Mine Sealing

Author: Prof. Dr.-Ing. habil. Heinz Konietzky
(TU Bergakademie Freiberg, Geotechnical Institute)

1 Introduction

The purpose for mine sealing is:

- Reduction of hazards to humans and animals
- Protection of cultural and natural incl. mineral resources
- Reduction of subsidence
- Reduction of contamination of biosphere
- Reduction of emission of hazardous gases
- Utilization of underground space for storage purposes

Mine sealing has to consider vertical and inclined shafts, horizontal access drifts (tunnels), but also underground drifts and ramps and to some extend also boreholes (e.g. ventholes). Depending on potential hazard (risk) mine sealing will executed in a very different manner. Hazardous mine openings are a frequently encountered phenomenon (see also Fig. 1.1), for instance:

- Heath (2009) detected 244 unsafe abandoned mine openings alone in the central mining area of Johannesburg.
- Over 500 partly unsafe openings exist due to former mining activities of the WISMUT mining company in Saxony (status 2014).

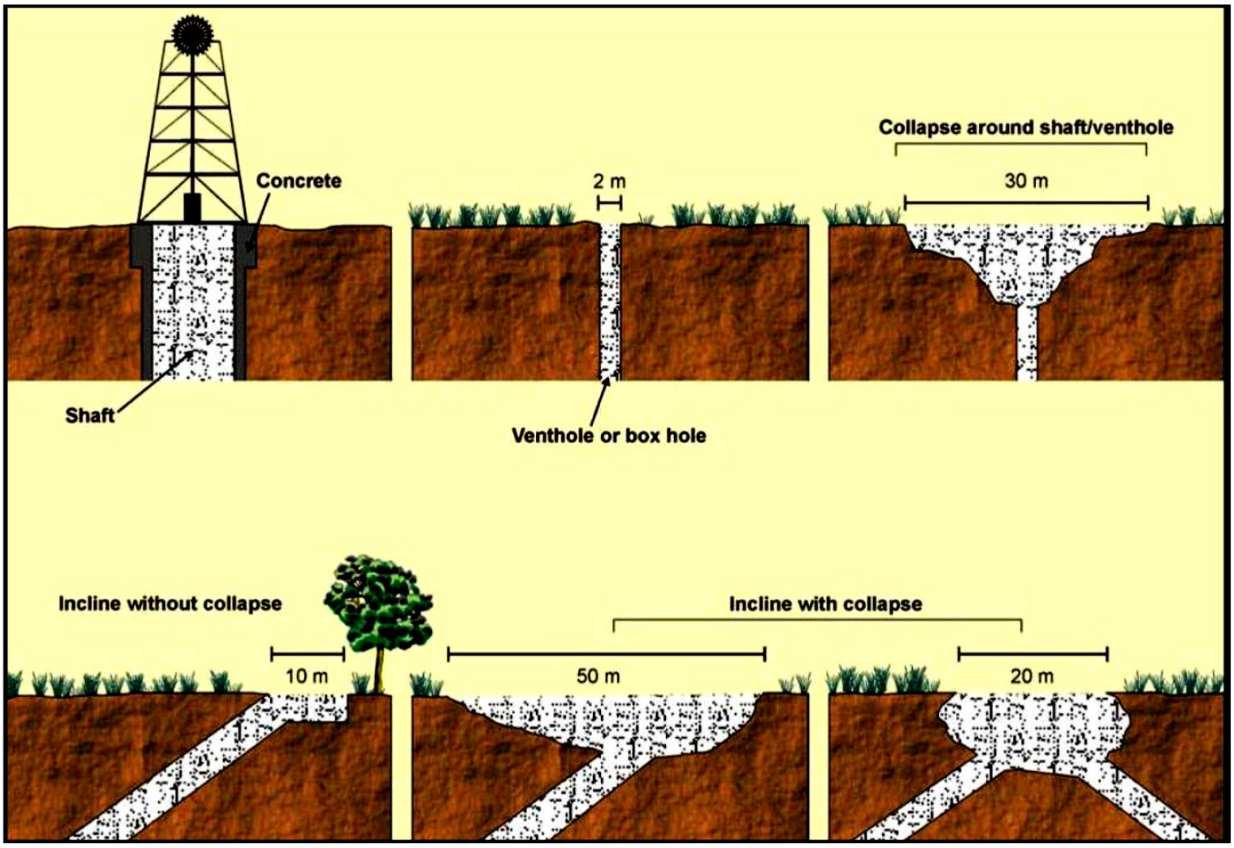

Fig. 1.1: Typical examples of openings which need sealing (Heath, 2009)

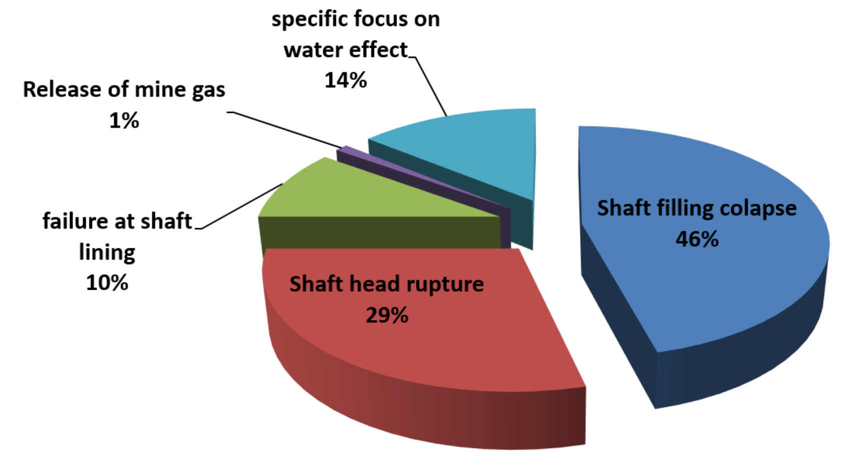

Fig. 1.2: Shaft failure analysis (after: Salmon et al., 2015)

