

THE REPLACEMENT OF PILOT TUNNEL TBM RING GEAR IN HSUEHSHAN TUNNEL

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ABSTRACT

The ring gear of Pilot Tunnel TBM (Tunnel Boring Machine) is the end gear of TBM cutterhead (CHD) torque transmission series, jointed with TBM CHD through CHD adapter & clamp ring, and drives TBM CHD to bore via torque transmission of 6×160 kw electrical motors and gear reducers. The reason to replace TBM ring gear bases on more than one tooth of ring gear has been broken by some complex factors. If not to replace it in time, consecutive and serious damages on pinions & main bearing will cause a lot of progress and cost loss. The key activity to replace TBM ring gear is how to remove TBM CHD weighted 40 Ton and how to position ring gear correctly. It will be easy to have a gantry or mobile crane to do it in factory or some open spaces. In fact, TBM is always enclosed with rock during making tunnel process and has no extra room for storing CHD & ring gear absolutely. Therefore, constructor has to create such room in tunnel and find appropriate measures for the key activity. There are two times to replace TBM ring gear in Pilot Tunnel within approx. 7 km TBM boring length and 13 years' Pilot Tunnel construction. It shows different localized room for such activity each time.

Keywords: TBM, ring gear, cutterhead (CHD), gear reducer, pinion.

INTRODUCTION

The 12.9km long Hsuehshan Tunnel is the critical path projects in the Taipei-Ilan expressway construction project. After considering the geological structures, environment protection, safety, the length of the tunnel and cross section, engineering costs, construction duration requirement and improvement of technology, the recommendation suggested that TBM construction be the method adopted. To cope with the possibility that a number of faults would be encountered, for avoiding rock fall and miry ground that might cause injury to workers and machine alike, the double shield type of TBM used in excavating the channel tunnel was selected for construction.

This long-suffering double shield TBM, the first adapted TBM in Taiwan, The Robbins Company (TRC) made (No.153-269), 4.819m ϕ , used in making Pilot Tunnel since Dec., 1992, had finished its given job to carry ceaseless confidence and expectance of Hsuehshan Tunnel Construction (HTC) team through firmly to the end in Dec., 2003. In a retrospective synthesis, Pilot Tunnel TBM encountered 13 times to fall in geological

stuck, 2 times to replace TBM ring gear, one time to reform full steel structures of CHD neck of TBM, 3 times to take CHD apart from TBM for above two activities, one time to replace TBM tail shield, one time to replace six rotors of TBM six main drive motors, 10 times to replace pinions of gear reducers, 2 times to replace inner planetary gears of gear reducers, several times to replace main thrust, auxiliary thrust cylinders and countless times to modify TBM to cope with adverse geological structure within 11 years' TBM boring length: 5,168m of full face boring and 1,663m of invert cutting, 6,831m in sum total.

Among all above mentioned activities of replacement, the most time-consuming and cost-consuming event is the replacement of TBM ring gear. It is not a merely mechanical work. As we know, a working TBM is always enclosed with rock during making tunnel process and has no extra room for taking CHD apart & storing ring gear absolutely which are essential activities for the replacement of TBM ring gear. Therefore, tunnel engineer has to create safely enough room in the tunnel; mechanical engineer has to find appropriate measures

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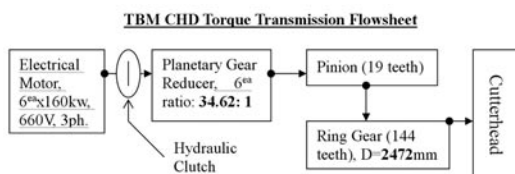
for handling all mechanical works; electrical engineer has to do all wiring works to offer lighting and electrical power to all civil and mechanical activities. In brief, a successful replacement of TBM ring gear needs a perfect cooperative effort among tunnel engineer, mechanical engineer and electrical engineer.

There are two times in total to replace TBM ring gear in Pilot Tunnel within 6831m TBM boring length and 13 years' Pilot Tunnel construction. The first time to replace TBM ring gear in Pilot Tunnel is in April, 2000 and the best selected location (Sta. 38k+921.45) is at designed A cavern of #3 Ventilation Interchange Station. The second time to replace TBM ring gear in Pilot Tunnel is in Nov., 2002~Jan., 2003 and the inevitably selected location (Sta. 35k+316.26) is at a few hundred meters ahead of #2 Ventilation Interchange Station. It shows different localized room for each replacement.

WHY TBM RING GEAR MUST BE REPLACED

The ring gear of Pilot Tunnel TBM is the end gear of TBM CHD torque transmission series, jointed with TBM CHD through CHD adapter & clamp ring, and drives TBM CHD to bore via torque transmission of 6 160 kw electrical motors and gear reducers. The following [TBM CHD Torque Transmission Flowsheet] shows torque flow clearly; all components composed of torque flow must always keep in good function during torque transmission process, no one is exempted.

For instance, if some teeth of gear are broken on planetary gear reducer or pinion or ring gear, then not only torque transmission will break down (i.e. TBM shut down) immediately, but also the fallen out fragments of broken teeth are capable to insert into the accurate clearance between any two normal contact teeth which are doing torque transmission and cause them irrecoverable serious damage. If the broken gear can't be replaced in time, more and more fallen out fragments of successive broken teeth will break continually the remaining teeth of gears and even invade to damage main bearing until TBM shut down



catastrophically. Hence, for the long-term advantage of TBM boring, once any broken tooth of gear is found, the subsequent replacement of broken gear must be scheduled cautiously and immediately, especially to the most time-consuming and cost-consuming replacement of TBM ring gear.

In fact, Pilot Tunnel TBM (see Fig.1 ~ Fig.4) is a modern, complicated and double-shielded tunnel making machine, in addition to TBM CHD torque transmission system, ZED system, electrical power system, water supply and cooling system, hydraulic system, pneumatic system, PLC system, ventilation system, safety monitoring system, emergency lighting and power supply system, transportation system and back-up system, each system of them does essential matters with TBM boring. To replace the worn or broken parts in these systems to keep TBM boring is the same as important as to replace TBM ring gear to keep TBM boring, even though the former is much easier than the latter. Hereinafter, we will focus on two replacements of Pilot Tunnel TBM ring gear in Hsuehshan Tunnel.

