Dr. Ulrich Rehm
Tunnelling Consultant GmbH

Dr. Ulrich Rehm | Tunnelling Consultant GmbH, Lotzbeckstr. 25, D-77933 Lahr

Ron Tzur
Alto Maipo Hidroelectrico
Cerro El Plomo 5420 Oficina 803
Las Condes, Santiago
Chile

[redacted]

17.05.2017

Draft report on TBM tunnelling for Alto Maipo .

Dear Mr. Tsur.

Please find attached my draft report on TBM tunnelling for the Alto Maipo headrace tunnels.

Thank you

Kind regards

Dr.-Ing. Ulrich Rehm
(CEO)

Report on TBM tunnelling
For the Alto Maipo Project
Chile

Client: **CNM**

Date: **17.05.2017**
Author: **Dr.-Ing. Ulrich Rehm**

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Content

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Report on TBM tunnelling for the Alto Maipo Project in Chile

Overview

CNM Joint Venture (JV) requested a report based on my expertise to check and analyse the current and actual situation, in regard of the applied open gripper-TBM, in order to give an assessment for further TBM tunnelling of tunnel El Volcan from portal V5 and in tunnel Alfalfal II from Portal VA4.

During my site visit to Chile, from 1.-5. April 2017 for evaluating the chances of on-going tunnelling with the open gripper-TBM, I came to the conclusion, that the safety of the TBM-personnel especially working in the rock support area became the dominant part of my expertise for review, all due to the bad rock conditions encountered in the El Volcan tunnel and as I was informed due to several collapses that have been recorded to date in both tunnels.

My assessments in this report are closely related to the report of Dr. David Powell [2] who is a further geotechnical expert employed by the JV whom I met on the site on 4./5. April 2017

The two tunnels I inspected were the 14,1 km long EL Volcan with portals V1 and V5 and the 6,23km long Alfalfal II tunnel with portal VA4. The problems which lead to an interruption of TBM mining occurred at the El Volcan tunnel V5.

The geological situation is pretty well described and analysed in detail in Dr. David Powell [2] separate report of which I refer to herewith.

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Based on the tender documents (see also contract document 600-TU-ETG-001 Annex 1 volume 4 [3]) the TBM-type to be used was clearly pre-defined which was unmistakably an open gripper-TBM due to the described gripper-pads and the required conventional rock support measures to be installed.

General requirements for gripper-TBM tunnelling

The open gripper-TBM which is specified in the contract documents was originally designed for competent stable hard rock conditions since it provides only a very short-shielded section at the front which mainly serves as flexible gripper-shield to stabilize the cutter- head. This front-shield acts also as a protection wall against unhealthy dust generated by the disc cutters on the cutter- head. It also includes the all-important mechanical components of the main-drive of the cutter-head, which occupies the whole space within the front shield-body. The only very limited, mechanical protection provided in the so called L1-area (between back of the front-shield and gripper pads) are several steel strips (fingers) extended over a limited area at the crown from the rear part of the roof-shield blade (see fig. 1). These steel-fingers don't provide any protection to the staff in case the side-wall collapses (see fig. 2). Furthermore in case of very large rocks, blocks will drop on these fingers, and the risk occurs of rock debris, sliding along the fingers (or falling in-between them). Subsequently resulting in high risk of injuring people standing in that area (see fig.-sequence 3-5 taken in the El Volcan tunnel V5). These pictures clearly illustrate that the finger-shield provides only limited protection against rock fall.

Given this situation of the unprotected L1-area makes, the open gripper-TBM is working in a high risk environment, and further, in the case of unstable rock conditions the risks are increased.

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

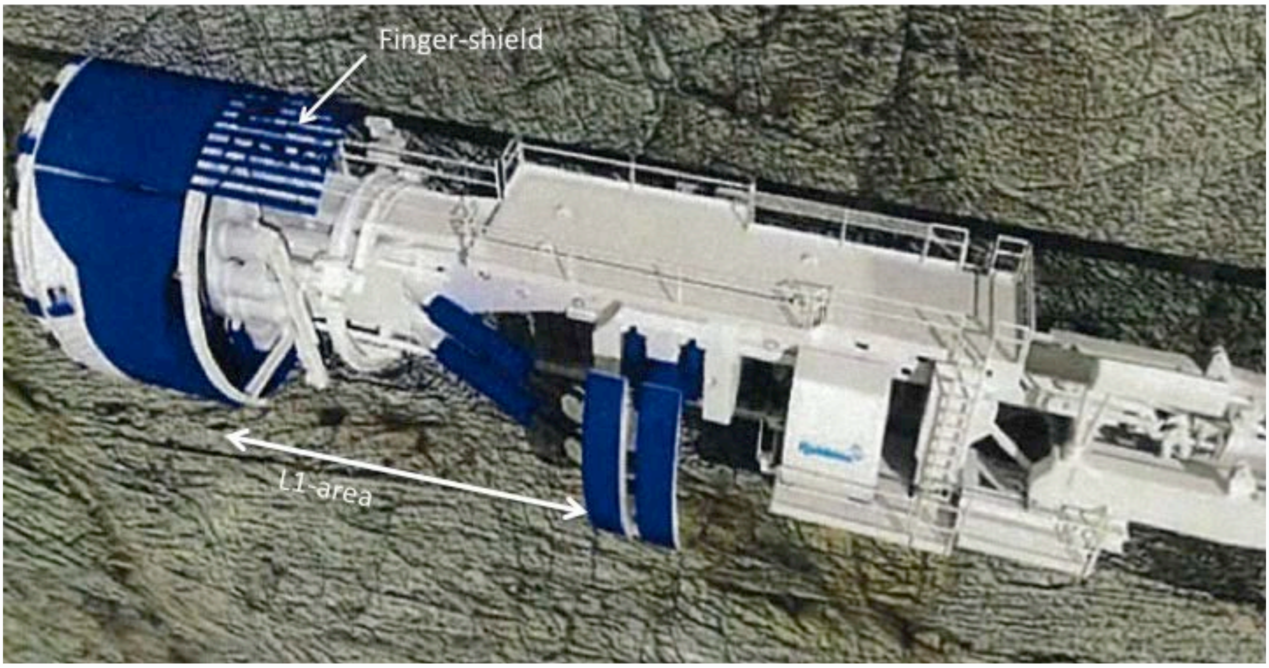

Fig. 1: Main beam Machine MB1219-314-1 (gripper-TBM) showing unprotected L1-area and front-shield with finger-shield.

Fig. 2: Example of an open gripper-TBM in Switzerland showing collapsed side-wall within the L1-area providing no protection for the staff.