Salmon et al. (2015) investigated 1023 shafts worldwide and found that 322 of them showed collapses with different failure modes (see Fig. 1.2). They have shown that shaft filling collapse and shaft head rupture are the main reasons for shaft damage. They also documented, that a remarkable percentage of the shafts (about 30%) experience damage (see also Lecomte et al. 2014).

2 Selection of mine sealing method

The selection process for an appropriate sealing concept needs the following information:

- general dimensions and conditions of openings (shaft, tunnel, borehole etc.)
- potential hazards caused by water and air pollution
- depth of openings
- stability, deformability and weathering of the surrounding rock mass
- surface and groundwater situation
- quantity and quality of water discharge
- proximity to human and wildlife activity
- required safety levels
- considered and required lifetime of sealing construction
- compliance with permissible limits and regulations

Due to the different orientation of gravity in respect to opening axis, sealing constructions in vertical openings (e.g. vertical shaft) are different from those in horizontal direction (e.g. tunnels). To reach water- and gas-tightness in horizontal openings is much more difficult.

3 Sealing materials

The materials used for the sealing constructions have to fulfil two functions:

- Tightening in respect to fluids, gases and bulk material transport
- Stabilising of the opening (avoiding of further collapse, restriction of further evolution of excavation disturbed zone etc.)

Besides stabilising and tightening of the opening (shaft, drift, tunnel etc.) itself, in some cases also the excavation disturbed zone (EDZ) has to be treated (sealed). This has to be done by injections (grouting).

To fulfil the above-mentioned different functions, different materials – often combined – are used, like:

- asphalt / bitumen
- clay (bentonite)
- ballast material (crystalline rocks, gravel)
- sand
- special concrete (e.g. MgO-concrete, Sorel-concrete, Salt-concrete)
- polyurethane foam
- crushed salt

4 Selected typical constructions

In terms of lifetime mine sealings can be divided into:

- Short-term measures
- Long-term constructions (several decades)
- Permanent constructions

Short-term measures include:

- Fencing
- Steel wire screens
- Steel grate closure
- Steel plate closure

Long-term constructions include:

- Concrete caps
- Steel reinforced concrete caps
- Polyurethane foam plugs

Permanent constructions:

- Backfill closure
- Blast closure
- (Heavy permanent cap)

- Self-supporting plugs
- Anchored plugs

The following figures 4.1 - 4.5 illustrate some of the above-mentioned constructions. More complex ones for special purposes as discussed in chapter 6. Numerical modelling can be used to find optimum solutions and to determine safety factors in dependence on opening size, geometry and rock mass properties (see Fig. 4.6).

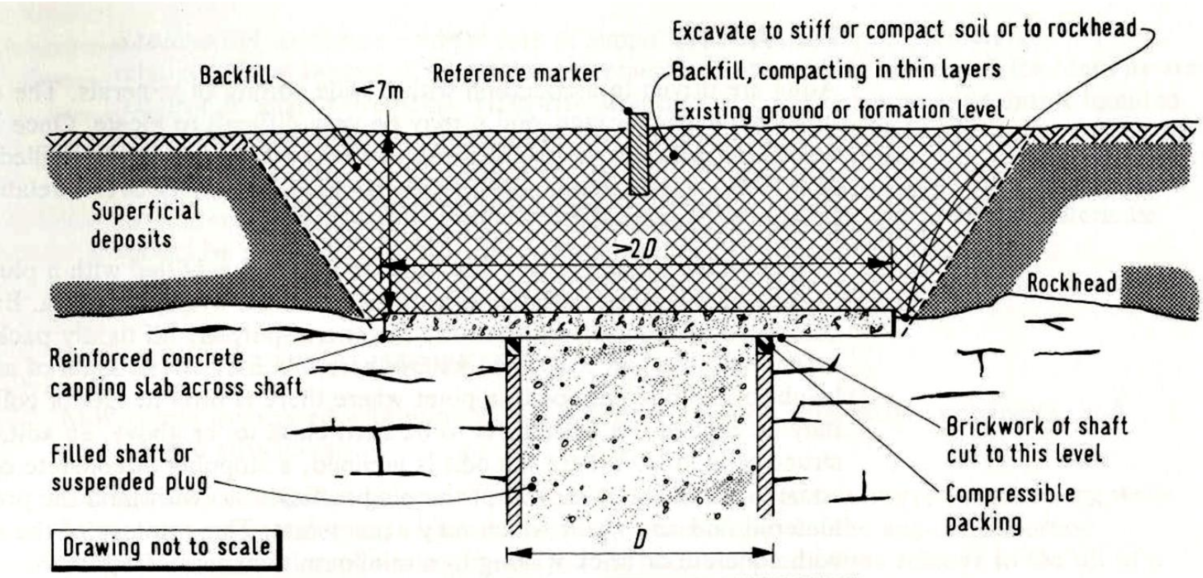

Fig. 4.1: Typical concrete cap (Heath, 2009)