COMMON PROCEDURES FOR TWO REPLACEMENTS OF TBM RING GEAR

Most procedures for two replacements of TBM (TRC made, No.153-269) ring gear are common except the procedures to decide the localized size of disassembly chamber, the pattern of heavy-duty lifting equipment, the method to take CHD apart from TBM and to fix CHD safely, the way to transport ring gear (2472mm ϕ , 2190kg) and the place to store it. The common procedures are mostly related to mechanical job which working sequences are strictly specified as different model of TBM by TBM manufacturer. The user shall follow the service manual, enclosed drawings and recommendation of TBM manufacturer to do formally the replacement of TBM ring gear step by step. We shall list all items and its basic requirements in relation to the replacement of TBM ring gear as follows but not go too far in explanation of mechanical details for the sake of deviation from main topic:

Preliminary Procedure Section 1: Disassembly Chamber

The basic recommendation is the TBM will remain stationary during this procedure since there must be approximately six meters in front of TBM for parts storage. This is opposed to moving the TBM forward and

afterward which would require the placement of invert plates and rail each time the TBM would be moved forward. Also it will prevent the removal of the plates, rewinding of the high voltage cable, water hose and stuffing the incoming vent line back into the cassette each time.

The height of the hoist beams in this chamber would be determined once a 30 ton hoist is chosen or a gantry crane. There must be at least 60cm of clearance between the hook and the top of the shield. The horse beams installed would have to be able to deal with a maximum lift of 45 tons. The chamber should be shotcreted and as water tight as possible.

The hoist beams would extend 2.5 m behind the forward shield. This will facilitate the cutterhead adapter lifting device and give appropriate structure for the heavy lifts.

Once the operation is complete it would be possible to pour concrete gripper pads through this section, to assist the TBM start up.

Weights of lifts:

Cutterhead with cutters	89,000 lbs (40,455 kg)
Ring gear	4,819 lbs (2190 kg)
Cutterhead adapter with main bearing	Approx. 15 tons

Preliminary Procedure Section 2: Miscellaneous Items

1. Ring gear must fit through the back up sections. A template should be made and passed through. Any interference must be corrected.
2. A transport boogie must be designed to transport the gear from the portal to the 3 ton hoist and into the by pass tunnel.
3. The by pass tunnel must be enlarged to allow passage of the ring gear to the chamber. A monorail should be installed to assist in transportation.
4. All tools and materials must be available at the time of disassembly.
5. Proper welding procedures must be followed and each welder should be made aware of them before welding on TBM, ie...ground cable must be on the piece being welded.
6. Each part will be properly cleaned before being installed on TBM. Cleaning materials must be available, especially a non flammable solvent, since



Fig.1 TBM & operator console in TRC, USA



Fig.2 Final inspection of TBM before launching



Fig.3 TBM back-up system & Pilot Tunnel



Fig.4 Layout of Main Tunnels & Pilot Tunnel

welding, torches and air arc's will be used in a confined space.

7. Proper safety procedures will be used and the required equipment available at all times during the working shifts.
8. Since we are working with the "heart" of the TBM, cleanliness is of utmost importance. Access to working area should be limited to the people working on the job and or inspectors of a limited number.
9. All "flag notes" on the Main Bearing Assembly drawing will be adhered to, strictly. Any deviation will result with the piece being dismantled and installed correctly.

Preliminary Procedure Section 3: Tool List (omitted)

Detailed Procedures for Removal of Main Drive Motors and Gear Reducers

The purpose of these procedures to remove six main drive motors and gear reducers from inside of TBM prior to the integral removal of ring gear, main bearing and CHD adapter is to prevent damage from ring gear and to save time on removal & installation of this heavy integral set.

- (1) Major tool required: (omitted)
- (2) General mechanical tools required: (omitted)
- (3) Special tools and accessories: (omitted)
- (4) Miscellaneous equipment required: (omitted)
- (5) Items to be removed from the left side of TBM conveyor:
 - * Remove accumulators and place on top of hydraulic valve rack.
 - * Disconnect necessary control cables and lift PLC box onto top of conveyor.
 - * Remove ventilation duct from conveyor frame. (This is to be removed from the CHD support back to the probe drills.
 - * Remove access ladder into CHD (remove MOYNO pump if required).
 - * Weld spreader bar on cross brace of erector and remove.

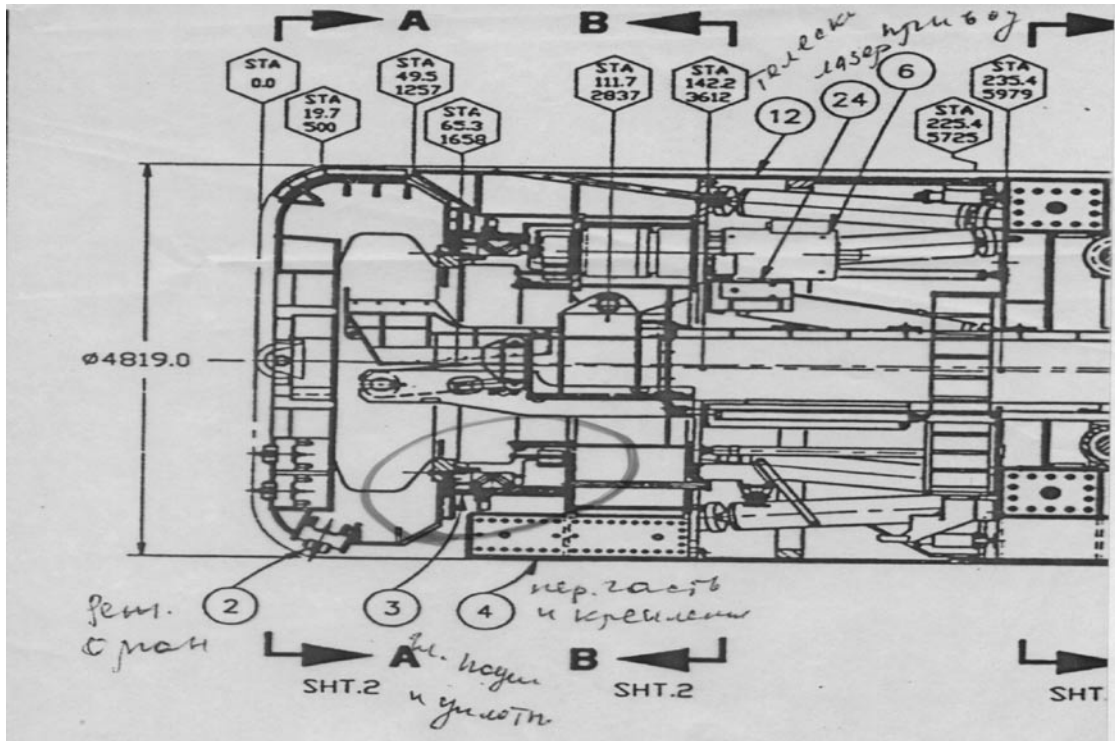
(6) Items to be installed and disconnected:

- * Install 5 ton trolley and beam.
- * Install steel beams over propel cylinders to create a working platform.
- * Label and disconnect hoses from motors and gear boxes.
- * Disconnect electric motors.
- * Pull back and tie up miscellaneous hoses and cables for more working space around motors and gearboxes.
- * Install additional trolley on 3 ton service beam (if needed).
- * Weld lifting eyes in forward shield (center above motors).
- * Remove inching unit from M2 and place on top of conveyor (label all hoses).
- * Other items that may have to be removed: conveyor retract chain guard, conveyor retract control valve, temposonic cylinders.