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

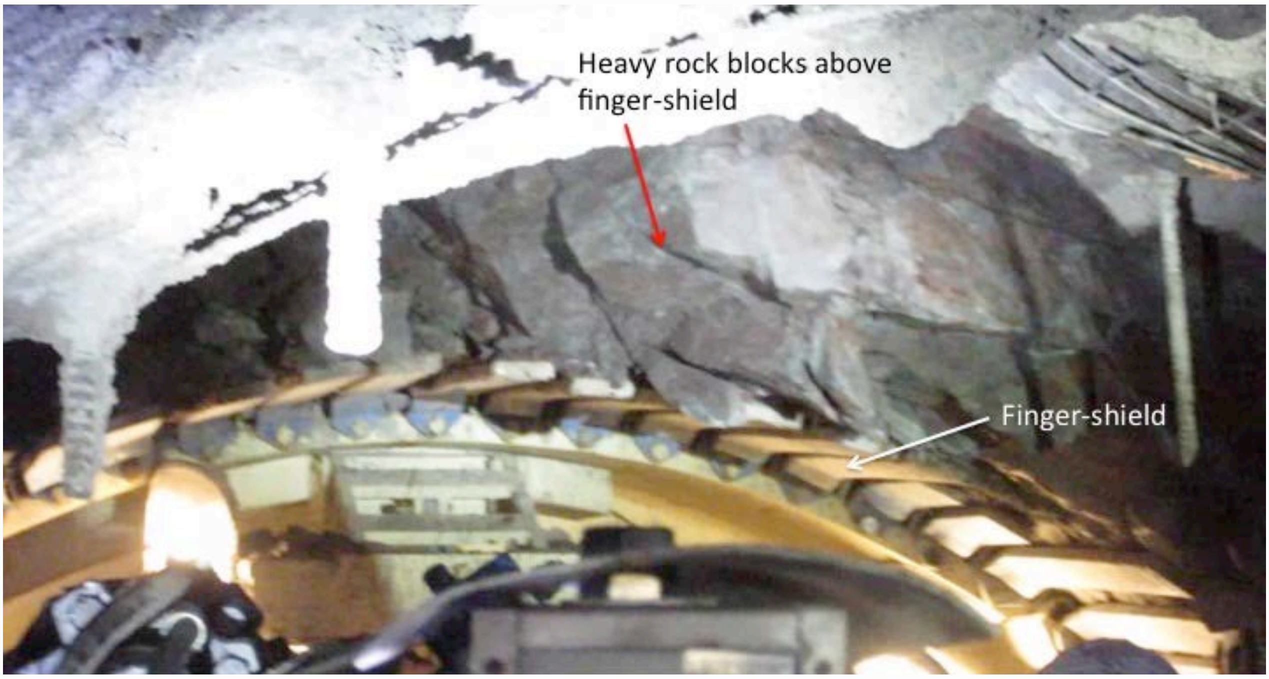

Fig. 3: Situation on gripper-TBM in El Volcan tunnel V5 at CH 13+883 with fractured rock blocks above finger-shield.

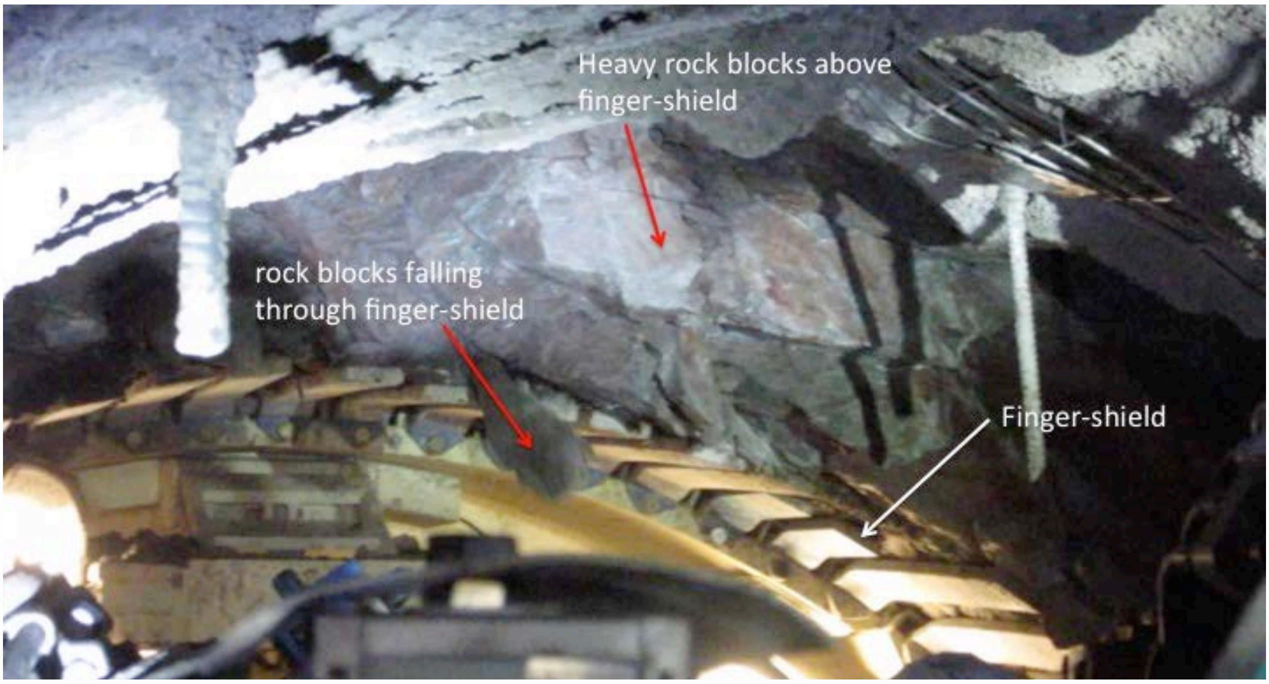

Fig. 4: Situation on gripper-TBM in El Volcan tunnel V5 at CH 13+883 with fractured rock block starting collapsing through finger-shield.