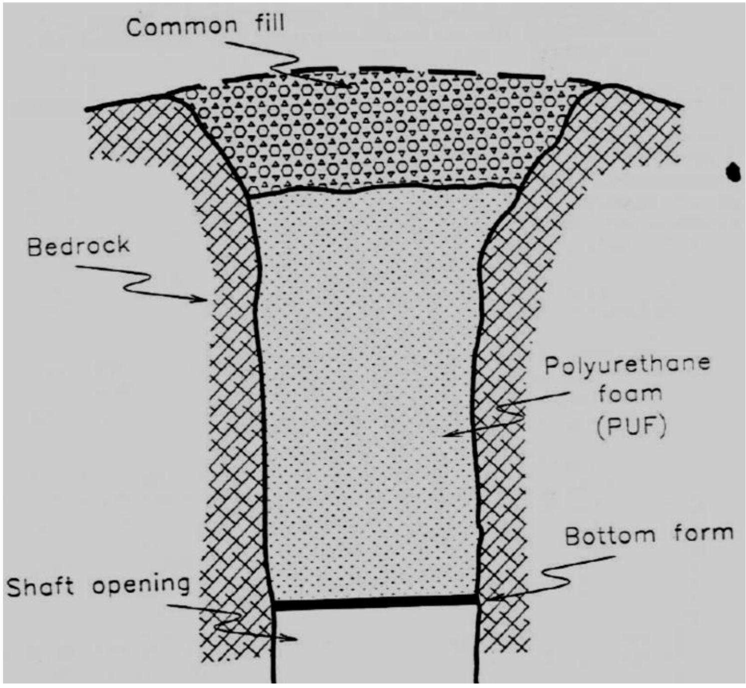

Fig. 4.2: Typical polyurethane plug (Heath, 2009)

Fig. 4.3: Shaft capping (Bhowan, 2019)

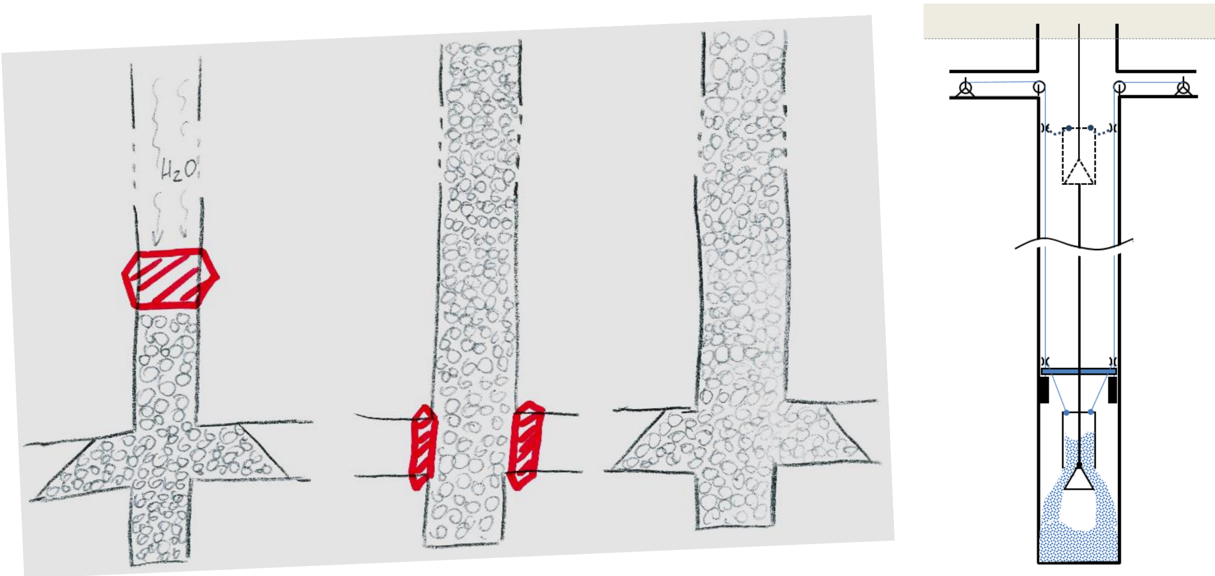

Fig. 4.4: Different shaft sealing options (red: dam), right: ballast filling procedure