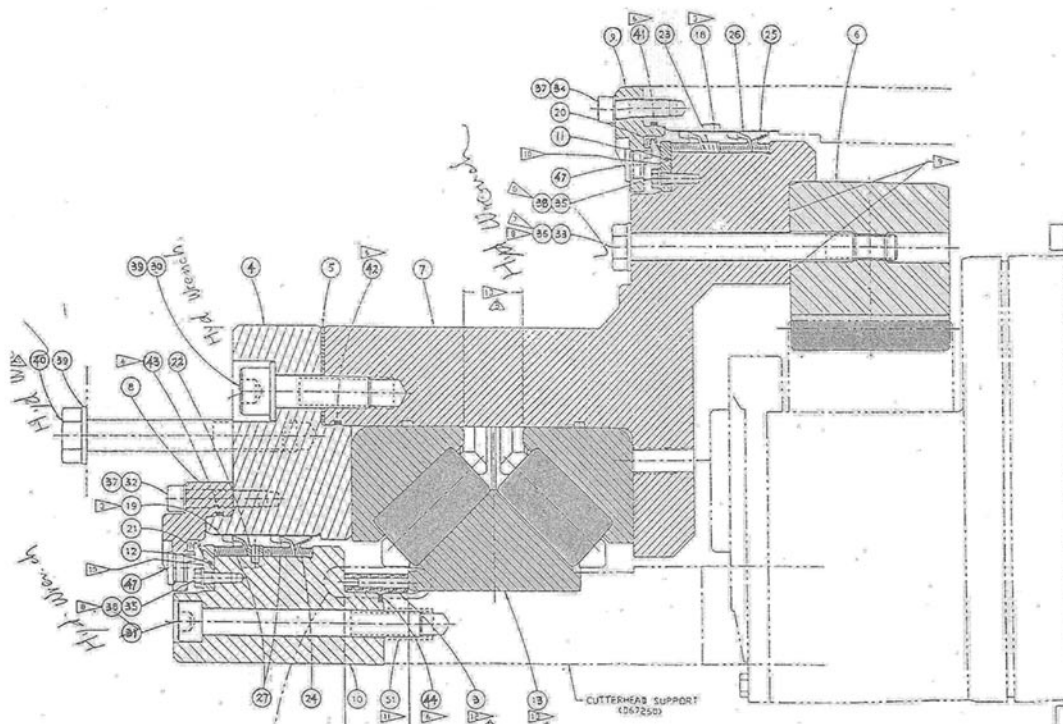
Detailed Procedures of Replacement of TBM Ring Gear with Enclosed Dwg.1 & 2

1. Prepare all tools and materials required from tool list supplied.
2. Complete enlarging by pass tunnel and excavation in front of TBM as required. It would be very useful to also have a monorail system in the by pass tunnel for transporting gear into chamber.
3. Install two 30 ton lifting hoist or one 60 ton gantry crane (if available) in chamber.
4. Insure new ring gear will pass through back up system to entrance of by pass tunnel. Make a template of wood or other light material to verify. Remove or re-support structure as needed. This basic plan is to remove required pieces from TBM and move forward in the chamber and support pieces to free up hoist for further work.
5. Remove shroud from top of forward shield (if exist).
6. Cut two 30cm slots in top of forward shield to allow hoist chains to get as close to main bearing assembly as possible.
7. Weld two 30 ton pad eyes to CHD at the centerline of hoist beams. Exact location was determined at the

- time of installation.
8. Connect hoist to CHD and partially take the load with both hoist. Shackles must be rated for lifting weight.
 9. Remove CHD retaining bolts, item #40 (this one and the following item #number refer to Dwg.2), HHCS M36 x 240, using hydraulic torque wrench and 6 point socket.
 10. Install 12 M36 x 500 studs in bolt holes to control CHD as it comes off of the pilot.
 11. Using two 15 ton hydraulic jacks, push CHD free of pilot. Gain control of CHD with hoist and move to forward section of tunnel. Support CHD using rock bolts or beams to hold in place. Unhook hoist and move back to TBM. Remove studs from CHD adapter and save for future use during assembly.
 12. Remove muck ring using pad eyes and the hoist. Store with CHD.
 13. Remove muck chute hopper using pad eyes and hoist. Store near CHD.
 14. Remove outer V-housing retaining bolts, item #8, M20 x 90 SHCS.
 15. Install 12 M20 x 300 studs in bolt holes to control pieces as it is removed.
 16. Weld two 1 ton pad eyes on V-ring housing under centerline of hoist. Remove housing and place near CHD, vertically.
 17. Remove outer clamp ring, item #12, retaining bolts, M20 x 90 SHCS.
 18. Install twelve M20 x 300 studs and remove ring. Store out of the way.
 19. Remove outer seals, item #22, #24 and #27. Store on back up section for later inspection.
 20. Remove outer seal carrier, item #10, retaining bolts, M30 x 260 SHCS.
 21. Install twelve M30 x 300 studs.
 22. Weld two 5 ton pad eyes onto carrier under centerline of hoist. Remove outer seal carrier and store forward in tunnel.
 23. Remove inner seal ring, item #9, retaining bolts item #34 and #37, M20 x 70 SHCS.
 24. Install 8 M20 studs.
 25. Weld two 1 ton pad eyes onto inner seal ring and remove. Move forward and store.
 26. Remove inner clamp ring, item #11, retaining bolts, item #35 and #38, M12 x 35 HHCS.
 27. Install 6 M12 studs and remove ring. Move forward and store.
 28. Remove inner seals, item #23, #25 and #26. Store on back up section for later inspection.
 29. Loosen, but do not remove clamp ring, item #4, retaining bolts, item #30 and #39, M36 x 120 SHCS. This is to relax the preload of the main bearing.
 30. Weld two 30 ton pad eyes to CHD adapter, item #7, under the centerline of the hoist. Use extreme caution when welding Ground lead must be on the piece that is being welded.
 - 30A. If a special lifting adapter is being used, attach it to CHD adapter under centerline of hoist.
 31. Install four 15 ton hydraulic jacks between CHD support and back side of CHD adapter. Access is through gear box holes #1, #3, #4 and #6.
 32. Take the weight of the CHD adapter with the hoist. Carefully and slowly extend hydraulic jacks evenly until main bearing is clear of the shaft. Avoid cocking the adapter as it comes off. Depth micrometers must be used to control the movement of the bearing and adapter is perpendicular and parallel.
 33. Move bearing and adapter assembly forward far enough in the tunnel to allow the old ring gear to be laid down in the tunnel, once removed. Brace and support CHD adapter assembly. Remove hoist.
 34. Remove ring gear, item #6 retaining bolts, items #33 and #36. Install eight M30 studs to control ring gear as it is removed.
 35. Bring new ring gear into chamber and install.
 36. Re-assemble in reverse order leaving the CHD off.
 37. Replace pieces cut out of forward shield to facilitate the hoist access.
 38. Install drain holes in CHD support.
 39. Install CHD.
 40. Install gear reducers and motors.



