22 Decompression in tunnel construction using the hydroshield process

Experience in Switzerland with decompression tables adapted for construction sites in accordance with the ZH-L16 model

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Abstract
Tunnelling by the hydroshield technique requires workers to be exposed to overpressure for the inspection and repair of cutting tools. For decompression purposes, we used the Bühlmann model ZH-L16 which was specially adapted to meet the needs of the construction site. In order to examine the validity of the model we retrospectively evaluated 1,961 overpressure exposures (OEs) registered during the first phase of construction, which ranged from 1 to 3.4 bar. Exposure times varied widely from 5 to 455 min. and decompression times from 3 to 271 min. The overall rate of decompression sickness was 0.56% (11 cases: 4 knee pains, 4 shoulder pains, 1 shoulder-chest pain, 2 skin bends. There were no central nervous lesions). Four of the cases happened within the highest pressure range of 3.0 - 3.4 bar (101 OEs), 3 within the next lower range of 2.5 - 2.9 bar (180 OEs) and 3 within the remaining pressure ranges (1,762 OEs). Therapeutic recompression with pure oxygen proved successful in all cases. In conclusion, we consider the Bühlmann decompression model to be a satisfactorily appropriate procedure for construction sites. One important risk factor for decompression incidents seems to be an uncomfortable body position resulting from a cramped air lock. A more spacious one should therefore be mandatory.

Keywords: Decompression for construction sites, Bühlmann model ZH-L16, Overpressure exposures, Decompression sickness, Therapeutic recompression, Risk factors.

1 Introduction

The demand for efficient traffic routes and environmental requirements resulted in the start of construction in 1990 of a new, 6.3 km-long rail tunnel at an altitude of 530 m above sea level in the Grauholz area (Berne). Construction was implemented using a tunnelling machine of the Herrenknecht type incorporating a hydroshield to cope with the water-bearing ground. This technique requires workers to expose

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themselves to overpressure when inspecting and repairing the 11.6 m cutting wheel. To meet the problems of decompression, the construction consortium opted initially for the German decompression tables (1972). However in our capacity as the institution responsible for working safety in our country, we at SUVA rejected these as being too risky. We therefore had to provide other decompression tables which would also permit working times of more than 2 h at excess pressures of 3 bar and more.

2 The ZH-L16 model

In Switzerland, new decompression tables for air diving from three different altitudes (0-700 m, 701-2500 m, 2501-4500 m above sea-level) were introduced in 1986. These ZH-86 tables were calculated using the ZH-L16 model by Bühlmann (1986, 1988 and 1990). A detailed explanation of the background to this would go beyond the scope of this paper but, in summary, it represents an empirically derived mathematical algorithm expressing the almost linear relationship between absolute ambient pressure and tolerated inert gas overpressure in the tissue, represented by 16 half-value times. This model was considered a suitable basis for the construction-site decompression tables. DYNATRON, an engineering and consulting company, had the required software at their disposal and subsequently produced the tables we needed. They are structured in steps of 0.1 bar and permit decompression with air, as well as with pure oxygen, from 0.9 bar (Table 1). Preceding exposures automatically extend the decompression times of the following one, where the amount of excess time is indicated by 'repeat groups', marked by letters.

Table 1. Examples of decompression times

Overpressure (bar)	1.2		1.8		2.4	
Working time (min)	120	180	120	180	120	180
Decompression time (1) Druckluft-verordnung (1972)	4	4	27	46	67	112
(2) Bühlmann tables ZH-L16 (Grauholz/1989)	2	4	35	79	94	207