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

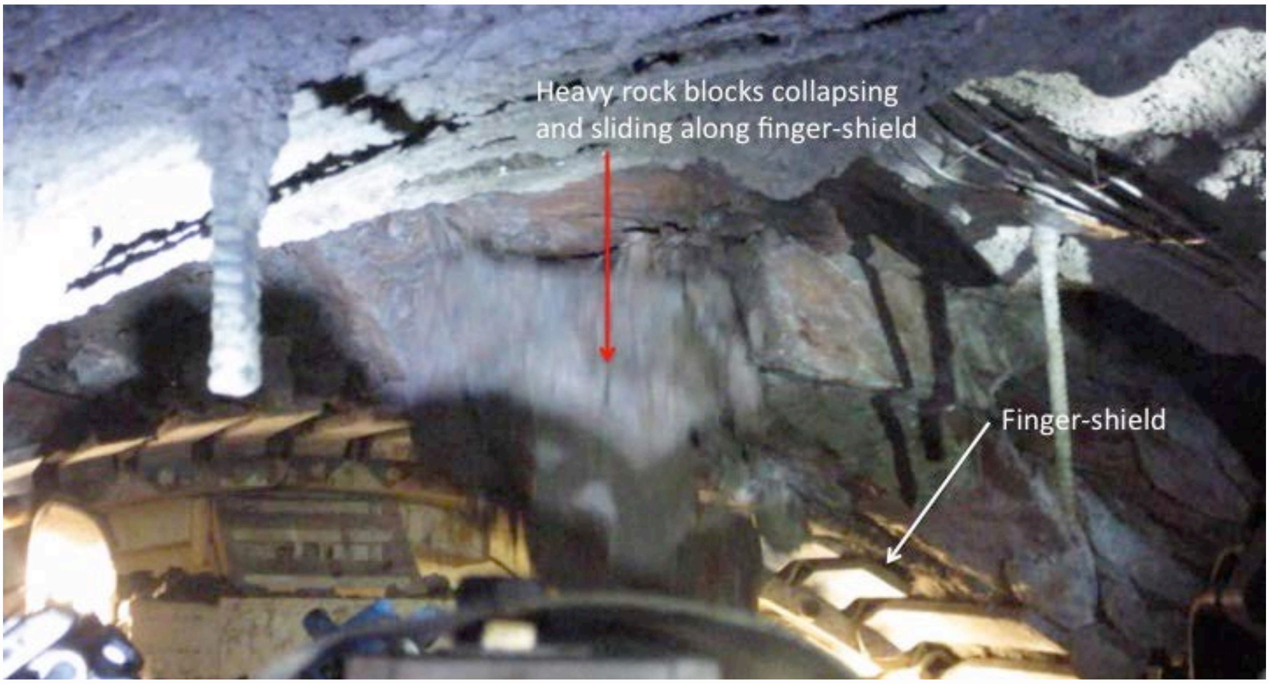

Fig. 5: Situation on gripper-TBM in El Volcan tunnel V5 at CH 13+883 with fractured rock block s collapsing and sliding along finger-shield.

In regards to cutting forces against the face, and to achieve suitable penetration the gripper-pads mounted on each side of the TBM guide-frame, have to provide the appropriate gripping forces. As a reference and based on industry expectations the friction ratio between pads and rock can be assumed to be approx. 1/3, i.e. the total gripping forces (of both gripper-pads) should be approx. 3 times of the thrust force going to the cutter-head. Furthermore for generating these required high gripping forces the rock mass quality at the side-walls has to be good enough to provide an appropriate abutment for the gripper-pads. Otherwise, the required forces on the disc cutters to crush the rock at the face cannot be generated. Therefore, unstable rock conditions do not only severely, put at risk the safety of the TBM operators, within L1-area which subsequently questions the basic feasibility of the TBM itself. The open gripper-TBM has no alternative system to move forward in case the side-walls of the tunnel cannot provide appropriate abutment the personnel is therefore forced to improve the conditions within the unprotected L1-area around the gripper pads (see fig. 6). Therefore, it is included, in the case of very bad rock

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

conditions at the side-wall within the gripper-pads area, the operators have no options but to stay in their positions and wait for the execution of the required rock improvement works – subjecting the operators to high risk and in danger,

Fig. 6: Example of an open gripper-TBM in Switzerland with improved rock conditions under gripper-pads to provide stable abutment.

Fig. 2 and 6 clearly show the space-limited working area around the gripper-pads and in comparison to the unsafe conditions for the operators to work in.

In the illustrations above, the force-transmission is directly into the rock through the gripper pads and this is a decisive difference to a shielded TBM, which uses pre-casted segmental lining as directly abutment for thrust force transmission making the shielded TBM more independently from rock mass quality. Therefore a minimum rock mass strength – i.e. not related to an isolated small rock sample but to the whole area under the gripper

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

pads – is required for allowing the gripper-pads to be pressed against without disturbing the rock mass. It is obvious the more fractured the rock mass the lesser, the rock mass strength is, despite the single rock sample of this rock mass would provide enough strength.

The basic physical concept behind the gripping technology of the main gripper pads or the front gripper-shield is to either transferring forces and to stabilize the TBM, i.e. controlling destructive vibrations which are inevitably generated by the disc cutters when crushing the rock at the face under very high thrust forces. In case of poor rock conditions which in turn cause over breaks at the gripping areas, this important physical principle cannot be applied properly anymore.

I.e. mechanical vibrations cannot be transferred satisfactorily into the rock through the pads and the gripper-shield.

This will firstly cause very disturbing working conditions and risk of injury, to the operators with constant loud and unpleasant vibrations. Additionally there is physical increase in risk of destabilizing jointed/altered rock around the whole front-shield area as well as in the L1-area.

These conditions have to be avoided as the noise is so load and disturbing injury to personals hearing can be caused, even with reasonable safety equipment.

.

In my experience on other hard rock projects it I have identified these high vibrations can also have destructive impact on sensitive TBM-components like the electrical motors of the main drive of the cutter head and related components (pinions, clutches, gearboxes, main bearing etc.).

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Fig. 7: Damaged drive motors of a comparable open gripper-TBM in Canada.

Risks are present that these very important TBM parts can either be damaged by frequently too high vibrations or directly by rock fall, and since the drive-motors are closely positioned to the unprotected L1-area (see fig. 7). Long delays to production shall be prevail thereafter as the maintenance works on these special TBM parts are substantially long to execute, which in consequence will have adversely impact on the time dependant failure processes of the rock.

This will extend risk period to the L1 area of the TBM, a situation that must be avoided where possible

General criteria for choosing an open gripper-TBM

In my experience on tunnel project the most important criterion for choosing a certain tunnelling machine is whether it is technically feasible for the given circumstances and underground conditions. Being technically feasible does not automatically imply for an open gripper-TBM that it is also fit for purpose in terms of safety, and when it comes to outstanding unforeseen geotechnical conditions then safety as well as performance must assessed for risk.

It should be apparent, that the performance rate of an open gripper-TBM is strongly related to the effort for rock support. In the case of this project, and providing the safety conditions within the L1-area allow for the proper use the equipment provided by the (technically feasible) TBM the and its “fit for purpose” cannot be questioned. However in the case heavy rock debris collapsing onto the L1-area, and also as rock support works cannot be executed anymore due to the high injury risk to the operators, my findings are.

Although the selected TBM fulfils all technical requirements and could be feasible, however with the poor rock conditions and combined with, the very restricted space on the small TBM it cannot be deemed to be “fit for purpose”.

I have also identified from the records in the case of rock fall not only do we risk with safety and damaged equipment, damages to the rock support installation occur (as happened on the V5 TBM. This in turn increases the Risk of injury to the operators and others who are in attendance.