Dwg.1 Vertical section of Pilot Tunnel TBM, the area in red circle is magnified as Dwg.2



Dwg.2 Magnification of Main Bearing (green & brown), Ring Gear (yellow), Pinion (purple), etc...

THE FIRST REPLACEMENT OF PILOT TUNNEL TBM RING GEAR

Background Description

- (1) One broken tooth on TBM ring gear (see Fig.5,6) was found by TRC superintendent in 5 Aug., 1994 after taking out No.5 main drive electrical motor and gear reducer, this activity was one of TBM CHD torque 33% up enhancement program. This program included the replacement of 7 rotors (one for spare) in main drive motors for keeping max. torque existence longer and the replacement of 7 sets (one for spare) planetary gears in gear reducers for promoting reduction ratio of gear reducers from 26.05:1 to 34.62:1 to increase 33% of TBM torque for boring strugglingly under adverse geological structure. At that time, TBM encountered the 7th stuck and geological structure (Chingyin Fault) was very bad. In fact, it was not the right place and right time to replace TBM ring gear. Furthermore, by Dye Penetrate Test and Magnetic Powder Flaw Test, we assured only one broken tooth on TBM ring gear. Finally, we decided to grind the profile of broken tooth for not contact with normal teeth of pinions to prevent from further damage and resume TBM boring right after TBM got out of the 7th stuck until suitable geological structure coming.
- (2) The position of TBM CHD at the 10th geological stuck (Dated 5 Feb., 1996) is Sta. 39k+079 which is closed to the designed A cavern of #3 Ventilation Interchange Station. In addition to taking a few years to do detour tunnel (which started from middle, left side of TBM back-up system and created enough space to allow backhoe, loader, locomotive and muck car to work inside for speeding up the tunnel progress) to solve adverse geological problem in front of TBM and to reduce the stuck times of Pilot Tunnel TBM, we also consider the designed A cavern of #3 Ventilation Interchange Station (see Fig.7) is a ideal and ready-made location to replace TBM ring gear, not only to save the time and cost to create a new room for the replacement of TBM ring gear and partial shotcrete backfill of this room later, but also the transportation paths of 60 ton gantry crane components, TBM ring gear with its accessories and new tail shield plates can be easy to arrange from detour tunnel or Northward Tunnel.
- (3) The new non-mechanical-notch TBM ring gear with its accessories reimbursed by TRC was ready in RSEA warehouse since 1995. When one

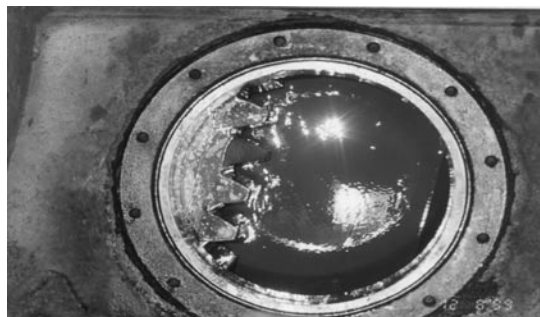


Fig.5 One broken tooth of TBM ring gear



Fig.6 Broken fragments of ring gear & pinion



Fig.7 The first replacement of TBM ring gear



Fig.8 Dismantled TBM ring gear & main bearing

broken tooth of TBM ring gear was observed at Sta. 39k+818 (TBM commenced full-face boring from Sta. 40k+159) in 5 Aug., 1994, TBM timer showed 212.3 hr only. In such a short TBM boring length and running hours, it was no other acceptable reason to explain why the tooth of ring gear broke except existed mechanical problem of ring gear. Through FEA studies of ring gear tooth, TRC concluded that the tooth failure was caused by one or a combination of the following: (a) Manufacturing defects such as grinding step (mechanical notch) and non-uniform case (metallurgical notch). (b) Very low cycle fatigue (1~1000 cycles). (c) Overload due to non-uniform load distribution along the tooth flank from gear reducer deformation at peak clutch torque.

Carry Out the First Replacement of TBM Ring Gear at Sta. 38k+921.45, TBM Timer: 617.40 hr

1. Disassembly Chamber: (at A cavern of #3 Ventilation Interchange Station)

1.1 Geological description:

- (a) The rock of excavation face: mainly consist of gray to grayish black fine to medium grained quartzitic meta-sandstone, intercalated with thin layers of carboniferous shale or argillite, therein the bedding were well developed, lots of cross bedding were also observed.
- (b) Structure condition: no fault or shear zone observed; bedding attitude measured as N15~30E / 15~20SE; the attitude of 2 sets of open joint measured as: N10W~10E / 70~80W , N80W / 70 ~ 80NW.
- (c) Groundwater condition: ooze,
- (d) Rock Mass Rating (RMR) : 22 to 46

1.2 Construction period and created concaved area:

- (a) Construction period of disassembly chamber takes about six months, one reason is geological factors which need more rock bolts and shotcrete to make up fissures and invasion of strata, the other reason is the construction of this chamber is not on the critical path of HTC; therefore, manpower and equipments are not enough to shorten its construction period until March, 2000.
- (b) Created concaved area reaches to 14m long x

12m wide. The center line of this area matches with the axis of Pilot Tunnel TBM for easy to do the subsequent replacements correctly.