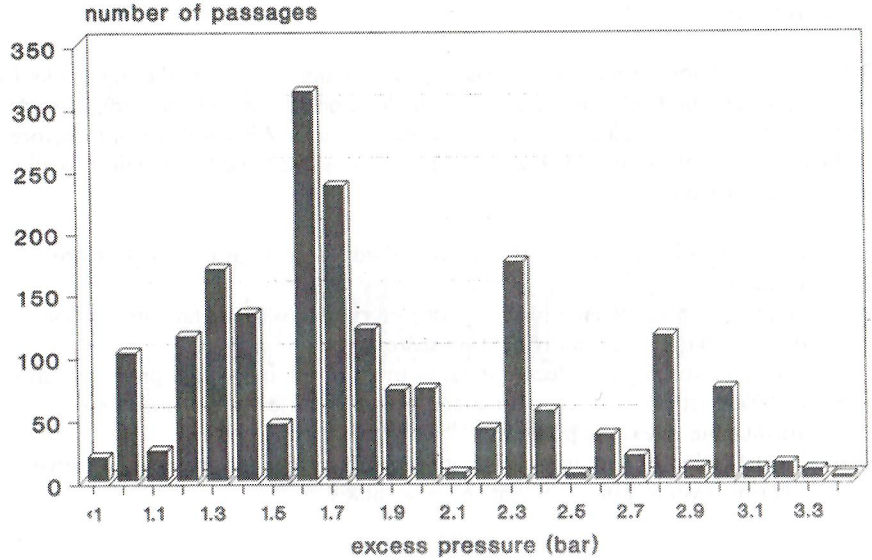

Fig. 1. Passages through air-lock/pressure stage

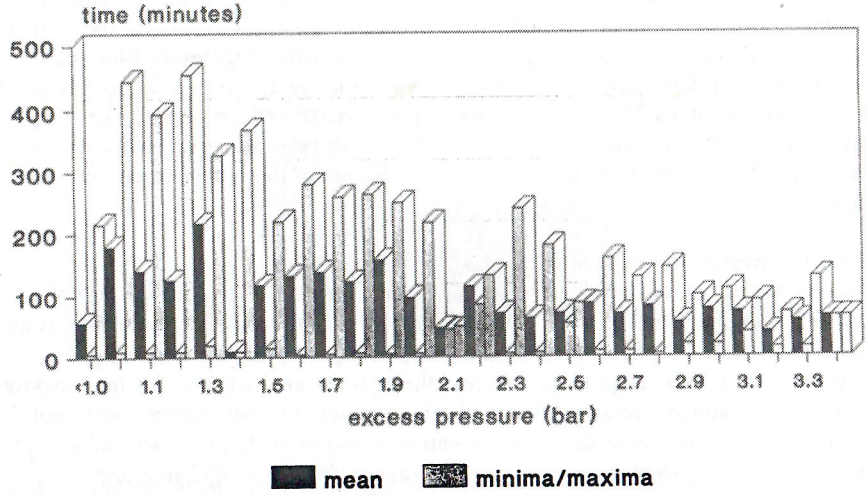

Fig. 2. Mean working times over individual pressure stages

3 Retrospective evaluation

The following items were at our disposal for evaluation purposes: the log books for the air-lock, the log book for the sickness air-lock on site and the records of each worker's preventive medical examination filed with us. What follows is therefore a retrospective evaluation of available data, which – we hoped – would provide the following information:

- Characteristics of the workforce concerned in terms of excess pressure medicine.
- Overall number of individual air-lock entry and exit movements and their distribution over the individual pressure stages.
- Average working and decompression times at the individual pressure stages.
- Characteristics, number, course and possible causes of any incidents attributable to excess pressure.
- Identification of certain risk factors deducible from the incidents observed.
- Interim, overall assessment of the new tables.

4 Results

Of 86 workers, 63 passed regularly through the air-lock, while 23 passed through once or only a few times. As a result, the latter group only accounted for 82 out of a total of 2,043 compressed air exposures. As we have no preventive medical records on them and none of them was affected by an excess pressure incident, they are not included in the following. The 63 workers from 9 different European countries in the first group were 34.6 years old on average (range 21 to 54) and had a body weight of 98.2% (76 to 134%) by the Broca Index (= weight (kg)/height (cm) - 100). Almost two thirds of them, 63.3% to be exact, were working for the very first time under the excess pressure conditions in the tunnel construction described here.

4.1 Compressed air exposures

As mentioned, 63 workers passed through the air-lock 1,961 times during the first construction phase between 15/1/90 and 16/7/91. Entry and exit movement peaked at 1.6 bar with 307 exposures and decreased at higher pressure with only 2 exposures at 3.4 bar (Figure 1). Access through the air-lock was for the purposes of inspection, maintenance and repairs. Such activities, by their nature, were not distributed regularly over the period mentioned and their duration was subject to wide variations. Working times therefore ranged from 3 to 455 min and decompression times consequently from 3 to 271 min. On average, working times gradually shortened from about 200 min in the lower pressure range to about 50 min in the highest one, and decompression times from 2 to about 120 minutes (Figures 2 and 3). For one worker there was a maximum of 2 to 3 exposures within 24 h.

