.m. on Sunday to allow equipment maintenance and job site cleaning until the other shift starts again at 7 p.m. Each shift had a full day off to adjust the time difference during the shift-changing weekend.

Equipment and facilities

Both tunnels adopted the jumbo drilling machine for excavation. However, for muck-out, shotcrete, ventilation, and equipment maintenance, different equipment and facilities were utilized. Table 13 summarizes the major differences in the equipment and facilities. Experience has indicated that all these differences relate to the productivity difference in tunnel construction. The shotcrete method is a major factor affecting the productivity difference. The wet shotcrete proved to be much more efficient than the dry one used in the Nangkang No. 2 Tunnel. Also, the quality and amount of rebound can well be controlled in wet shotcrete. As a result of this study, the Taiwan Area National Expressway Engineering Bureau will specify wet shotcrete to be used in all future rock tunnel projects. The capacity of the truck relates to the speed of muck out in the tunnel. A higher capacity will reduce the time needed in the cycle progress. The Pengshan project utilized a bigger truck to facilitate the muck-out process. Ventilation is another vital factor affecting the workers in tunnel construction. A better ventilating system not only provides fresher air for the workers but also increases the productivity and efficiency of the workers. The ventilation facilities of the Pengshan Tunnel were much better than those of the Nangkang No. 2 Tunnel. Productivity improvement was then possible for workers in the Pengshan Tunnel project. Finally, since both contractors did not provide additional equipment, a regular equipment maintenance program in the Pengshan project does help to reduce the idle time due to equipment breakdown. In the Nangkang No. 2 Tunnel project, equipment maintenance in the tunnel was concluded to be inadequate and resulted in more equipment breakdown than the Pengshan Tunnel.

Management approach

Three aspects of management can be identified to account for productivity difference. The first is the salary and bonus system. According to the survey of the workers, the monthly salary of Columbia operators was about 75 000 NT, while the Thai and Philippine workers were paid less than 30 000 NT per month. Although a bonus system was designed in the Nangkang No. 2 Tunnel project so that each worker could get an extra 1000 NT per metre for monthly progress greater than 50 m, the effect of this bonus system was not significant. Since the monthly progress depended mainly on the geological conditions, the workers of the Nangkang No. 2 Tunnel worked harder to get more bonus only when encountering Type IV rocks; for Type V or VI rocks, the bonus motivation totally failed. Instead of implementing a bonus system, the Pengshan Tunnel provided well-organized living dormitories and entertainment facilities for foreign workers. Improving living environment proved to be more efficient than a monetary bonus in this case study.

The second management aspect is the overall working environment on the job site, such as the lighting in the tunnel, the leveling of the working road, the drainage of incoming water, and the dryness of the road. All these factors would influence the productivity performance and are dependent on the management approach of the contractor. In this regard, the contractors of the Pengshan Tunnel created a much better working environment than the Nangkang No. 2 Tunnel and thus a better productivity performance became possible.

The third aspect is safety and health inspections. According to the records of safety and health inspection, the Nangkang No. 2 Tunnel received nine severe and two minor violations, while the Pengshan Tunnel received only two severe and one major violations. A payment deduction was issued for any safety and health violation in these two tunnels to ensure that the contractors did care about the safety and health issues on the job site. The contractor of the Pengshan Tunnel did pay more attention to the safety concern than the contractor of the Nangkang No. 2 Tunnel and thus created a safer working environment for productivity improvement. During the construction period, there was no major accident in the Pengshan Tunnel. However, a fatal accident occurred in the Nangkang No. 2 Tunnel. The falling rocks hit the crew and resulted in one death and one severe injury of the Thai workers. The safety records and lost time injuries of these two tunnels are shown in Table 14.

Table 14. Safety records and lost time injuries.

	Nangkang No. 2	Pengshan
Accident	2	2
Death	1	0
Disable injury	2	3
Total lost time (man-days)	138	42
Total employment (man-days)	113 541	192 394
Total employment (man-hours)	943 018	1 997 749

Discussion

Tunnel construction has become a major part of infrastructure developments in Taiwan since the 1990s. About 70 rock tunnels are currently in design for the High Speed Rail Project and the highway network in Taiwan. The total length of these tunnels is about 180 km. Most of these rock tunnels are designed using the new Austrian tunneling method. Several of these are large-scale rock tunnels with a length of more than 5 km. The productivity performance of these large-scale long tunnel excavations will significantly attribute to the success of these infrastructure projects. All the experience learned in previous tunnels should be examined carefully to improve the productivity performance of future projects.

From the owner's point of view, these two tunnels were both awarded based on the lowest bid. Sinotech Engineering Consultants Inc. prepared the same unit price for various types of rock excavation. The bid price for the Pengshan Tunnel was about 78% of the owner's budget (awarded in 1993). However, in 1994, the bid price for the Nangkang No. 2 Tunnel was only about 70% of the owner's budget. During these periods, the construction market in Taiwan was very competitive and many contractors had to decrease their profit in order to survive. At the time when the Nangkang No. 2 Tunnel was awarded, the owner may have thought that with the same productivity and quality the money would be saved. However, this study revealed that the monthly progress of the Nangkang No. 2 Tunnel was about 20 m less than that of the Pengshan Tunnel. Interviews with representatives of the owner confirmed the following comment:

"The money saved in the Nangkang No. 2 Tunnel is not worthwhile. If this project could be re-awarded to another contractor, the owner would be willing to pay more for the productivity and effectiveness observed in the Pengshan Tunnel project."

Concluding remarks

This study compared and analyzed the productivity differences of two large-scale long rock tunnel construction projects, the Pengshan and Nankang No. 2 tunnels. Both tunnels were part of the Taipei–Ilan Expressway project. The cross section, construction method, and contract type were all similar. However, essential differences in productivity and monthly progress were recorded. This study classified the key factors for these differences as geological condition, working crew, equipment and facilities, and management approach. Based on the productivity data analyses and comparison of these two tunnels, the following points are suggested for productivity improvement of large-scale rock tunnel projects:

(1) The employment of multi-skilled crews was effective for productivity improvement in rock tunnel construction. To further improve the productivity, experienced operators should also be specified in the multi-skilled working crew. In this case study, the Italian/Columbia crew performed much better than the Japan/Thai crew.

(2) Based on the cycle time analysis, the shotcrete process was identified as a major influence factor for excavation productivity. In the NATM process, the wet shotcrete with jumbo arm proves to be performing more efficiently than the dry one.

(3) A regular equipment maintenance yard and sufficient capacities for ventilation and muck out are also essential to the productivity of tunnel construction. Although the equipment and facilities may cost more, the benefits of productivity improvement and schedule progress justify the cost.

(4) A well-managed site environment can increase the motivation of workers and the productivity of various equipment. In this case study, the contractor of the Pengshan Tunnel has demonstrated the productivity difference through better management of the site environment. The experience learned in this study is useful for future projects of similar nature.

The owner of these projects, the Taiwan Area National Expressway Engineering Bureau, is responsible for the construction of the highway network in Taiwan. The results of this study provide detailed insight and valuable suggestions for future tunnel construction. Tunnel construction plays an important role in infrastructure development in many countries, especially in Europe, Japan, Taiwan, and America. For large-scale long tunnels, the productivity of excavation is undoubtedly the most critical issue for the success of the entire project. The productivity performance of the international joint-ventured contractors in this study can be a valuable lesson to other owners and contractors who may be involved in rock tunnel construction projects at present or in the future. The productivity analysis and comparison of this study also provide a useful reference for future large-scale rock tunnel projects in the world.

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