The risk for getting into the above described trouble increases with smaller TBM sizes as the efficiency and quality of the provided equipment for rock support drops severely with the available space in the L1-area. In the situation of restricted space given on the small Alto Maipo TBMs the safety of the operators is furthermore depending on the time-wise availability of rock support measures, as not all equipment can be installed or used simultaneously and thus not instantly. In respect to the required time for mobilisation of certain rock support measures (as a result of the given constraint space conditions) and the given time dependency of geotechnical destabilizing effects this has further negative

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

impact resulting in increased safety risk to the operators.

Regarding the application of shotcrete which is normally a helpful device for quickly secure unstable rock sections this can only be applied automatically through a shotcrete robot approx. 35m behind the cutter head for the Alto Maipo TBM due to the restricted space conditions. Within the more critically L1-area, where safety is paramount, and which is much closer to the cutter head where rock collapses shotcrete cannot be automatically applied, and needs to be executed very difficult way by hand,

i.e mobilisation time and quality of manual application make the operation less efficient.

A possible solution to reduce this risk of fractured rock conditions would be to frequently grout from within the L1-area.

Additionally as Owners approvals are required for short creating, delays are occurring and contrary to this in an effort to avoid water ingress or to stabilize weak rock this has to be a relatively quick operation, which is not the case and adds to the safety risks, which have to be mitigated. From a rock-mechanical point of view grouting of (the unforeseen) horizontal shear zone is anyway a very difficult challenge because of the high risk the grout won't stay in the rock but just flowing along the shear zone back into the open tunnel.

So for choosing an open gripper-TBM the geotechnical information as basis for a reasonable choice have to be as precisely as possible especially for the weak rock sections like fault zones because there are not much tolerances allowed in differing between predicted and actually ground conditions for an open gripper-TBM. If rock conditions occur increasingly more difficult and to a certain extent than predicted the use of an open gripper-TBM will very likely turn quickly into a critical situation. In turn this risks on safety of the operators then the conditions change and the TBM can no longer be identified as "fit

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

for purpose"

Regarding the choice of an open gripper-TBM there is no official national (Chilean) or international standard in existence or available which can clearly assign TBM-types and match these to geotechnical classification systems. The international tunnel association (ITA) has published a paper in 2000 *'Recommendations and Guidelines for Tunnel Boring Machines (TBMs)'* which offers recommendations on the application of TBM-types related to certain geotechnical conditions. Most of the content of this paper is taken from the German DAUB (a world-wide highly respected committee for underground construction) article "Empfehlung zur Auswahl von Tunnelvortriebsmaschinen" (recommendation for the choice of Tunnelboringmachines) which was last up-dated in October. 2010.

Fig. 8 shows the relevant extract for open gripper-TBM taken from the latest DAUB release which indicates that the application of an open gripper-TBM is possible starting at rock mass rating (RMR)-values of 41 representing fair rock conditions; below that (RMR<41) the use of gripper-TBM is judged as "critical".

For the purpose of this Report on the TBM I have identified the need for following cross reference to the separate report prepared by Dr David Powell.

So, referred to table 41 (page 38) of Dr. Powell's report 2 approx. 21,3% of the initial section of the El Volcon tunnel V5 was under these critical conditions which is quite high and thus questioning the recommendation of an open gripper-TBM. This is also confirmed by taking into account the upcoming tunnel sections with coverage up to 1.500 m where RMR values below 41 should be very likely expected

The RMR-system is based on 5 columns whereas the assessment of the quality of the joint set system alone has an impact of 70% on the total classification. Any mistakes or changes

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

concerning the assessment of the joint-set-system therefore quickly causes a severely change in rock classification classes and thus also in the effort for rock support measures and tunnelling performance rate. This means for a proper use of the RMR-system the description of the quality of the joint-set-system preferably at tunnel level should have been investigated in detail, in order to achieve a reliable assessment, in relation to the RMR class.

As a separate issue in the selection of the TBM, account should have been taken on the severely changeable rock conditions which are very likely to occur – especially in the highly heterogeneous Andes -

	Festgestein (Hard rock)					
Gesteinsfestigkeit [MPa] Rock compressive strength [MPa]	0 – 5	5 – 25	25 – 50	50 – 100	100 – 250	> 250
	–	o	+	+	+	o
Bohrkern- Gebirgsqualität [RQD] Core sample - rock quality designation [RQD]	sehr gering very poor 0 – 25		gering poor 25 – 50	mittel fair 50 – 75	gut good 75 – 90	ausgezeichnet excellent 90 – 100
	–		o	+	+	+
Rock Mass Ratio [RMR] Rock Mass Ratio [RMR]	sehr schlecht very poor < 20		schlecht poor 21 – 40	mäßig fair 41 – 60	gut good 61 – 80	sehr gut very good 81 – 100
	–		–	o	+	+
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0		0 – 10	10 – 25	25 – 125	> 125
	+		+	+	o	–
Abrasivität (CAI) Abrasiveness (CAI)	kaum abrasiv not very abrasive 0,3 – 0,5		schwach abrasiv slightly abrasive 0,5 – 1	abrasiv abrasive 1 – 2	stark abrasiv very abrasive 2 – 4	extrem abrasiv extremely abrasive 4 – 6
	+		+	+	o	o
Quellverhalten Swelling behaviour	kein none		gering poor	mittel fair	hoch high	
	+		+	o	o	
Stützdruck [bar] Supporting pressure [bar]	0		0 – 1	1 – 2	2 – 3	3 – 4
	+		–	–	–	–

+ Haupteinsatzbereich / Main field of application
o Einsatz möglich / Application possible
– Einsatz kritisch / Application critical

Fig. 8: Latest recommendation for hardrock gripper-TBM use of the German committee of tunnelling (DAUB, ITA-AITES) [1].

So the RMR-system as the base for rock classification with no reasonable precisely investigation on the joint-set-system should only been used when the adopted tunnelling system allows for a wide range of changed rock conditions which in the selection of an open gripper-TBM is not the case.

Besides the basic decision on which type of TBM should be used for the project the contractor needs precise geotechnical information in the tender docs for reasonable estimations of the expected time and costs to mine the tunnel. For this purpose, various rock classification systems have been introduced which were mainly developed for the classical conventional tunnelling method (often called NATM – new Austrian tunnelling method or drill and blast (D&B) or shotcrete lining). The classical D&B tunnelling method is more flexible and thus can better react on surprisingly changes of rock classes compared to a gripper-TBM. Therefore planning of a gripper-TBM tunnelling project requires precisely defined and reliable rock classification classes along certain geotechnical sections and thus more comprehensive geotechnical investigations, than compared to those D&B works. It is obvious from my findings, that too many (unforeseen) changes of the rock quality along increasing difficult conditions in the tunnel shall interrupt the automated mining process of a TBM frequently, and thus will slow down its performance rate dramatically. This is again because there is only limited space available for rock support within the L1-area on the open gripper-TBM and as mentioned above the basic thrust-force transmission requires reliable stable rock conditions. Therefore the degree of reliability on the geotechnical information in the contract does much affect the quality of TBM tunnelling more than it does for D&B works.