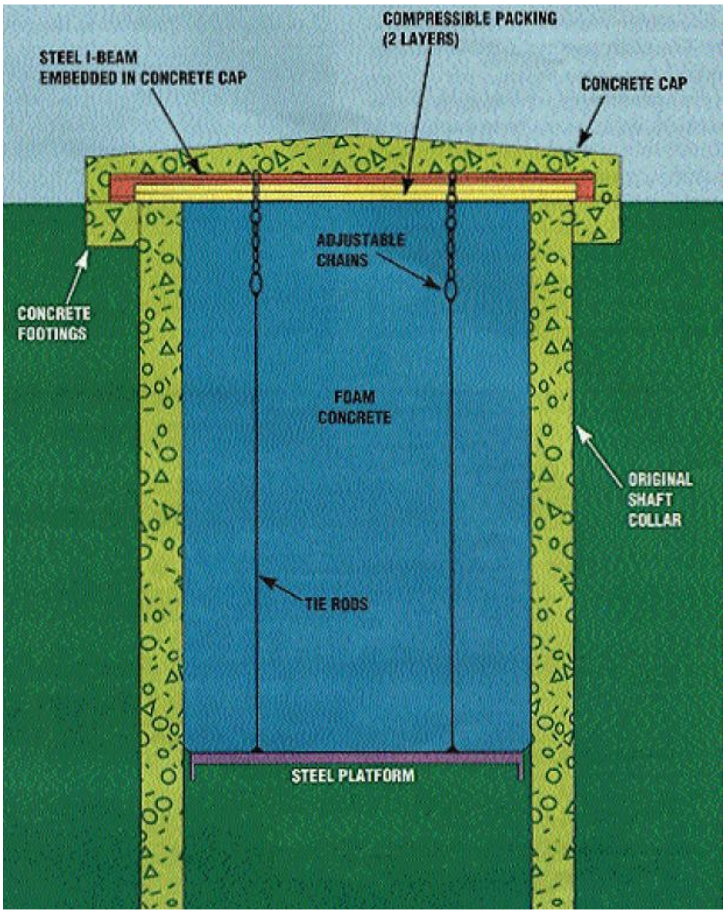

Fig. 4.5: Shaft sealing with foam-concrete plug and cap (Koski, 1994)

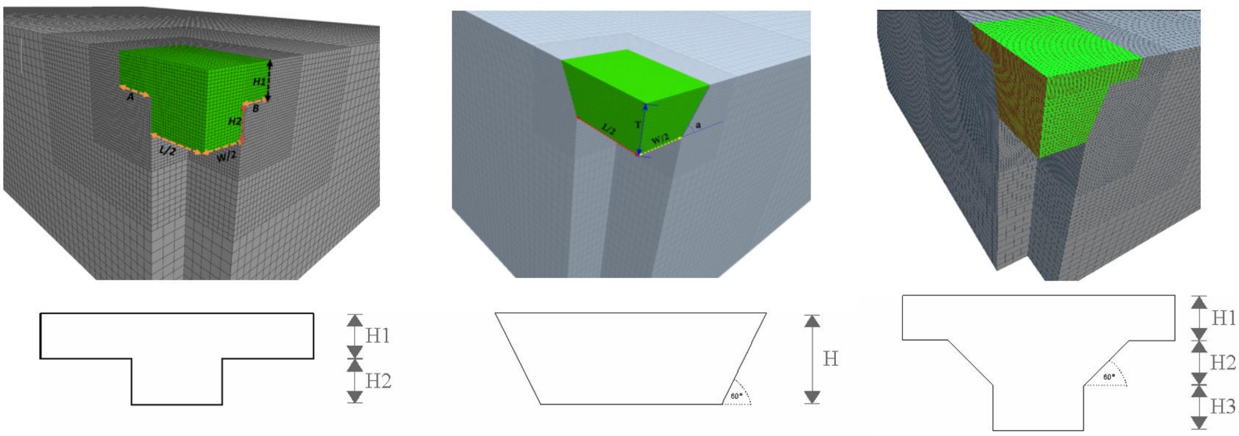

Fig. 4.6: Shaft concrete capping options investigated via numerical modelling (Konietzky et al., 2014)

5 Numerical simulation of shaft filling

The shaft filling process with ballast is a highly dynamical and discontinuum mechanical process, which needs a special simulation procedure. Particle based approaches (e.g. Nguyen, 2016; Bock & Prusek, 2015) provide the capability to simulate the complete filling process considering the falling backfill, the movement of backfill, the development of compaction and pressure built-up. It can also consider the breakage of ballast particles. Fig. 5.1 illustrates the simulation of backfilling a shaft with a connected drift (filling station). Fig. 5.2 shows the simulation for different shaft constellations and Fig. 5.3 shows the influence of different falling heights of the ballast.

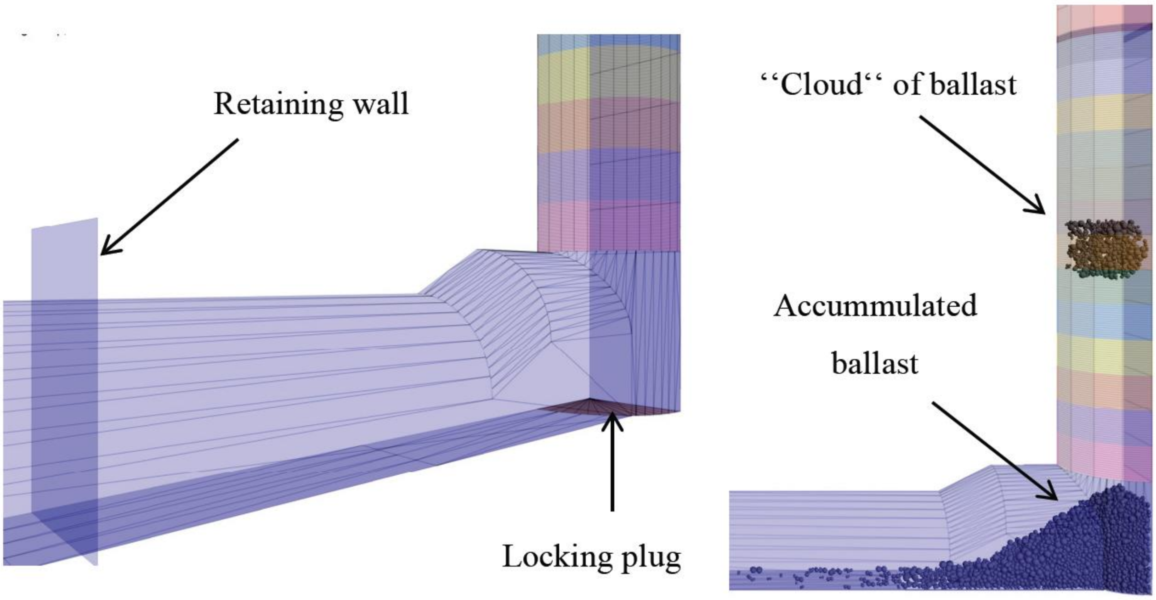

Fig. 5.1: Simulation of backfilling a shaft with connected drift (Nguyen, 2016)