2. Assemble 60 ton and 10 ton Gantry Cranes in Disassembly Chamber:

- (a) Build 10 1m x 1m x 1.5m concrete foundations for 10 structural H250 columns of gantry cranes in disassembly chamber to fit 9.8m span and 14m traveling length of these cranes.
- (b) Move all components of 60 ton and 10 ton gantry cranes into disassembly chamber from the way of Pilot Tunnel and detour tunnel carefully.
- (c) Use heavy duty forklift and special designed hydraulic working platform to erect 60 ton and 10 ton gantry cranes in disassembly chamber safely. It takes about 60 days to finish (a)~(c).
- (d) Secure the erected structures of gantry cranes by adding essential supporting structures against surrounding rock wall to prevent it from shaking during heavy loading for safety.

3. Bring New Ring Gear in and Broken Ring Gear out of Disassembly Chamber:

- (a) A template is made and passed through Pilot Tunnel and detour tunnel. Any interference is corrected prior to bringing new ring gear (see Fig.7, at the bottom) into disassembly chamber.
- (b) Broken ring gear is useless at all, hence, it is cut to pieces for easy to move out of tunnel and discard. We also find several lightly damaged teeth on this broken ring gear and #3 & #4 broken pinions must be changed with this replacement of TBM ring gear.

4. Move CHD out of TBM, Secure It Safely and Commence the First Replacement:

- (a) Follow previously mentioned "Detailed Procedures of Replacement of TBM Ring Gear with Enclosed Dwg.1 & 2" to release CHD from TBM correctly. Use 60 ton gantry crane to lift CHD up carefully and shift it to right side of disassembly chamber (see Fig.7).
- (b) Upright TBM CHD and secure it by adding effective supporting structures (see Fig.7).

- (c) Use special lifting adapter (see Fig.7, in the center) to lift, move out the integral set (see Fig.8) of ring gear, main bearing and CHD adapter from TBM very carefully. Shift it to left side of disassembly chamber and commence to replace TBM ring gear in accordance with "Detailed Procedures of Replacement of TBM Ring Gear with Enclosed Dwg.1 & 2".

Based on statistic, the required time interval from moving CHD out of TBM, the integral set of ring gear, main bearing and CHD adapter out of TBM, replacing broken ring gear and so on, to rejoin CHD to TBM under supervision of TRC is one month only (2 April, 2000~1 May, 2000). It shows very clearly, the time-consuming activity within the first replacement of TBM ring gear is to make disassembly chamber. By the way, we omit the removal of 6 main drive motors and gear reducers out of TBM in this event. It makes some difficulty to move the integral set of ring gear, main bearing and CHD adapter out of TBM and to rejoin it to TBM, but it is helpful to the progress of detour tunnel.

THE SECOND REPLACEMENT OF PILOT TUNNEL TBM RING GEAR

Background Description

- (a) At Pilot Tunnel Sta. 36k+214, TBM timer: 1407.55 hr, five broken teeth (see Fig.9 & Dwg.3) on TBM ring gear were founded by RSEA mechanical foreman and TRC TBM operator in 8 Aug., 2002. As a result, TRC Manufacturers Representative strongly recommended "TBM can't continue boring at all" in Memo dated 10 Aug., 2002 and summarized the risk assessment for the continuation of TBM boring without changing the ring gear (or named as bull gear) as follows:

- * Main bearing: Currently we believe that it is serviceable, test results will follow ASAP. Continued boring will put the bearing in a situation whereby it becomes extremely vulnerable to damage from shattered gear steel entering the bearing race.
- * Ring gear: Situation unchanged by continued boring, it is unserviceable now.
- * Gear reducers: Will be destroyed by further boring. Replacement could take 6 months delivery unless second hand units are available.
- * Lube system return pumps: Return / Scavenge

pumps will be destroyed.

- * We must take advantage of the current favorable rock conditions to do these repairs, ensuring that the safety of the Pilot Tunnel personnel is not compromised.
- * There can is know comparison between the prevailing rock condition at present compared to the rock condition prevailing at the location of the previous ring gear failure. Therefore strategies from previous failure have known credibility in the management of the existing problem.
- * The safe guards proposed by RSEA to monitor and stop the TBM??? In the event of amperage increase will not prevent further damage to the ring gear and gear reducers. The misalignment of the gear reducer pinions to ring gear will occur suddenly causing catastrophic damage before the theoretical shut down occurs.

At that time, the Southward Main Tunnel TBM had stopped for welding seriously damaged TBM gripper, preparing to do full face boring and was impossible to resume boring within two months. It meant the two existing TBM in Hsuehshan Tunnel will cease production simultaneously. Client stated clearly that they just can't accept this situation and production in Hsuehshan Tunnel had to keep going anyway. Under such rigorous circumstances, the chairman of RSEA came to Pei-I construction office in 12 Aug., 2002 and convened a conference right away especially for Pilot Tunnel progress. In conference, he spoke gently but firmly about the current severe pressure of HTC on RSEA and convinced all TRC attendants successfully to assist TBM to bore again ASAP until the Southward Main Tunnel TBM resumed boring. He promised to take all responsibility in relation to TRC anxiety about current TBM. He encouraged Pilot Tunnel team to set some regulation and discipline on operation, maintenance and inspection frequency of TBM for longer distance and time to bore.

Through Dye Penetrate Test to ensure only five broken teeth on TBM ring and to grind the profile of these broken teeth as before for not contact with normal tooth of pinions to prevent from further damage, Pilot Tunnel TBM resumed boring in 15 Aug., 2002 eventually.