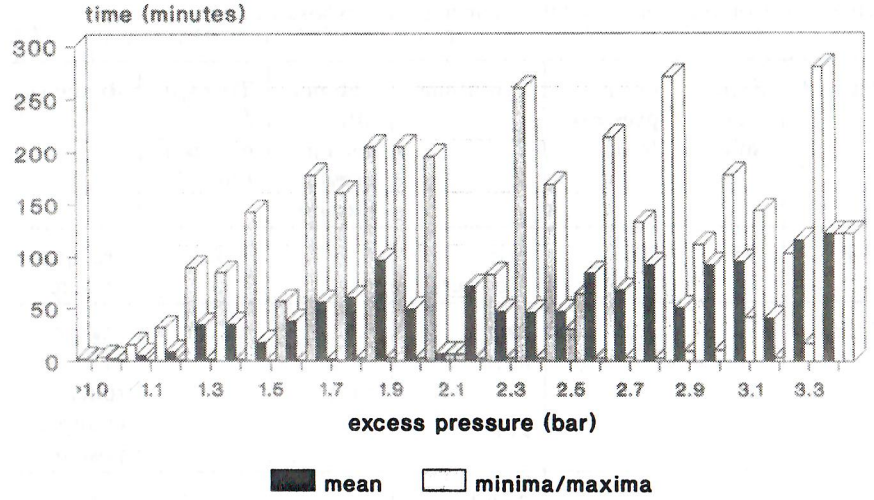

Fig. 3. Mean decompression times over individual pressure stages

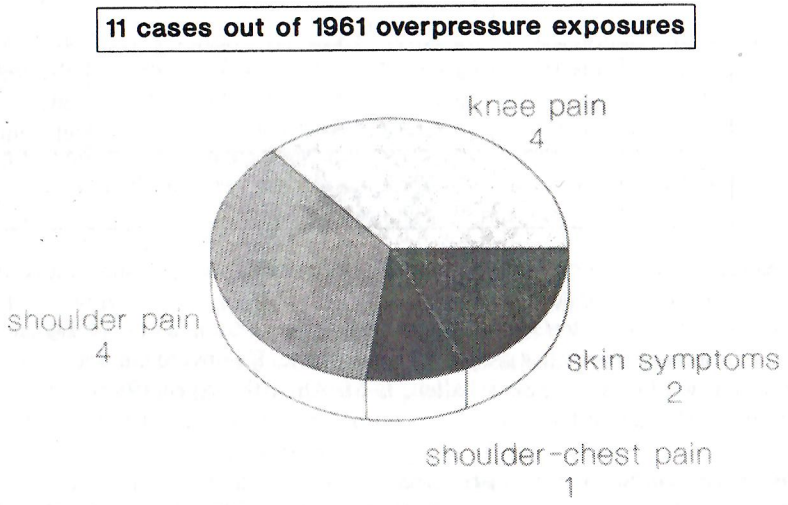

Fig. 4. Incidents attributable to excess pressure

Table 2. Decompression incidents occurring after exposures above 2.5 bar

Patient	Exp. time (min.)	Over-pressure (bar)	Symptoms	Latency after decom-pression (hours)	Therapy & duration (hours)	Remarks
F.F.	95	2.6	pain r. shoulder	4	* (4.5)	cramped posture
M.B.	75	3.0	pain r. knee	1.5	A (2.5)	change of rollers, cramped posture
5 days later	95	2.8	pain l. shoulder	6	* (4.5)	ditto
M.P.	75	3.0	pain r. shoulder	7.5	A *Hosp.	ditto
O.B.	94	3.0	pain l. arm, thorax	4	A (3.0) Hosp.	ditto
D.A.	90	3.0	pain l. knee	5	* (3.5)	Control and cleaning
K.J.	175	3.0	red spots on skin	3	* (3.0)	

* Treatment with pure oxygen and gradually decreasing overpressure-intervals of 55 min. from 1.5 bar to 0.6 bar

A Treatment according to German recommendation (Merkblatt für die Behandlung von Erkrankungen durch Arbeiten in Ueberdruck, Hautpverband der gewerblichen Berufsgenossenschaften, D-St. Augustin, April 1989)

( ) Length of therapy in hours

4.2 Incidents caused by excess pressure

During the period of observation, 10 workers were involved in 12 incidents. As Figure 4 shows, 11 cases were of decompression sickness and one case of barotrauma of the middle ear. Among the 11 cases of decompression sickness, nine concerned arthralgia and myalgia, with the knees and shoulders or upper arms being affected four times each plus one case of the left upper arm in combination with chest pains and headache. Skin symptoms were also observed twice (red spots,