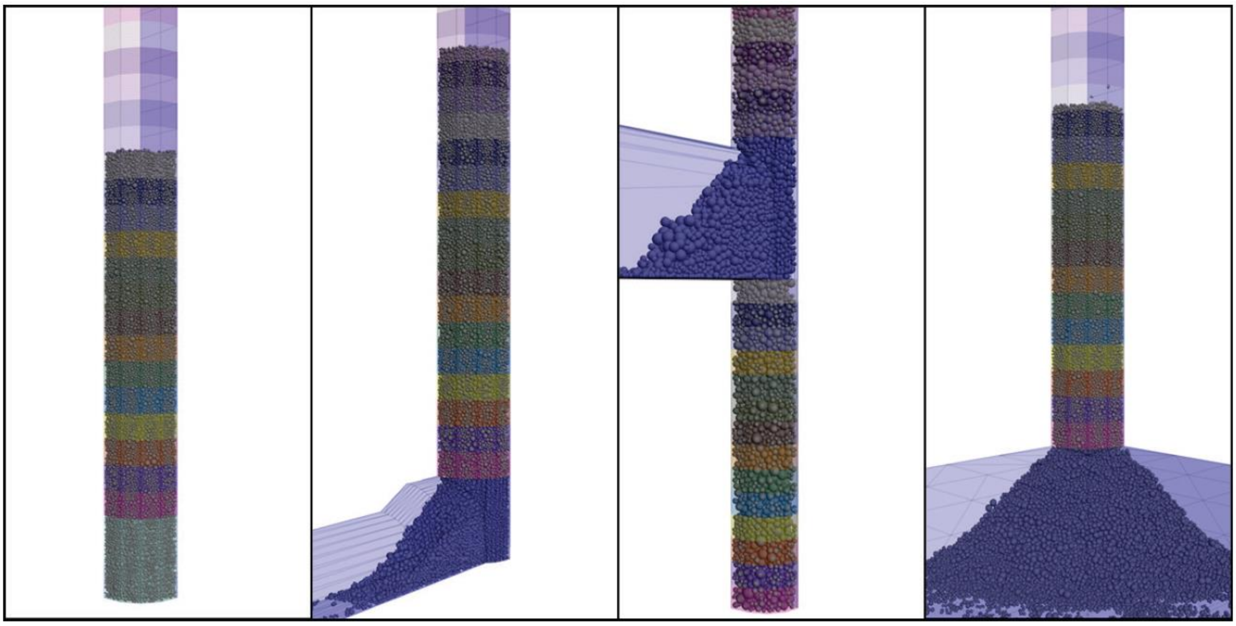

Fig. 5.2: Simulation of backfilling a shaft without and with connected drifts (Nguyen, 2016)

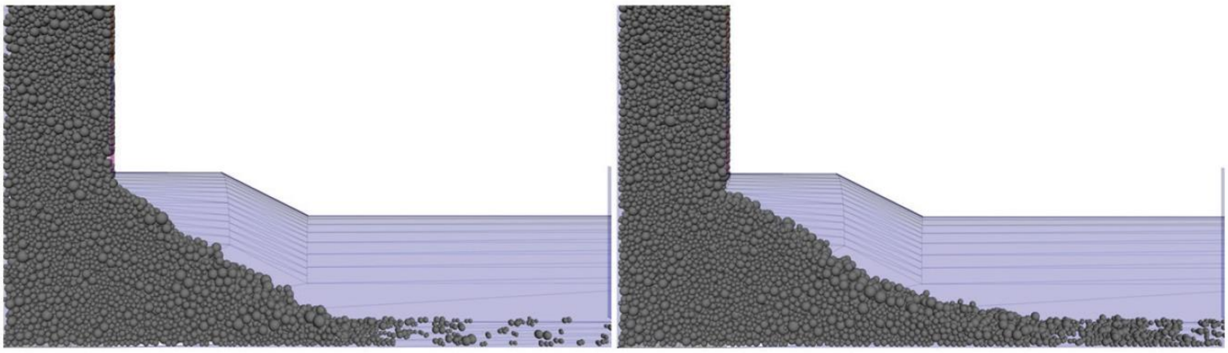

Fig. 5.3: Simulation of backfilling with lower (left) and higher (right) falling height of ballast (Nguyen, 2016)

