Mobile Stoppings in Complex Subsurface Operations[1]

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Abstract: Emergency situations in subsurface structures hold specific challenges, particularly in the case of highly dissected underground structures (several levels, winding, high penetration depths). Successful mission accomplishment is primarily linked to the existence of a functioning ventilation system, which must be understood and controlled by the emergency forces. This paper presents the development of a physical separation of the zone transitions to enable interventions in the air flow conditions by means of ventilation elements which can be quickly deployed and relocated. Besides the availability of specialized units capable of setting up the necessary ventilation sections, expert knowledge in the *SubSurface Operations Cell* (SSOC) and a suitable ventilation simulation is needed to define these sections. The interdisciplinary development of a customized mobile ventilation door is an essential building block for managing complex underground operations. The establishment of zone crossings even in large cross-sections allows effective ventilation interventions in two-lane underground traffic structures with a large longitudinal extension.

Key Words: complex subsurface operations, SubSurface Operations Cell (SSOC), ventilation flow, ventilation simulation, traffic tunnel

1. Need for Complex Subsurface Operations

Complex underground operations can take place in a hostile environment characterized by widely branching underground structures over several levels, unfavorable air conditions, gas propagation, hazardous substances, electricity, geotechnical influences, water ingress, and an adversary who is proactive and familiar with the environment (Hofer 2018, p. 541). Rapidly growing *subsurface service structures* are critical infrastructures or parts thereof which have an essential importance for the maintenance of important societal functions. Their disruption or destruction has a serious impact on health, safety or economic and social well-being of the population or the functioning of government institutions (Bundesministerium für Landesverteidigung 2020, term "Kritische Infrastrukturen"). In addition to responders, a large number of civilians is certainly affected, and crisis management requires a multi-stakeholder approach (Hofer 2018, p. 542) which can be facilitated by the S6-model of **S**afety and **S**ecurity **S**trategies for **S**ubsurface **S**ervice **S**tructures (Hofer 2020a). The definition of complex underground operations was a decisive prerequisite for developing an operational procedure (Hofer 2021) and its essential core is the definition of deployment zones to allocate space and tasks. The deployment in the red contact zone is assigned to those elements with the best equipment and training, whereas the adjacent yellow consolidation zone as well as the green saturation zone pose fewer challenges in terms of specialization (Fig. 1) - a circumstance that has also been taken into account in development of an inter-actor curriculum for training within the KIRAS project ETU-ZaB (Galler and Hofer 2021, p. 109).

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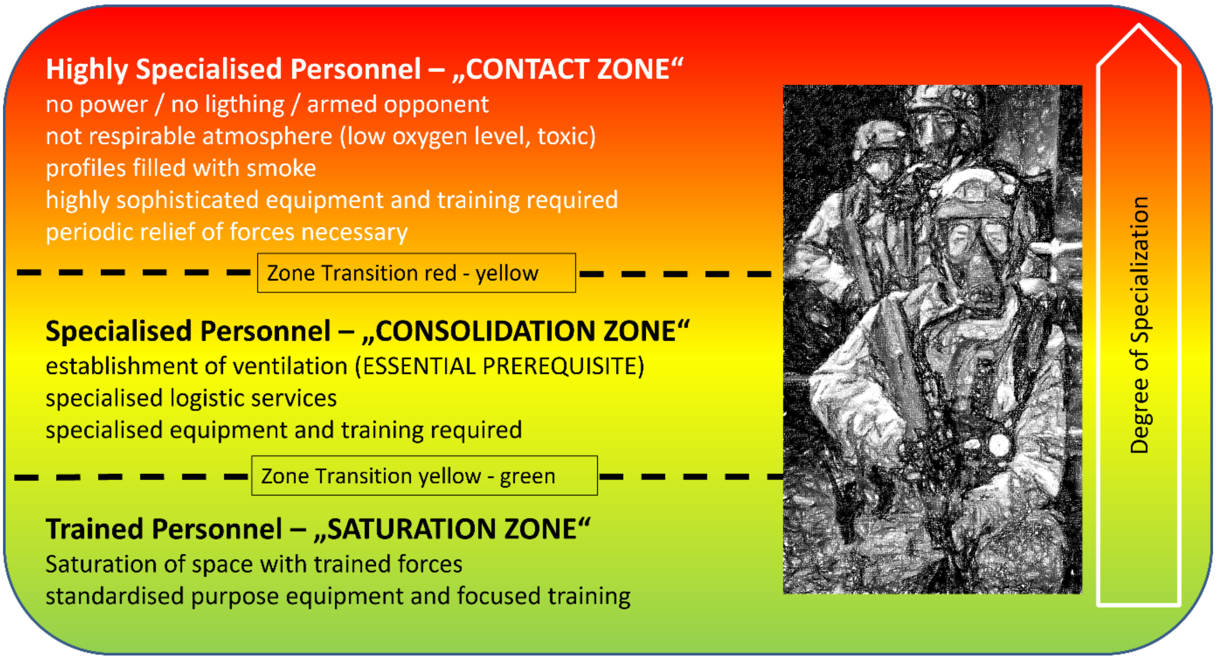