Additionally to the rock classification systems some TBM-tunnelling performance models for predicting TBM advance rates, forces on the cutting tools and their expected wear rates have been introduced whereas two are most famous: the empiric more rock-mechanically based NTNU model from Trondheim/Norway and the numeric more TBM-mechanically based CSM (Colorado school of Mines) from the USA. Both provide a vital base to the contractor for estimating the required time for mining through a certain tunnel section – but only if all required geotechnical input parameters are available. Like for the rock classification classes, all geotechnical TBM performance-models can only be as good as the quality of their input values are, i.e. how comprehensive the geotechnical site-investigation works have been executed. The requirements for an appropriate application of the NTNU model are beside the so called drilling rate index (DRI) and the cutter life index (CLI), which can be determined in a lab, a detailed investigation on the rock mass fracture system in-situ including detailed information on the degree of fracturing (spacing between the weakness planes, orientation). Furthermore the principal stress orientation in the ground also has a decisive impact on the penetration of the disc cutters into the rock and thus on the performance rate of a TBM.

All TBM-performance prediction models estimate just the net penetration rate (mm/rev) of the cutting tools per cutterhead revolution into a certain homogenous rock section. They do not calculate (only roughly estimate) the gross advance rate (m/h) of the whole TBM tunnelling system including stoppages for rock support works, TBM maintenance or whatever interruptions. The total advance rate of the whole tunnelling system therefore can only be estimated based on rock classes along homogenous rock sections plus a reasonable assumption on the number and the length of intersected fault zones which have the decisive impact on the total duration for mining along the whole tunnel.

Therefore in regards to the above mentioned general requirements for the choice and the reasonable application of an open gripper-TBM it can be stated that for the Alto Maipo project they have been mostly not fulfilled by the owner due to the lack of basic geotechnical information (see also report of Dr. David Powell [2]).

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Actual conditions of the gripper-TBM tunnelling for Alto Maipo

The actual situation regarding mined tunnel lengths at the time of my site visit early April 2017 is described more detailed in the report of Dr. David Powell[2] . Tunnelling of the gripper-TBM in the EL Volcan tunnel (V5) was stopped and the TBM disassembled; the reassembly on portal VA4 started excavation on 21th April 2017. .

The following figures show some of the critical geological situations in the EL Volcan tunnel (V5) shortly before tunnelling was interrupted; the unsafe conditions for the operators can are illustrated on fig. 11 and fig. 12:

Fig. 9: Huge overbreaks above finger-shield in the V5 EL Volcan tunnel (CH 13.883).

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

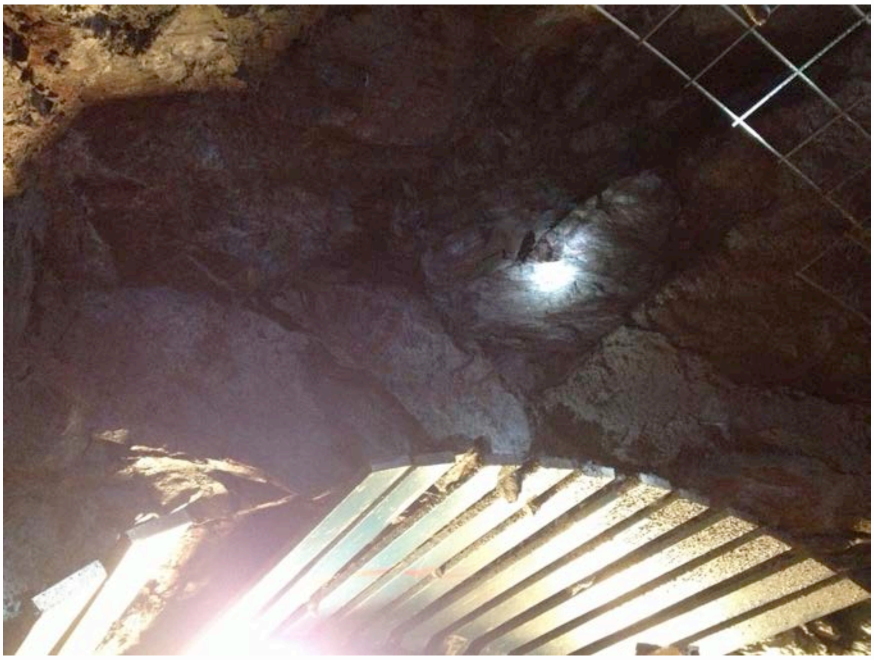

Fig. 10: Huge overbreaks above finger-shield in the V5 EL Volcan tunnel (CH 13.884).

Fig. 11: Massive rockfall debris from overbreaks within L1-area in the V5 EL Volcan tunnel (CH 13.887).

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Fig. 12: Massive rockfall debris from overbreaks within L1-area in the V5 EL Volcan tunnel (CH 13.884).

Fig. 13: Heavily sheared rock supported by the McNally system (which flex under the heavy load) in the V5 EL Volcan tunnel (Ch 13.250).

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Fig. 14: Heavily sheared rock with high water ingress supported by flexing McNally system in the V5 EL Volcan tunnel (Ch 13.248).

Fig. 15: Critical working conditions in the V5 EL Volcan tunnel under flexing McNally System (Ch 13.266)

Fig. 16: Space-restricted working conditions in the V5 EL Volcan tunnel (CH 13.280).

These photos taken in the El Volcan tunnel (V5) impressively demonstrate and confirm that a gripper-TBM is the most high risk TBM-type with the geological conditions incurring with the operators always directly facing the critical ground conditions. Even all rock support measures as requirements in the tender documents have been executed but in very limited due to the very restricted space available in the L1-area and the corresponding geometrically restrictions of a gripper-TBM. Therefore it is questionable whether any of the demanded rock support technologies in the requirements of the contract could have successfully avoided these huge overbreaks as shown in the figures above. It is more likely what is stated in the general chapter on open gripper-TBM above, i.e. extremely unforeseen bad rock conditions shifted the initially feasible gripper-TBM into "not fit for purpose" conditions. It was the contractor's inititative to introduce the McNally system which temporarily helped to overcome the increasing poor conditions. However as the

McNally system is not designed for carrying big heavy blocks falling from the crown or against water ingress this is again a confirmation that the safety of the operators are increasingly at risk in the L1-area even with the McNally system and its difficult working conditions.