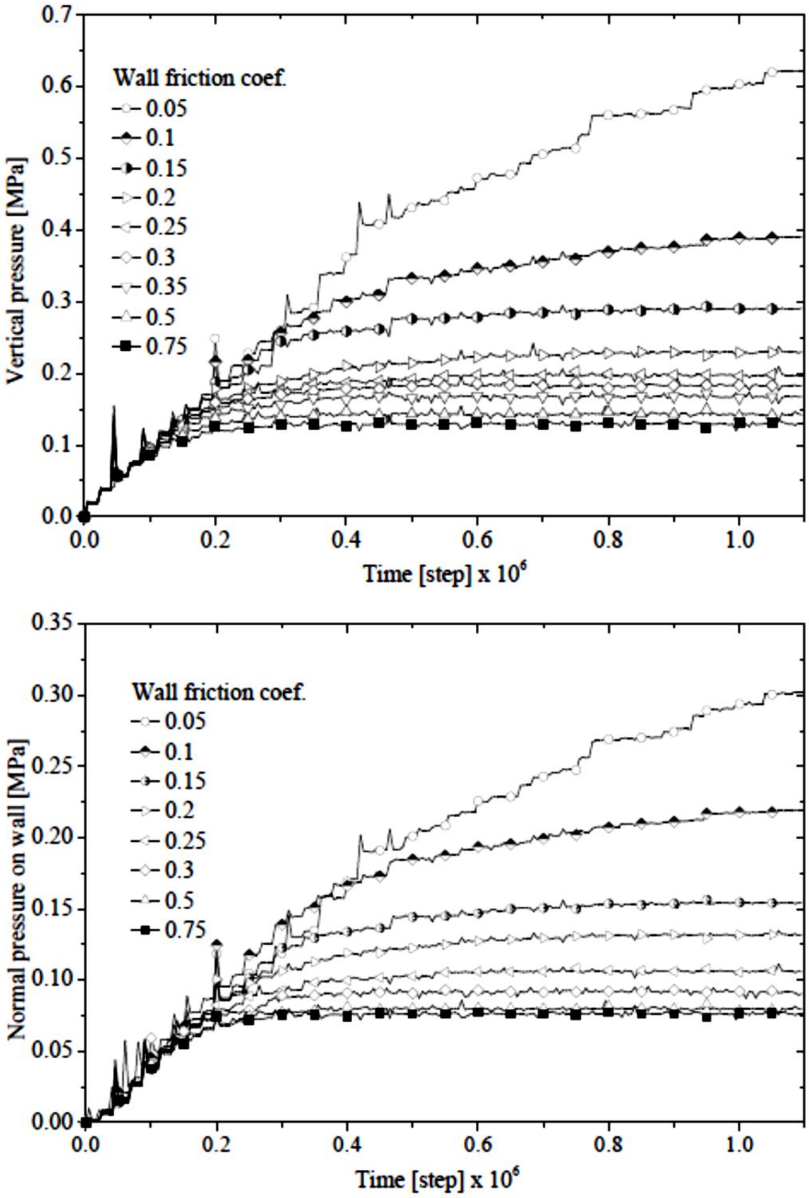

Fig. 5.4: Vertical and horizontal (wall) pressure as function of wall friction (Nguyen, 2016)

Fig. 5.4 shows the evolution of vertical and horizontal (shaft wall) pressure in dependence on frictional properties of the shaft wall. Please note, that the particle-based methods can well reproduce the so-called silo-effect, which is very important to get correct pressure values.

Bock & Prusek (2015) have investigated the pressure generated by the ballast to the dams. Fig. 5.5 illustrates the simulations and Fig. 5.6 shows the results for different positions of the dams (retaining walls).

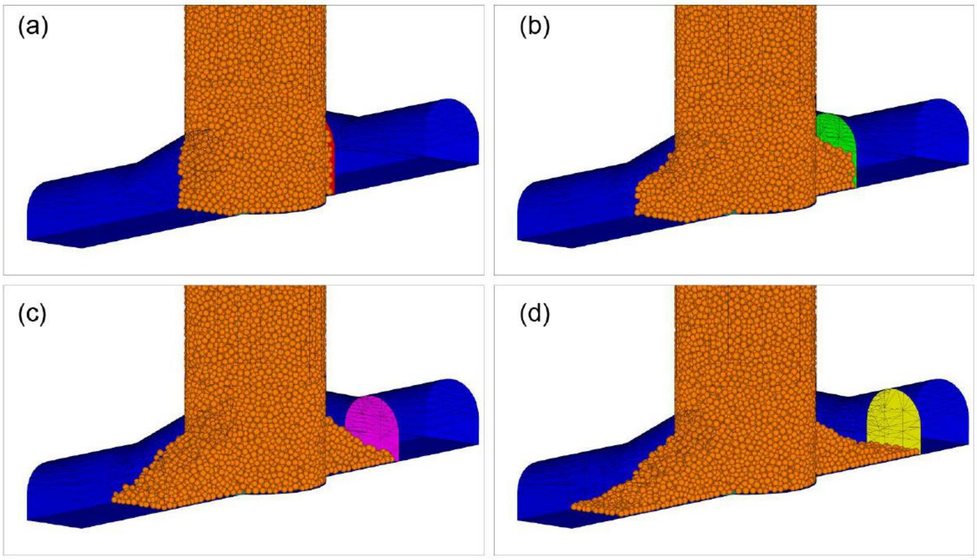

Fig. 5.5: Simulation of shaft sealing considering different positions of a dam (Bock & Prusek, 2015)

Model	Dam location	F_{dam_1}	F_{dam_2}	F_{plug}
	m	kN	kN	kN
Variant 1	0,4	408	423	2086
Variant 2	2,4	83	81	1974
Variant 3	4,4	25 (45)[1]	23 (38)[1]	2002
Variant 4	6,4	2 (54)[1]	1 (38)[1]	1983