Figure 1: The three zones in complex underground operations make an important contribution to the safety of the deployed forces as well as the civilians involved (Graphic: Hofer).

Especially in the case of highly dissected underground structures (several levels, winding, high penetration depths), this subdivision is necessary and linked to a functioning ventilation system, which must be understood and controlled by the emergency forces. Constant interventions of the ventilation are required to physically separate the transition zones and enable forward-deployed forces regular relief from the hostile environment in the contact zone. Planning and installation of these ventilation sections depends on expert knowledge in the *SubSurface Operations Cell* (SSOC) (Hofer 2020b), the use of applications to determine the flow conditions and a specialized unit capable of operating mobile ventilation elements (ventilation screens, ventilation doors, brattices, ventilators). Integration of these data into the truly comprehensive Common Operational Picture (tcCOP) by means of RApid Data Integration and Visualization (RADIV) is a key requirement for the assessment of the situation (Hofer et al. 2022).

2. Development Status

As subsurface service structures vary in terms of expansion, cross-sections, and ventilation concepts, also the existing technological approaches are quite different. For small cavity cross-sections (around 10m² cross-sectional area) solutions could be found which can be erected quickly with simple means. The brattice proposed by (Nikolaev et al. 2020) consists of prefabricated frame elements, a circumferential air-filled hose and fire blankets clamped in between offering higher stability whereas the "Scheuer model" brattice (Fig. 2) consisting of a fire hose filled with compressed air and plastic sheeting can be erected faster and offers more flexibility concerning the shape of the cross-section.

Challenges increase with growing diameters railway and road tunnels. Textile curtains in the “Roppener” tunnel serve to reduce the speed of longitudinal flows (Aigner Tunnel Technology GmbH k.A., p. 3) so that as little fresh air as possible is extracted via the exhaust air flaps. The Roppener system functions but is unsuitable for the requirements of complex operations due to its inability to withstand higher pressure differences between the zones and complex installation requirements (Henn 2010, p. 1).

The Inflatable Tunnel Plug is based on the principle of an air-filled hose around the entire cross-section with a fitted plastic tarpaulin providing an opening for a duct and a way through for people. This solution was developed to cut off the oxygen supply in tunnel fires (Lindstrand Technologies 2008) and is not suitable for frequent passage including vehicles. The Inflatable AirStop with Emergency Personnel Safety System completely fills the cross-section and allows people to pass through (ABC Ventilation). Such solutions can be custom made, but the size and material required make them unwieldy for large cavity cross-sections and require significant amounts of compressed air and usually a power supply for the blower to maintain shape stability. Therefore, such solutions are out of the question at the red - yellow zone transition, as here it cannot be assumed that there is a secure power supply or sufficiently copious quantities of available compressed air.

In summary, the following requirements can be placed on a mobile ventilation door:

- Erection / dismantling within a maximum of 30 minutes.
- Sufficient reduction of the volume flow over the entire cross-section.
- Minimum headroom of 3.5 metres (passage for military vehicles).
- Easy handling without additional climbing aids and power supply.
- Fabricated of fire-resistant material.
- Low installation effort during construction and retrofitting.

3. Methodology

After development of the operational concept (Fig. 1) and definition of the requirements the basic principle for the ventilation door was designed. It foresaw a plastic tarpaulin fitted into the standard cross-section, secured with ropes, offering a passable opening, and using surrounding flaps providing self-sealing under pressure. Three phases of testing at the “Zentrum am Berg”[2] were conducted to gain insights on handling under operating conditions, leakage, and the effect of installation in the entire ventilation system. In the first phase, the basic principle was tested using a double plastic film fixed with circumferential static rope and load securing nets (Fig. 2).