During my visit to the El Volcan Tunnel V5 on April 5th 2017 the critical hydro-geological conditions was observed. The tunnel was only accessible with watertight boots (see fig. 11) since the water ingress was by far bigger than predicted in the contract documents (see also report of Dr. David Powell[2]). As experienced in many worldwide tunnel projects and also confirmed by the recommendation of the DAUB/ITA (see fig. 8) the application of an open gripper-TBM allows only for a relatively small change in water flow rate which otherwise will turn the working conditions not only within the L1-area into extremely unsafe.

The relatively high amount of water ingress into the El Vulcan tunnel V5 (which is also described in the report of Dr. David Powell within chapter 4.2 [2] theThe misleading hydrological conditions assumptions in the tender documents will very likely become a much bigger issue for tunnelling with an open gripper-TBM as assumed for both tunnels. as also Dr. Powell wrote in his report.

Furthermore and based on the Dr. Powells report the hydrological conditions will very likely to become more of an issue as assumed and experienced to date for both of the tunnels.

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

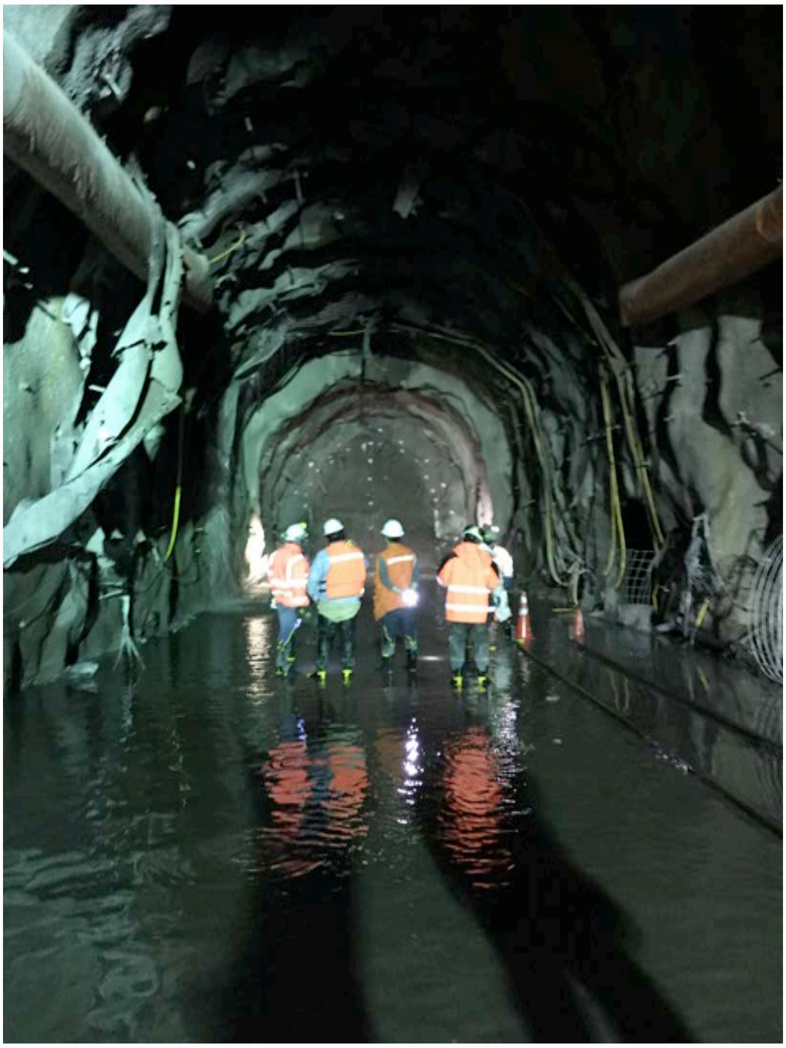

Fig. 17: Visit of El Volcan Tunnel V5 on 2. April 2017 observing water inflow rates of approx. 10-15l/sec.

Another critical observation during my visit, was in the Alfalfal II Tunnel VA4 were a sudden collapse occurred on February 2016 at CH 0+553. As it can be seen in fig. 18 the collapse is not a wedge-block problem that could have been controlled with standard support composed of bolts, spiles and shotcrete. The failed Material was completely degraded and crushed, it can be described more like spoil than rock, in addition it can be seen some rock blocks that could have been part of the competent layer below the sub-horizontal shear zones. If this collapse could have taken place during TBM operation major parts of L1 and L2

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

area would have been buried and workers' safety could have been seriously compromised with resulting injury or even fatalities.

Fig. 18: Sudden collapse in the Alfalfal II tunnel (VA4) at Ch 0+553.

The safety of the Operators is directly correlated to a given rock class. With the increasing difficult rock class the more unsafe the working conditions get, as can be evident from the figures above. With reference to the report of Dr. David Powell[2] the dramatic bad rock conditions in the V5 tunnel resulted from an unforeseen horizontal shear-zone which could present for a considerable further tunnel length. So the decision to stop the TBM was reasonable regarding this prognoses since under these conditions the open gripper-TBM is not fit for purpose and increases the risks for safety of the operators. This is valid for any other gripper-TBM of that size in this tunnel section.

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

With my check on the technical layout of the Robbins main beam machine the following comments are applicable as part of my report:

1. The spacing (distance between neighbouring disc cutters) of average 76 mm is designed for very high strength rock but ok; this leads beside an increased amount of crushed fines to a relatively high amount of disc cutters and thus requires a relatively high cutter head torque.
2. Theoretical required cutter head torque with 27 17''-disc cutters each carrying maximum 265 kN at a realistic penetration of 3 mm/rev leads to approx. 1.000kNm; the TBM provide 970 kNm at a very high cutter head speed of 16.7 rpm and 1.564 kNm at cutter head speed 0-10.4 rpm, so this is fine.
3. If the TBM would penetrate 3 mm/rev with maximum thrust force (267 kN/disc cutter) at highest possible cutter head speed of 16,7 rpm approx. 1.730 kW would be theoretically needed; the TBM has an installed cutter head power of 1.700 kW which is fine; so there is a relatively high safety factor included in the design of the drive engine which is very likely foreseen for the case of a jammed cutter head under squeezing rock conditions.
4. The maximum operating cutter head thrust of 7.209 kN is related to 27 17''-disc cutters times their maximum bearing capacity of 267 kN (27 x 267kN = 7.209 kN); subtracting this number from the maximum thrust forces installed of 9.000 kN leaves 1.791 kN for the gripper-shield skin friction which is approx. 25% of the main thrust which is ok; maximum installed gripping force (2 x 11.205 kN = 22.410 kN) fits rule of thumb to be 3 times the maximum operating cutter head thrust (22.410/ 3 =7.209 kN > 7.470 kN).
5. 50mm maximum overcut in radius is an average reasonable number.
6. 17'' back-loading disc cutters are common techniques; the cutter head structure is pretty stiff for cutting blocked hard rock; the star-type-distribution of the disc cutters over the cutter head is good in terms of a balanced symmetrical force distribution on the cutters.
7. 300t/hr mucking capacity of the conveyor belt includes a safety factor of approx. 1,5 related to the maximum theoretical advance speed of the TBM.
8. The front part of the TBM (see fig. 19) fulfils international standards in terms of well-proven gripper-TBM technology since Robbins is one of the early inventor of it; fig. 19

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

shows the classical long finger-shield of a Robbins TBM; rock support devices are all installed within the L1-area but difficult to be used due to the small size of the TBM (diam. 4,13/4,53 m).