()[1] Peak value

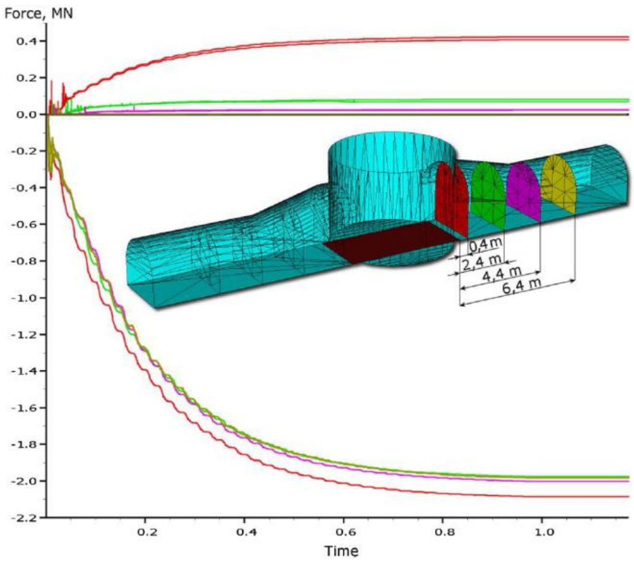

Fig. 5.6: Calculated forces on dams caused by ballast for dams at different locations (Bock & Prusek, 2015)

6 High level sealings for special purposes

In case fluids or gases escaping from the underground through mine openings, they create substantial threats to the biosphere. To avoid that, more complex sealing constructions are necessary. This concerns in particular:

- Underground radioactive waste repositories
- Underground toxic waste repositories
- Use of abandoned mines for underground storage of CO_2
- Use of abandoned mines for compressed air, H_2 or other gas storage

For such purposes the sealing system consists of several elements, has to be redundant and should guarantee very low permeability and long-term safety. Especially for sealing of radioactive or toxic repositories several evidences have to be submitted, like:

- Long-term stability and functionality considering also elevated temperatures
- Mechanical stability
- Sufficient degree of water- and gas-tightness
- Restricted deformability
- Restricted crack propagation
- Resistance against erosion and suffusion

Bertrand et al. (2015) and Dieudonne et al. (2015) discuss the use of abandoned coal mines for CO_2 sequestration. They propose a shaft sealing concept like shown in Fig. 6.1.

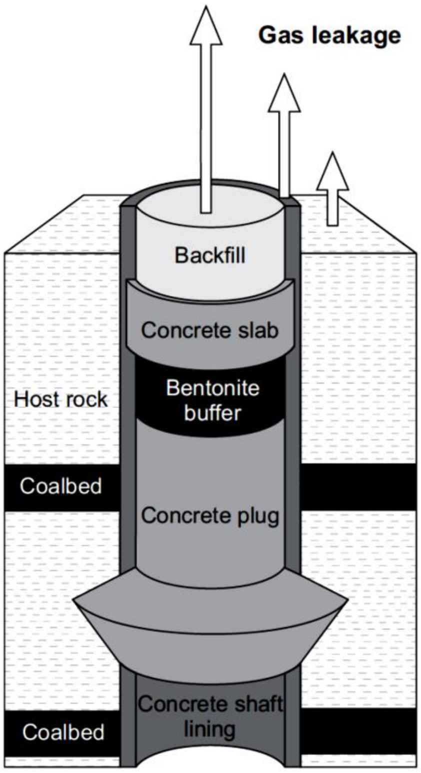

Fig. 6.1: Layout of coal shaft sealing (Bertrand et al., 2015; Dieudonne et al. 2015)