Figure 2: Left: The hose brattice - "Scheuer model" - a very easy and quick to erect option for small cross-sections (Photo: ÖBH, Scheuer). Right: Initial prototype of the mobile ventilation door made of plastic film and nets (Photo: Hofer).

In the second step, the ventilation door custom-made for the tunnel cross-section (truck tarpaulin fire-resistant - DIN EN 13501-1) was tested and examined for function and leakage. Using different ventilation patterns, the results from the ventilation simulation were checked for plausibility by means of point measurements. In addition, the fastening underwent a "stress test" with the maximum pressure of the installed fans. The third phase consisted of measurements of volume flow, pressure difference and tests of handling in general including assembly and disassembly. Those comparative measurements enabled a better understanding of the effects of interventions in the ventilation flow within the overall system and allow more precise statements to be made on the extent to which forecast accuracy is given for extended and more complex models. The use of artificial fog facilitated the identification of leakages as well as the behavior of the air flow.

Based on the above-mentioned requirements a plan of the mobile ventilation door "ZaB" (Fig. 4) consisting of the tarpaulin and the climbing aid integrated in the sidewall could be drawn up. The design of a climbing

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[2] https://www.zab.at

aid provides for a recess in the tunnel sidewall in which a permanently mounted steel ladder is installed to simplify the installation of the mobile ventilation door.