- (b) At Pilot Tunnel Sta. 35k+316.26, TBM timer: 1834.40 hr, thirteen broken teeth (see Dwg.3) on



Fig.9 Two broken teeth on ring gear



Fig.10 Two broken tooth on pinion

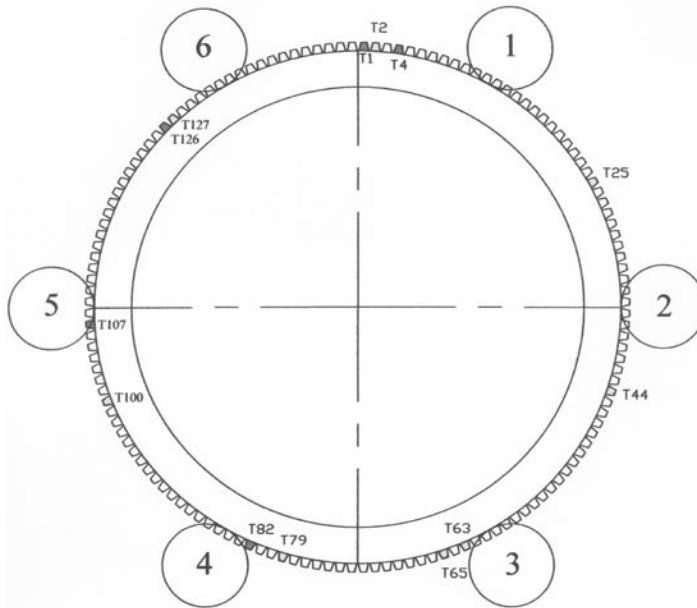
TBM ring gear were founded by RSEA mechanical foreman and TRC TBM operator in 8 Nov., 2002. It was inevitable result, but it still shocked and awoke up Pilot Tunnel team who were immersing in delight of successively breaking 300m limit of Pilot Tunnel TBM monthly progress, 348m in September and 319m in October, and finally passing through adverse, the hardest Quartzite Sandstone Formation, to merciless reality.

Because Main Tunnel TBM already resumed boring in 9 Sep. 2002 and the location of A cavern #2 Ventilation Interchange Station (Sta. 35k+550) was exposed 60m behind the end of TBM back-up system, it could be excavated at the same time with the second replacement of TBM ring gear to catch up with the integral progress of HTC. Therefore, the decision to replace TBM ring gear right here (stated as good geological condition) became a common consensus.

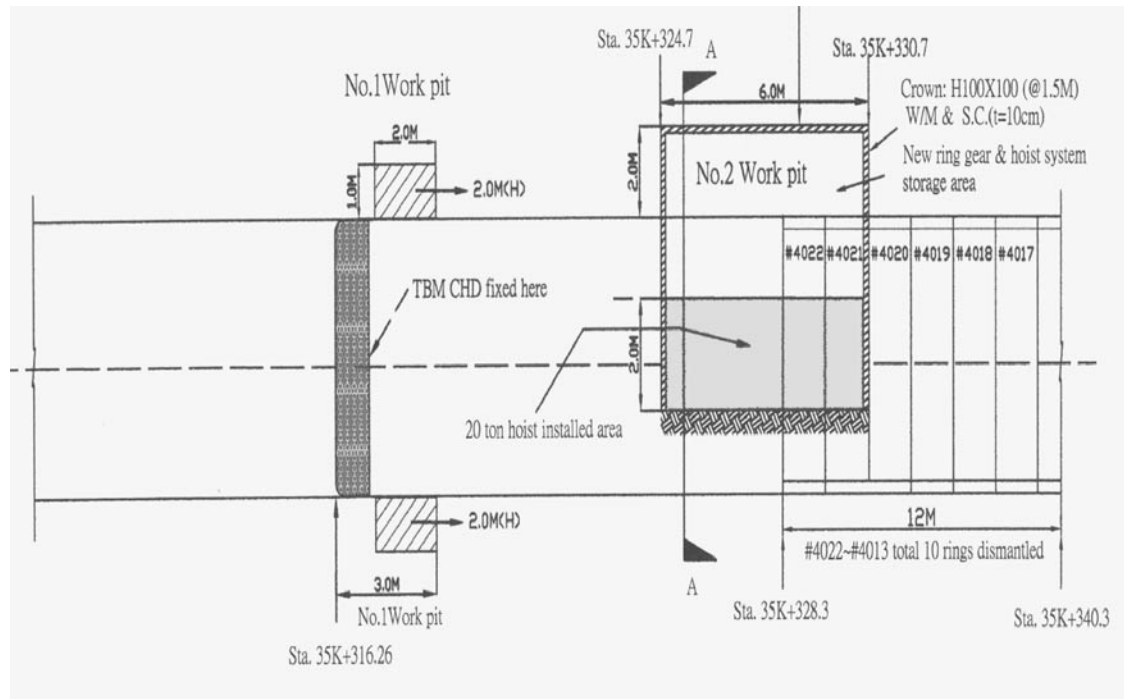
Carry Out the Second Replacement of TBM Ring Gear at Sta. 35k+316.26, TBM Timer: 1834.40 hr

1. Disassembly Chamber: (see Dwg.4 & Dwg.5)

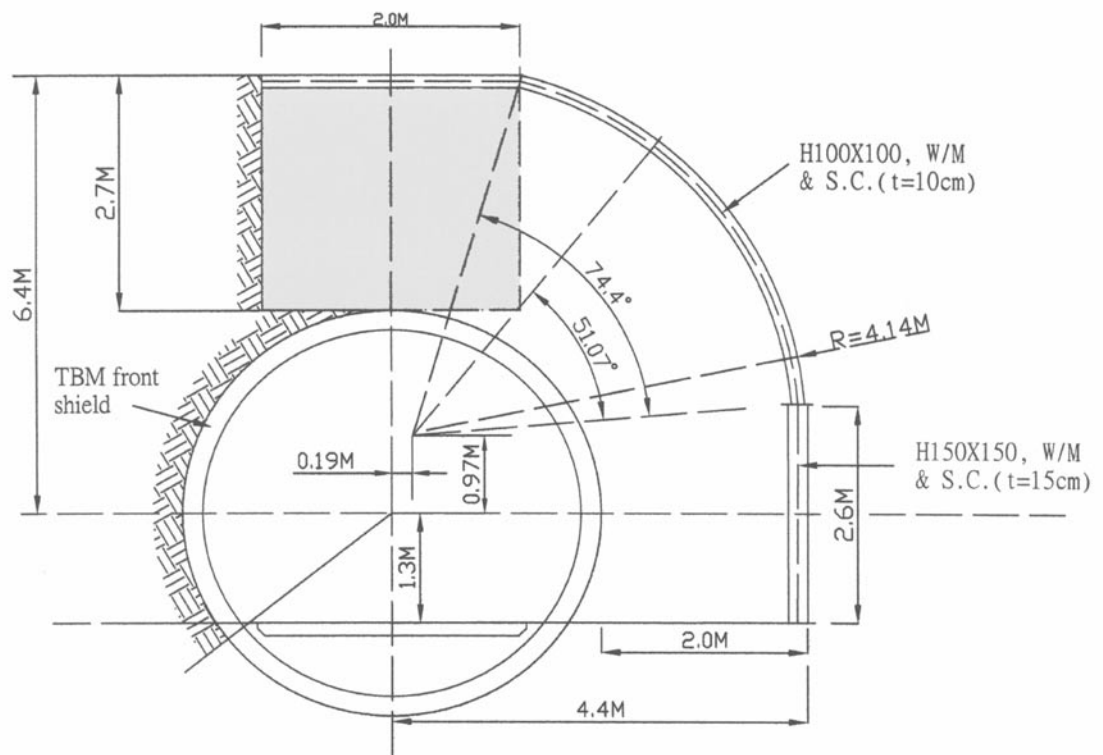
1.1 Geological description:



Dwg.3 Distribution of 13 broken teeth on TBM ring gear, 5 broken teeth in red color were found in 8 Aug., 2002, additional 8 broken teeth in yellow color were found in 8 Nov., 2002, the surrounding 6 small circle with number represent 6 pinions which distribute equally on TBM ring gear. The total number of teeth on ring gear is 144 while pinion is 19.



Dwg.4 Top view of disassembly chamber for the second replacement of TBM ring gear at Sta. 35k+316.26



Dwg.5 A-A section of Dwg.4

- (a) The rock of excavation face: mainly consist of argillite, with minor siltstone intercalated with fine sandstone.
- (b) Structure condition: no fault or shear zone observed; the attitude of three sets of joint measured as: N30~40W/40~50SW、N65~80W/60SW、N45~64E/40SE.
- (c) Groundwater condition: damp to flush
- (d) Rock Mass Rating (RMR) : 35 to 48

1.2 Construction period:

- (a) No.1 Work pit: Its dimensions is 1m wide x 2m long x 2m high (see Dwg.4, on left side) for each. The purpose of No.1 Work pit is quite simple for doing some supporting structures from both sides to hold TBM CHD upright firmly which is very important to rejoin precisely between TBM CHD and TBM front shield. Prior to make No.1 Work pit, TBM CHD has to be pulled back 3.6m (3 rings) to expose the required space. The mucks produced from making No.1 Work pit are dropped into TBM conveyor system from one empty cutter hole and discarded by TBM de-mucking system. It takes about 5 days counted from 8 Nov. 2002 to finish No.1 Work pit.
- (b) No.2 Work pit: Its shape is similar to an elbow of pipe (see Dwg.5). The purpose of No.2 Work pit is to create space for temporary storages of new ring gear, special lifting adapter, 20 ton hoist system components, dismantled broken ring gear, other necessary construction materials and offering 20 ton hoist system installation. No.2 Work pit is excavated from the entrance made by removing two side segments of #4022 & #4021 right after finishing No.1 Work pit. To use smartly TBM front shield as working platform for excavating 20 ton hoist installed area (see Dwg.4 & Dwg.5, area in yellow color) in higher position is one of designed advantages of No.2 Work pit. The mucks produced from making No.2 Work pit are dropped into TBM conveyor system and discarded by TBM de-mucking system. It takes about 10 days to finish the profile of No.2 Work pit. As to the detailed modification and secured rock bolts for 20 ton hoist installed area are left to the next stage of 20 ton hoist installation.

- (c) The real working space for replacement of TBM

ring gear between fixed alone CHD and #4022 in disassembly chamber is created merely by pulling TBM without CHD back 12m to expose the space, i.e. no construction period needed.

2. Release TBM CHD alone and Move new ring gear, special lifting adapter, 20 ton hoist system components and necessary construction materials into No.2 Work pit:

- (a) Push TBM forward 3.6m to against rock face at 35k+316.26 and secure TBM CHD firmly by inserting steel wedges at the bottom of CHD and welding supporting steel structures from No.1 Work pit to both sides of CHD. Make sure again.
- (b) Follow previously mentioned "Detailed Procedures of Replacement of TBM Ring Gear with Enclosed Dwg.1 & 2" to release CHD from TBM correctly. At the same time, move new ring gear, special lifting adapter, 20 ton hoist system components and necessary construction materials into No.2 Work pit.
- (c) Insure new ring gear will pass through narrow space of TBM operator console and back up system into No.2 Work pit. A template of wood was made to verify. Remove or re-support structure was done in advance. It takes about 4 days to finish (a) & (b).

3. Pull TBM without CHD back 12m, Secure surrounding rock of working space for replacement of TBM ring gear between fixed alone CHD and #4022 :

- (a) On the contrary to TBM boring, to pull TBM with or without CHD back 12m shall require the removal of 10 rings full segment, a lot of backfilled pea gravel & rail system, rewinding 12m of high voltage cable, water hose and stuffing the incoming vent line back into the cassette. Additional structures to help pulling TBM back are built accordingly. It takes about 6 days to finish (a).
- (b) According to recommendation of field geological engineer, we install essential number of rock bolts to secure surrounding rock of working space for replacement of TBM ring gear between fixed

alone CHD and #4022. Shotcrete & wire mesh will be done if needed. For preventing TBM to get stuck during 3 months replacement of TBM ring gear by invasion of surrounding rock, we inject some pea gravel into the gap between TBM shield and surrounding rock as the past successful experiences.

- (c) Prior to installing 20 ton hoist, one set of thick steel plate (1.25m wide x 6m long in total) was fixed and secured to rock by 12 rock bolts (max. 10 ton loading capacity for each) on the top of 20 ton hoist installed area. Two 6m in total I beam (400x150x12.5) are welded to secured top thick steel plate and 20 ton hoist body are installed in the center of two I beams in succession. Furthermore for safety, we use TBM front shield to build extra supporting structure for 20 ton hoist. It takes about 14 days to finish (b) & (c).