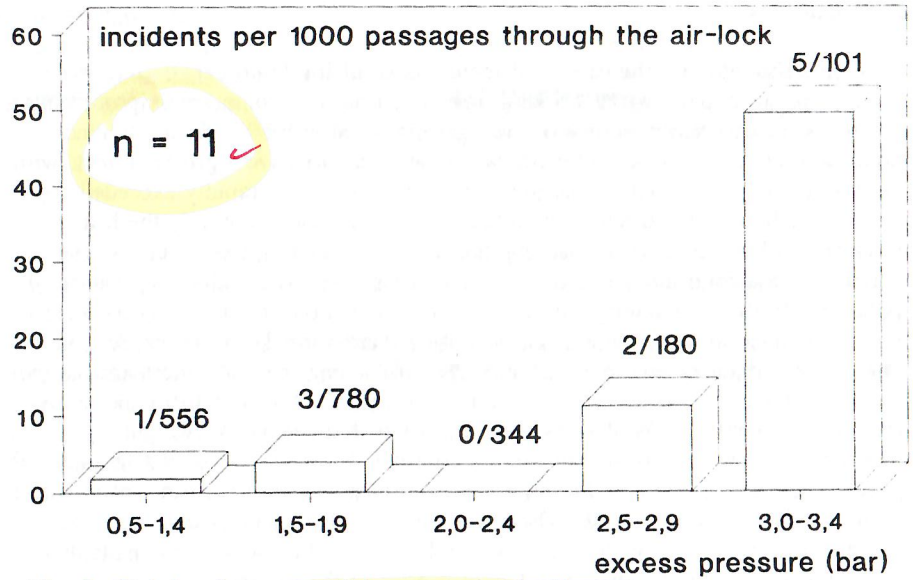

Fig. 5. Relative frequency of decompression incidents

itching, swelling). Details of the cases occurring after exposures over 2.5 bar are summarised in Table 2. The average latency between exiting the air-lock and the start of the complaint amounted to 5 h and 40 min (range 1.5 - 15 hours). Seven of these 11 incidents caused by excess pressure were concentrated on the 2.5-bar excess pressure stage, the remaining four, however, were distributed evenly over the lower pressure ranges in absolute terms. Four of the incidents took place on three consecutive days. As can be seen in Figure 5 – and this will come as no surprise – the risk of incidents increased as pressure rose.

4.3 The treatment and course of decompression incidents

With the exception of one case with skin symptoms, all the patients with decompression incidents were recompressed therapeutically following consultation with the doctor involved and, initially, on the construction site. This proved successful in 9 of the 11 cases. Two different styles of treatment were used, both of which, however, largely involved pure oxygen (Table 2). One patient felt no relief after the first course of treatment and another patient experienced no relief after the two combined methods. As a result, both had to be transferred for further treatment to the University Clinic in Zurich. However, after further HBO therapy, both were allowed to go home within 24 - 48 hours. It can be stated that all patients recovered fully.

5 Conclusions

5.1 Some thoughts on the causes of incidents resulting from excess pressure

Excess pressures and lengthy working times can lead to decompression problems as, due to the much greater volume of inert gas dissolved in the tissue, the limited predictability of individual and workplace-related factors have a greater effect, with the result that existing safety margins in the tables are more rapidly exceeded. Workplace factors of particular importance are, in our case, not only the heavy, physical work at times when changing the rollers and cutting tools, but also the deleterious environmental conditions, which occasionally reached a temperature of 30°C and 100% air humidity. It must also be pointed out that the workers were forced to adopt uncomfortable positions during their compulsory decompression phases when cramped in the 5.3 m^3 air-lock and leaning their shoulders against the corners, which could have had a contributory effect to the discomfort experienced in the upper extremities. Well-known risk factors such as being overweight or inexperience with compressed air are not considered to have played a role among the patients, as those concerned did not differ significantly from the entire group where these two factors are involved. The after-effect of previous entry and exit movements through the air-lock can largely be excluded as none of the patients had been exposed to excess pressure in the 24 h prior to the incident.

5.2 Overall assessment

The 0.56% incident rate of decompression sickness resulting from excess pressure in our group of patients is an expression of inadequate decompression (11 cases out of 1,961 overpressure exposures). Comparison with other construction sites is difficult, as hardly any relevant figures are available. In Munich (FRG) for instance, the 0.36% incident rate occurred within a much lower pressure range of 0.4-1.5 bar (Kessel, 1986; Mauermayer *et al.*, 1988) and in Kiel (FRG) with comparable pressures it was about 2% (personal communication). We believe therefore, that our results do not look too bad. With regard to the use of the tables, in particular the allowance for additional times in the form of repeat groups, those in charge of the construction site coped very well by trying to form consistent groups and by planning work assignments well in advance. As a result of the relatively low number of incidents, the additional costs caused by decompression times which were longer than anticipated were accepted by the construction consortium and the client. However, improvements are scheduled for the next construction phase and these will be implemented as far as possible. These mainly concern enlarging the working lock, which will improve seating comfort and prevent the adoption of a cramped posture. The possibility of decompression using oxygen is still a matter for discussion although the construction consortium has adopted a cautious attitude to this.

Acknowledgments

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