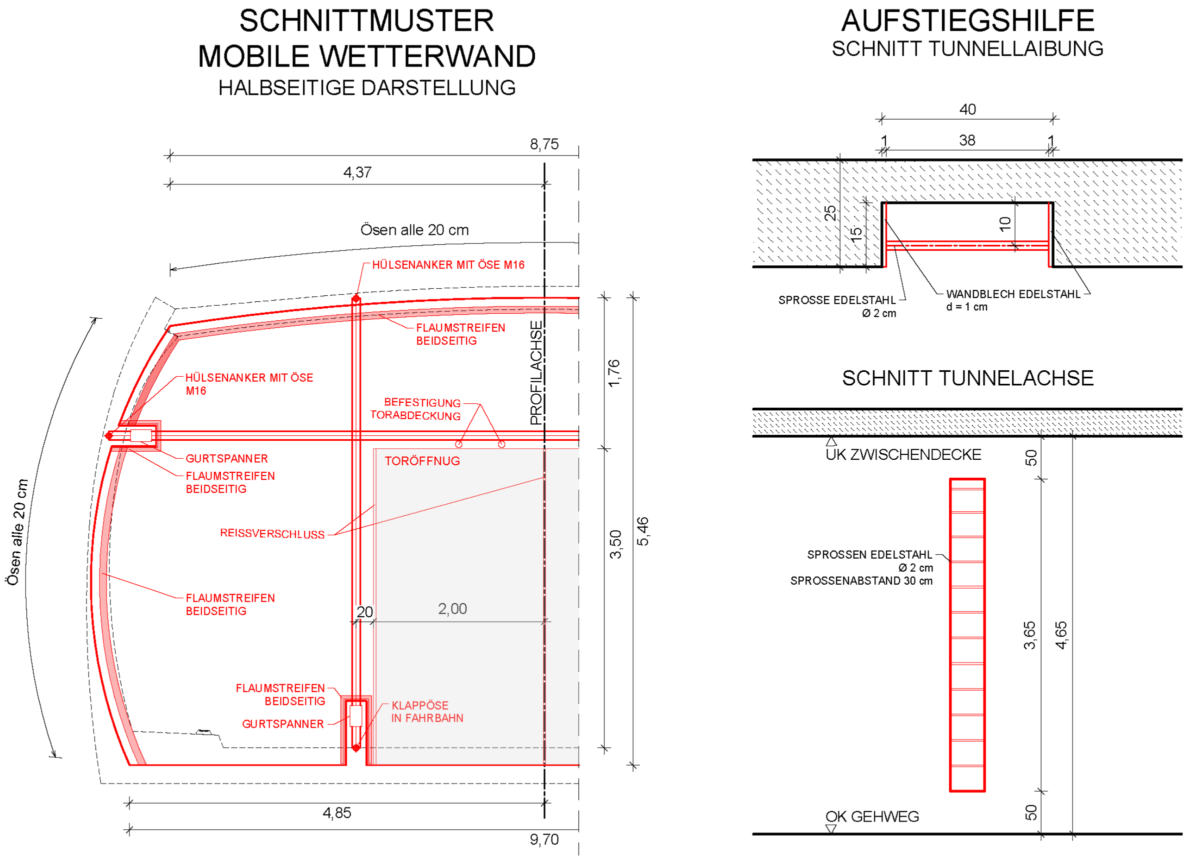

Figure 3 Left: Plan of the custom-made mobile ventilation door "ZaB" with tensioning straps integrated in the tarpaulin and a passage opening w/h=4.00/3.50 m. Right: Design of recess with permanently mounted climbing aid in the tunnel sidewall (source: Laabmayr, Salzburg).

In the case of the custom-made "ZaB" prototype (Fig. 5), sleeve anchors, folding eyelets, aluminum rolls and a circumferential steel cable were installed in such a way that the installation of the mobile ventilation door can be ensured by trained personnel within ten minutes. To keep the construction and maintenance costs as low as possible, metal, and synthetic components would be preferable.

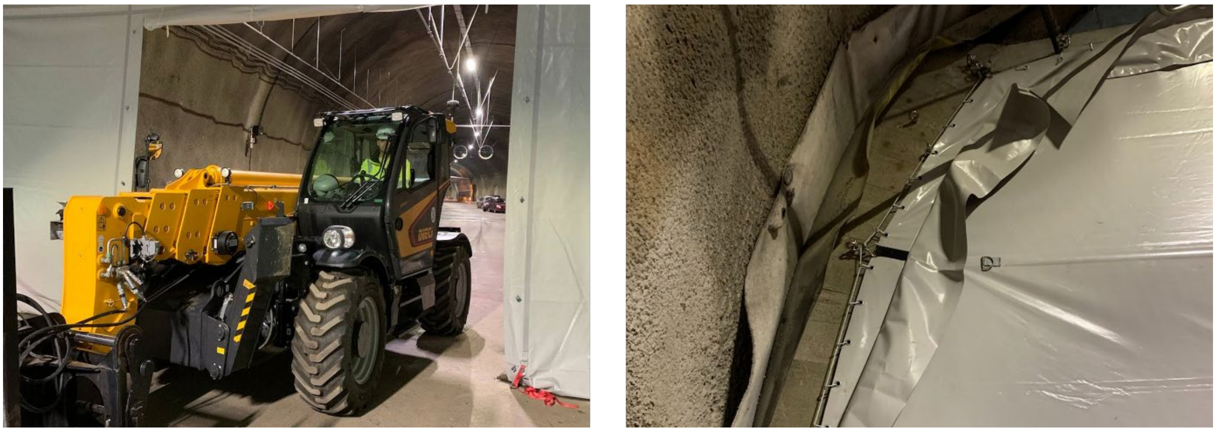

Figure 4: The custom-made mobile ventilation door (left), hooked into the surrounding steel cable with carabiners (right), in operation. The door cover is rolled up and fixed for passage, vertical and horizontal reinforcement straps, ground anchoring and the surrounding flap, which self-compacts under pressure are clearly visible (Photos: Hofer).

The tests have shown that the mobile ventilation door brings about a sufficient reduction in the volume flow in the weather path affected. However, the function of the gate and its tightness must be considered in the overall ventilation system.

4. Application of VENTSIM in the SSOC

The aim of using VentSim[3] ventilation simulation software is to obtain a rapid overview of the currently prevailing ventilation situation and to predict the effects of interventions as a basis for decision-making concerning the installation of ventilation control elements to guarantee sufficient fresh air in accordance with the operational requirements. Initially developed for planning the ventilation of underground mines VentSim can solve complex ventilation networks with just a few iteration steps. In contrast, CFD (Computational Fluid Dynamics) applications usually focus on the actual flow behavior in a defined model. Even though more information on the flow behavior can be obtained through these applications, model construction and calculation are time-consuming and limited to small sections.

During this study the use of VentSim to support complex underground operations by assessing the ventilation situation using the mobile ventilation door model "ZaB" was investigated. A three-dimensional ventilation model was created based on survey data containing important geometric information such as ventilation path length, cross-sectional shape, and cross-sectional area. Based on the basic geometric model, stoppings and fans were implemented. Resistance values of the stoppings were estimated by visual observation and the parameters of the jet fans were taken from technical data sheets. Friction coefficients of the individual airways were assumed from existing empirical values. This procedure corresponds to that in an emergency – a case in which not all required information will be available from the beginning (Fig. 3).