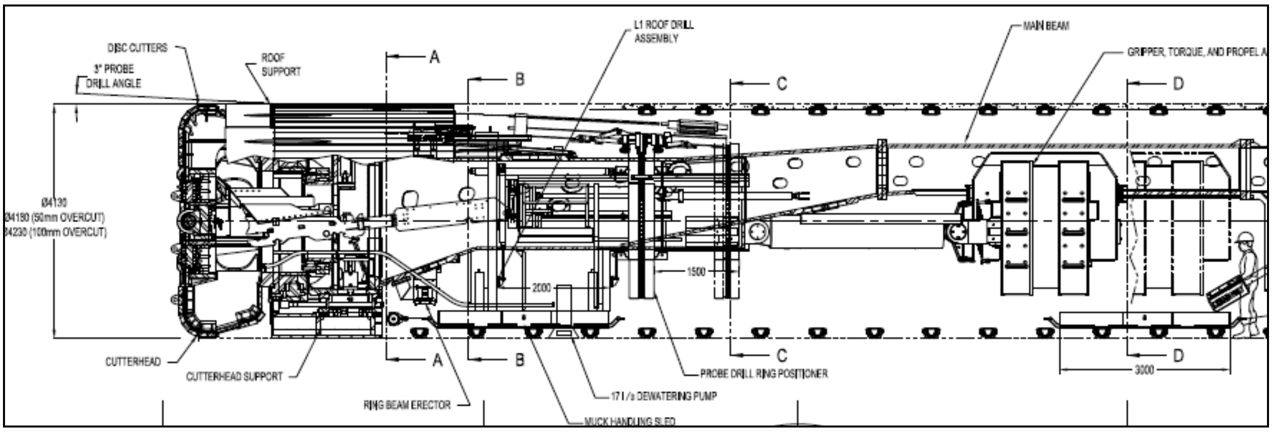

Fig. 19: Front part of a classical Robbins main beam TBM (MB1219-314-1).

Summarized it can be stated that the gripper-TBM for Alto Maipo fulfilled all technical requirements of the contract documents and successive change orders. However due to the relatively high torque demand in the technical specification the size of the main beam became relatively big which lead to a geometrically restriction for executing properly probe drillings and spiling through existing steel sets. This again reflects the special characteristic of this small open-gripper TBM, i.e. having all technical equipment installed which can only be limited applied to extremely geotechnical conditions. The restrictions for probe drilling and spiling were modified for the reassembly of this TBM at the Alfalfal II tunnel (VA4).

The TBM's efficiency during mining is mainly depending on the real faced rock classes during tunnelling. In this context the mixing of various given rock classes (R, GSI, RMR) in the contract documents is a bit confusing as Dr. David Powell [2]also stated in his report.

Finally the Owner decided to use the GSI (geotechnical strength index) system which offers a predominantly qualitative approach to correlate between rock and rock mass strength which it is not a common classification system for TBM tunnelling. It thus provides a wide range of interpretation to both sides either more pessimistic or optimistic. In my opinion the Owner decided for a too optimistic interpretation in the contract documents neglecting important information on weak zones which would have been decisive for the choice of an open gripper-TBM.

The GSI values of the contract documents have been calculated through an international accepted factor out of the RMR-values whereas the special sensitivity of the RMR system to the joint-set-system has been already described in the previous chapter. A more detailed investigation of the joint-set-system was obviously not done by the client. .

Given the rock classes in the contract documents they mainly represent rock strength values equal or bigger than 5 MPa which is close to the minimum value (4,7 MPa) the gripper-pads need to be pressed against the side-walls properly. But there is no quantitative information where and how often these low strength-values have to be expected which carries a high risk for the application of an open gripper-TBM corresponding to fig. 8 which assigns a “critical application” for low strength ground.
In low strength soil-like ground it is not only risky that the gripper-pads could disrupt weak side-walls but also the basic concept of mucking through a hard rock cutter head which is based on gravity induced flow of dry grainy debris along the muck chutes (see fig. 20) can very likely come to its limit. This will then slow down the TBM performance rate dramatically due to required cleaning works of the clogged cutter head and could even question the basic feasibility of further TBM tunnelling.

Therefore the lack of information about weak rock sections projected a false and artificial optimistic expectations on the tunnel conditions as well as the given values of the

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

Norwegian TBM-performance-prediction model NTNU. The parameters of the NTNU-model given in geotechnical tender documents (Appendix Z) include information about the drilling rate index (DRI) and the cutter life index (CLI). The DRI gives an indication on how good or bad a certain rock-type can be mined (bored) and the CLI helps to estimate the stand-up time of the disc cutters within the investigated rock types.

Fig. 20: Classical dry mucking with a hardrock cutterhead (left); clogged hardrock cutterhead after wet mucking through a fault zone (right, taken from a project in Turkey).

Summarized the given results (for samples 1-34) shown in the tables (pdf.-pages 187-192 of Appendix Z) give a positive prognoses in terms of expected borability and cutter lifetime which was confirmed for the intact rock sections during my stay on the job-site early April 2017. These results given in the NTNU tables can also lead to a too optimistic assessment of the rock quality.

As described before in this report, the NTNU-prediction-model is mainly based on rock-mechanical parameters including important information about the fracturing characteristics which are not given in the tender documents. Therefore it was not possible to apply this TBM-performance-prediction model appropriately during tender stage, and neither was it possible to estimate any reasonable performance rates within fault zones due to lack of information in the tender documents.

As mentioned several times before the open gripper-TBM is the most sensitive TBM-type in terms of mining through critical geotechnical sections. This includes rockfall within the L1 area, water ingress either through the cutter head or along the tunnel wall (L1, L2, L3 areas) or stress induced rock failure like spalling, rock burst or rock deformation through squeezing under high overburden which is all very likely to occur for the Alto Maipo tunnels.