4. Replace TBM ring gear in disassembly chamber:

- (a) Follow previously mentioned "Detailed Procedures for Removal of Main Drive Motors and Gear Reducers" to remove 6 main drive motors and gear reducers out of TBM. It is beneficial to remove the integral set of ring gear, main bearing & CHD adapter easily and inspect 6 main drive motors and gear reducers in detail in open space of Pilot Tunnel portal. Replace pinions if needed.
- (b) Move special lifting adapter into working space from No.2 Work pit and fix it on the integral set of ring gear, main bearing & CHD adapter. Use 20 ton hoist to lift and remove the integral set of ring gear, main bearing & CHD adapter out of TBM, then put it down slowly and show broken ring gear upward. Move new ring gear into working space from No.2 Work pit and follow previously mentioned "Detailed Procedures of Replacement of TBM Ring Gear with Enclosed Dwg.1 & 2" to replace ring gear. To replace wearing band is a highly cooperative job, it is done for the first time since Pilot Tunnel TBM came here in 1992. Broken ring gear is cut to pieces and stored in No.2 Work pit temporarily. So do the other waste materials and 20 ton hoist body. Once CHD and TBM rejoined later, the entrance of No.2 Work pit will be exposed, everything in it can be moved out of tunnel. It takes about one month to finish (a) & (b).
- (c) Actually, new ring gear replaced in this event is not "new", it is spare ring gear and come along with TBM in 1992, it has the same mechanical notch on one side as the first broken ring gear, it is spur gear type and reversible gear for double use. For better contact surface and the avoidance of stress concentration between ring gear and pinions, we send it to a large reliable mechanical workshop to do precise grinding for ring gear teeth prior to replacing TBM ring gear.
- (d) As a result of 3 months extension in TBM boring, all 6 pinions are found to be damaged (see Fig.10) seriously and must be replaced now. The problem is only one pinion in stock at present. Emergent orders are placed in two nations, one order of 6 pinions is in TRC, USA, original manufacturer of Pilot Tunnel TBM, we can get genuine parts but longer delivery time in comparison, the other order of 2 pinions is in Tainan, Taiwan, ROC, a famous mechanical equipment export world-wide manufacturer which we have ever cooperated in planetary gear fitness of gear reducers, it is reliable and shorter delivery time in comparison. When TBM resumed boring in 31 Jan., 2003 (the 84th day behind 8 Nov., 2002), we use only 3 pinions located at three apexes of a triangle to drive TBM CHD, one is made in USA while the other two are made in Taiwan. Finally, all 6 pinions were replaced by brand-new pinions within 8~11 Feb., 2003 for homogeneity.
- (e) Newly raised issue right after running out the stock of ring gear and pinions in this event, it is whether to buy spare ring gear and pinions or not in the successive journey of TBM boring. Prior to answering this question, we have to check some TBM boring data as follows:
 - (1) TBM boring length before the first replacement of ring gear: 1,238m (full face boring)
 - (2) TBM boring length between the first and second replacement of ring gear: 3,605m (2,520m full face boring & 1,085m invert cutting)
 - (3) TBM remaining boring length from the second replacement of ring gear (Sta.

35k+316) to the set TBM disassembly chamber (Sta. 33k+328): 1,988m (supposed to be 1,568m full face boring & 420m invert cutting)

To compare between (2) & (3), the answer is quite clear to say "NO". In addition to the geological structure of (3) has Argillite & Sandstone Formation which is much softer than the hardest Quartzite Sandstone Formation encountered in most of (2) full face boring length, we have strong confidence in present ring gear and 6 brand-new pinions. Even though the hardest Quartzite Sandstone Formation which causes strong vibration during TBM boring process is deemed as a suspect to break the teeth on ring gear, all people focus on the coming breakthrough of Pilot Tunnel instead of discussing and disputing on broken teeth issue.

5. Push TBM forward, Rejoin CHD to TBM and Prepare to resume TBM boring:

- (a) Prior to pushing TBM forward, the waste materials, broken ring gear and 20 ton hoist body must be moved into No.2 Work pit from the working place for the replacement of TBM ring gear in disassembly chamber. Especially to clean the bottom of working place as the same situation as TBM pulled back before, it is very important to rejoin CHD to TBM precisely. During push TBM forward, the biggest problem is the void of No.2 Work pit which locates on the right gripper of TBM and make TBM not available to get effective gripper force as normal TBM boring to push TBM forward. No.2 Work pit can't be backfilled now owing to something mentioned above are still stored inside. Therefore, some special structures for pushing each ring are built to offer the required reaction force to push TBM forward. Partial backfill in No.2 Work pit is done right after rejoining CHD to TBM and before TBM resume full face boring to offer effective gripper force as usual.
- (b) Rejoin CHD to TBM is similar to the joint of two space shuttles in space; it needs 100 % preciseness and full patience. When TBM is pushed forward to close to CHD about 1.2m, one TRC mechanical technician stay inside

of CHD with 1m long guide rods and use tunnel communication system to conduct TBM operator to drive TBM approaching CHD very carefully and make the holes of retaining bolts on both sides in alignment, then join them firmly as instruction. Muck chute, 6 main drive motors and gear reducers, other subsidiary components shall be installed in succession. Move out all supporting structures built from No.1 Work pit on CHD to make CHD free completely. It takes about two weeks to finish (a) ~ (c).

- (c) Test running of TBM CHD and all relevant systems are essential on preparation to resume TBM boring. For the time schedule, TBM resumed boring with half power temporarily in 31 Jan., 2003 until the replacements of all 6 pinions were finished in 11 Feb., 2003. The second replacement of Pilot Tunnel TBM ring gear takes 83 days in sum total counted from 8 Nov., 2002 to 30 Jan., 2003.

CONCLUSION

The major differences between the first and second replacement of Pilot Tunnel TBM ring gear are the configuration of disassembly chamber, the pattern of heavy-duty lifting equipment, the method to take CHD apart from TBM and fix CHD firmly, the way to transport ring gear (2472mm ϕ , 2190kg) and the place to store it. To use the bottom space of one finished ventilation shaft and the passage of this shaft to convey new ring gear from top of mountain to replace TBM ring gear is similar and localized to the first replacement of TBM ring gear in Pilot Tunnel. In comparison, the type of the second replacement of Pilot Tunnel TBM ring gear is commonly adopted around the world, not only the time of ring gear replacement is able to be controlled within 3 months, but also the situation of ring gear broken could be happened anywhere in tunnel but not allocated somewhere in tunnel.

To review whole process of the second replacement of Pilot Tunnel TBM ring gear, the time consumed on this event is possible to be shortened two weeks to 69 days from the recorded 83 days by the improvement of expediting materials supply such as new pinions, processed ring gear, structural materials used for pulling TBM back and pushing TBM forward, and the enhancement of cooperation, coordination among the people worked in Pilot Tunnel to save invisible time loss in or between each activity.

Be sentenced to death and extracted pieces by pieces in the midway of Pilot Tunnel, two "heart" operations and 13 geological stuck within 12 years' life, no chance to travel around the world like most of TBMs, if Pilot Tunnel TBM has consciousness as human being, he will regret to visit here. Maybe, the only worthy consolation to him is the coming TBM park located somewhere under bridge closed to the south portal of Hsuehshan Tunnel. It is a permanent house for him, a memorial place for people to ponder on his splendid performances in the past.

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