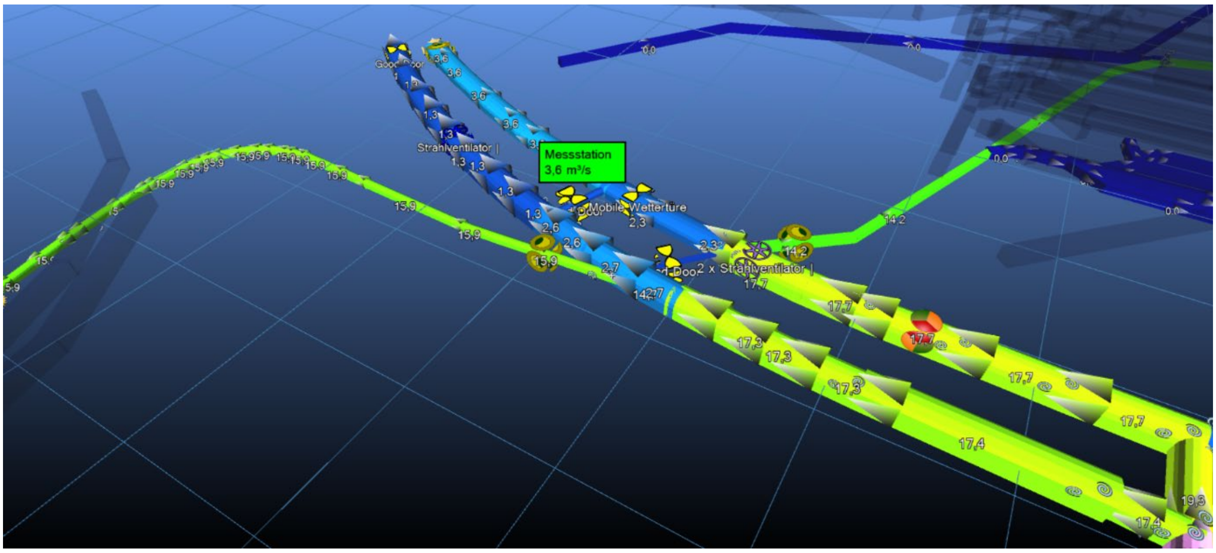

Figure 5: The application of VentSim in a complex underground operation allows good conclusions to be drawn at early stages of the operation (Graphic: Nöger with VentSim).

As soon as the first measurement data from on-site sensors or advancing elements are available, these are adjusted to the real conditions. In general, the more complex a simulation is, and the more unknown parameters must be considered, the greater the expected error of predictions.

Comparative measurements for validating the volume flow were carried out after assessing the ventilation network at a predefined point, and the flow velocity was determined using the fixed-point method. Four different test arrangements were selected for the function test of the mobile ventilation door as well as the reference measurements. The results of the simulation were compared with the measured volume flow based on plausible basic assumptions (essentially resistances, fan power, geometry), showing that even with simple assumptions a good agreement between predictions and measurements can be achieved – applying both to the prediction of direction and quantity. Thus, reliable forecasts can be made for mission planning, as soon as measurement data are available and the ventilation model can be calibrated to minimize differences.

The first tests using VentSim clearly showed that using the software brings about a quick overview of the prevailing weather situation and the needs of the SSOC for a quick assessment of the situation can be met.

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[3] https://ventsim.com

5. Summary and Outlook

The mobile ventilation door in combination with a ventilation simulation enables quick establishment of zone crossings. Those physical segregations are a prerequisite for operating in a wide-stretching subsurface infrastructure, the three test phases demonstrated effective volume flow reduction using this method during a complex subsurface operation.

For the implementation and use of mobile ventilation doors in underground cavity structures or tunnel systems, the further project-specific questions must be considered: storage, installation location and precautions in the tunnel. Those locations and precautions must be defined in advance for each project in coordination with the emergency organizations and prepared accordingly.

The development of the customized mobile ventilation door for large tunnel cross-sections is an essential building block for coping with complex underground operations and improves the operational capabilities even in large cross-sections allowing effective ventilation interventions in two-lane underground traffic structures with a large longitudinal extension.

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