Dynamic rock failure like rock burst predominantly under high overburden load is a very dangerous phenomenon that can severely injure (even kill) staff in the proximity where it randomly occurs (anywhere all along the tunnel alignment). It mainly occurs within stable brittle rock which is normally assessed to a rock class not demanding for any rock support measures (free standing). For these dynamic rock phenomena the McNally System seems to be a partly constructive approach because it offers an improved method for protecting the operators from rock fall. Nonetheless, to apply the McNally System all steel strips of the finger-shield have to be removed for putting the McNally steel straps into the steel pockets. Therefore, in this project there are no McNally straps used the operators within L1-area who would be totally exposed to the unprotected rock. Even small rock chips loosened by the vibration of the cutter head could then project or fire into the faces of the operators in the immediate vicinity. Therefore the contribution of increased safety expected from the McNally system is indeed a temporarily increased unsafe situation (without any steel-fingers). Whereas in the long term the McNally system seems to be the most safe method of working – but is a subject of lost efficiency just under those very poor conditions where it is needed mostly, With huge over-breaks it doesn't allow for a

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

reasonably abutment of the steel sets and rock bolts which the McNally straps need for fixation.

Not to forget: all rock support measures have to be done under extremely limited space conditions within the L1-area since the Alto Maipo TBM are relatively small. Therefore it will remain always a not avoidable not negligible relatively high risk of injury to our operatives.

Summary and conclusion

1. The selected open gripper-TBM is the most sensitive TBM to operate given the actual geological conditions on site, which with rock support measures being implemented create a very restricted space for operations (so called L1-area). Consequently, this makes the TBM operations extremely difficult and effectively takes the open gripper-TBM, beyond its normal effective designed capacities.

2. Additionally with knowledge now of the envisaged rock classifications and geological conditions the risks are now compounded and thus put the TBM operators in danger.

3. Due to the high risk situation the Owner must consider a change to the shielded TBM to improve the working conditions of the workers, as the current one may have been assigned due to the now apparent misleading geological information at the commencement of the contract. This TBM is now proofing its "Not fit for purpose".

4. It is my consideration that the selection of the open gripper TBM may have been selected or specified on the scenario of being able to switch from TBM to Drill and Blast, with this type of

Dr. Ulrich Rehm | Tunnelling Consultant GmbH | Phone +49 (0)7821 3270606 | Fax +49 (0)7821 3270607 | ru@ tunnelling-consultant.de | www.tunnelling-consultant.de

drilling being more practical, given the tunnelling skills available in Chile. Nonetheless this no longer feasible give the geology now being encountered.

5. Furthermore it would appear that the selection for the TBM has based on what appears now to be the wrongful method of classification of rock, which is highlighted in the separate Geological Report of Dr. David Powell[2]. It is now becoming apparent that, if the excavation continue with this TBM, there will be considerable increase risks from unsecure rock conditions as the work progresses along its alignment with increased overburden as it goes further into the mountain.

6. Furthermore, as the Owner has now decided to use GSI (geotechnical strength index) system which offers a predominantly qualitative approach to correlate between rock and rock mass strength I advise it is not an appropriate classification system for TBM-tunnelling. It thus provides a wide range of interpretation, with on a pessimistic or optimistic interpretation. In my opinion the Owner decided for a much too optimistic interpretation which may justifies the use of the open gripper TBM technology,

7. The information in the specifications represent rock strength values equal or bigger than the minimum value required for the gripper-pads to be pressed against the side-walls properly. However there is no quantitative information on where and how often these low strength-values have to be expected which carries a high risk for the application of an open gripper-TBM corresponding to international recommendations (ITA, DAUB). In low strength soil-like ground it is not only risky that the gripper-pads could disrupt weak side-walls but also the basic concept of mucking through a hard rock cutter head which is based on gravity induced flow of dry grainy debris along the muck chutes will very likely come to its limit. This will then slow down the TBM performance rate dramatically due to required cleaning works of the clogged cutter head and could even question the basic feasibility of further TBM-tunnelling.

8. The geotechnical information in the contract document (Appendix Z) include information related to the internationally well-known Norwegian NTNU TBM-performance prediction model, including only two input parameters the drilling rate index (DRI) and the cutter life index (CLI). Since the NTNU-prediction-model is mainly based on rock-mechanical parameters including important

information about the fracturing characteristics, which are missing, it was not possible to apply this TBM-performance-prediction model in anyway.

9. The given values of the DRI and CLI in Appendix Z represent a relatively positive prognoses in terms of the expected bore ability and cutter lifetime - for the intact rock section - which was confirmed for the intact rock sections during my visit to site early April 2017. However those results of the NTNU tables do not give any indications on the fault zones which also lead to a too optimistic assessment of the rock quality along the tunnel. This increases the difficulty on the operations as the open gripper-TBM, which is the most sensitive TBM-type, in terms of mining through critical geotechnical sections like fault zones or stress induced sections under very high overburden.

10. It would seem from my observations on site, that in order to improve the safety, the McNally System seems to be a partly constructive approach, as it offers an improved method for protecting the workers from rock-fall. However, to facilitate this installation, all steel strips of the finger-shield have to be removed for putting the McNally steel straps into the steel pockets. Therefore the consequence of increased safety offered by the McNally system has temporarily increased unsafe situation whereas in the long term the McNally system seems to be the most safe one – which looses its efficiency just under those very poor conditions where it is needed mostly – when huge over-breaks doesn't allow for a reasonably abutment of the steel sets and rock bolts which the McNally straps need for fixation. Other rock support measure like steel or wooden lagging between the steel sets to protect the operators from rockfall which originally comes from the NATM is very difficult to apply in a small open gripper-TBM and may severely delay the progress of the tunnelling advancement.

    Not to forget: all rock support measures have to be done under extremely limited space within the L1-area since the Alto Maipo TBM are relatively small. Therefore we all have an unavoidable risk for the safety of all workers operating the TBM in the tunnel.

    So, my professional recommendations based on extensive experience in operating and supervising TBM operations, and, after reading the Geological report presented Dr. David Powell[2], I would <u>not</u> recommend to continue with this open gripper-TBM

My recommendation is primarily based on serious safety concerns, with high risks of Injury and even death of the workers in the vicinity of operations.

It should also be noted major delays shall occur and additional costs shall prevail, if the Owner decides to continue with this TBM under the different geological conditions, and the successful completion of the Tunnels will be at risk.

Dr.-Ing. Ulrich Rehm
(CEO)

References

[1]: DAUB German Tunnelling Committee (ITA-AITES): „Empfehlungen zur Auswahl von Tunnelvortriebsmaschinen" (Rekommandation for the choice of TBM); www.daub-ita.de, Oktober 2010

[2]: DB Powell & Ass. LTD: „Review oft he tunnelling conditions relating to the Volcan and Alfalfal tunnels"; by David Powell; May 2017

[3]:600-TU-ETG-001 Annex 1 volume 4