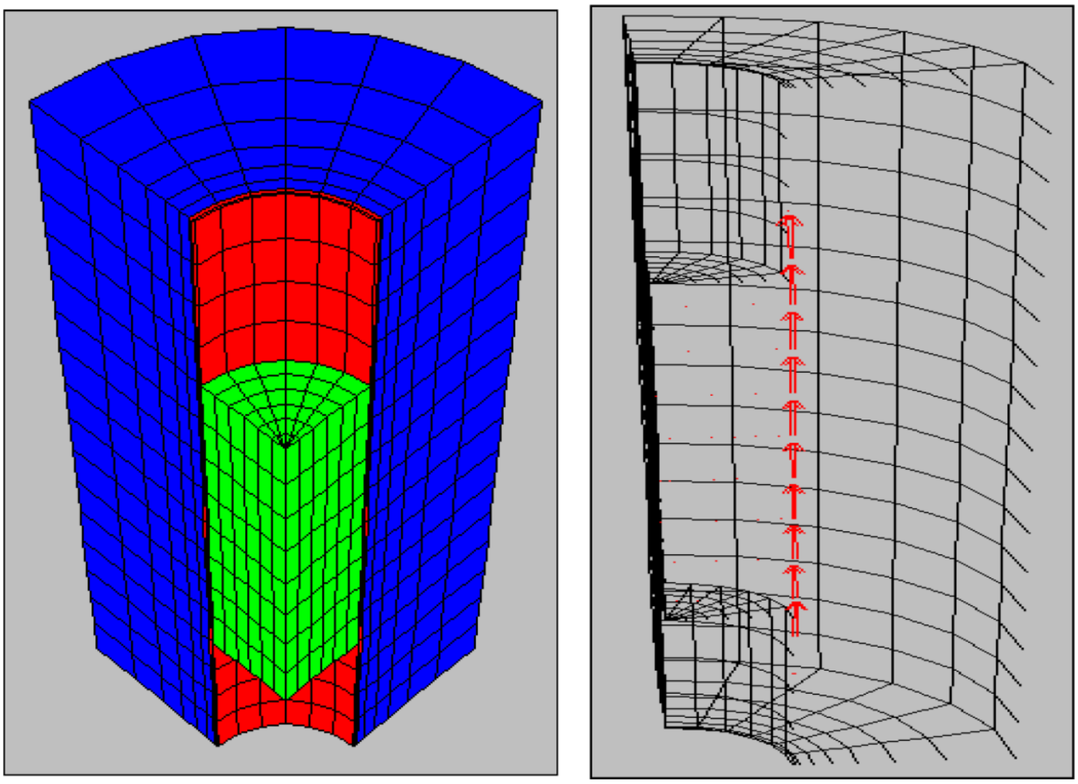

Fig. 6.2: Numerical model to investigate tightness of shaft sealing for compressed air storage in an abandoned salt mine (left: blue: salt rock mass, red: EDZ, green: sealing construction; right: flow vectors) (Hausdorf & Konietzky 2009)

Numerical simulation can help to define minimal requirements in respect to the tightness level, which should be reached with the sealing construction. Hausdorf & Konietzky (2009) have shown that for a project considering an abandoned salt mine for compressed air storage (shaft diameter: 7 m, length of sealing construction 21 m; see Fig. 6.2). They emphasize the importance of the EDZ (see Fig. 6.2 right)

Salt and potash mines need special sealing concepts to avoid contact between groundwater and salt layers. Otherwise, solution processes can contaminate the groundwater and subsidence processes incl. sinkholes can be triggered. Fig. 6.3 shows different sealing concepts applied in the German salt and potash mining industry. Fig. 6.4 shows some different shapes of plugs (abutments) used in the German salt and potash mining industry. Some of them are based on the principal of friction only, but most of them use formlocking (interlocking) in addition. An overview about the extensive research activities in respect to drift and shaft sealings for salt mines and repositories in salt in Germany has been given by Biegler & Gruner (2020).

For radioactive waste projects the highest sealing level is required. Fig. 6.5 shows at which locations sealings are needed. Fig. 6.6 shows different shapes of tunnel plugs and discusses their mechanical functionality. Fig. 6.7 and 6.8 show tunnel plugs designed for crystalline rocks. Exemplary, the sealing layout for the WIPP site in the US is shown in Fig. 6.9. Tab. 6.1 illustrates the functions of the different elements of the sealing construction.

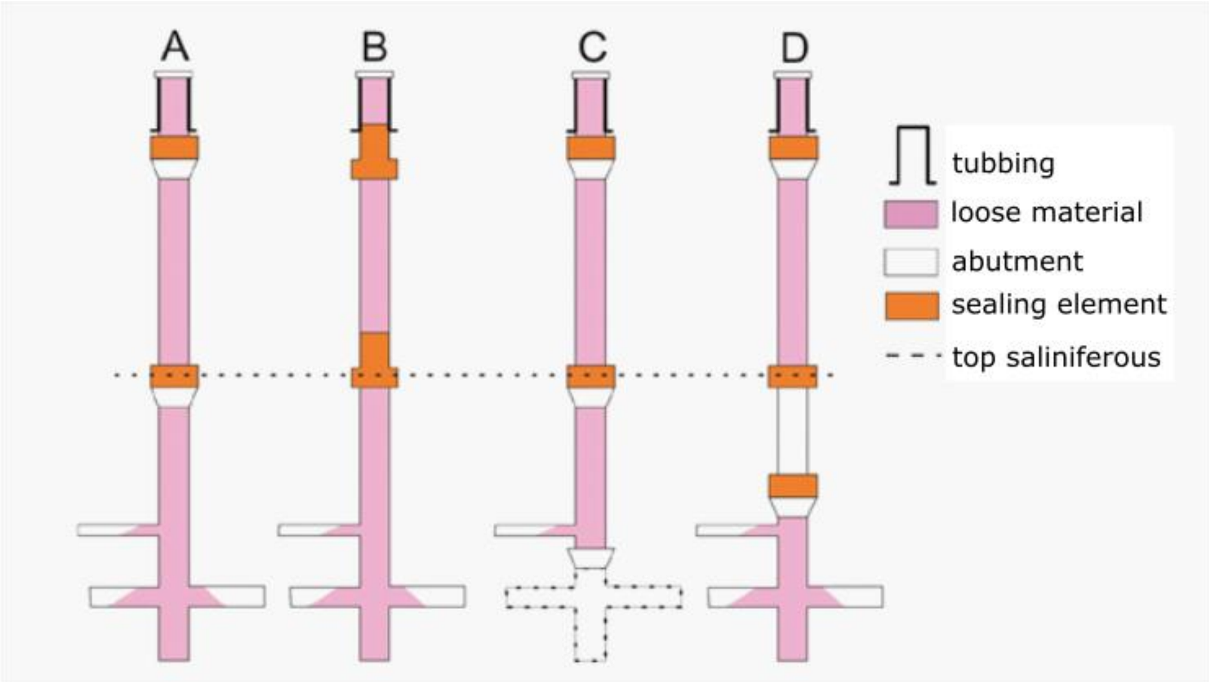

Fig. 6.3: Layout of salt mine shaft sealings (modified after Bartl, H. et al., 2003)

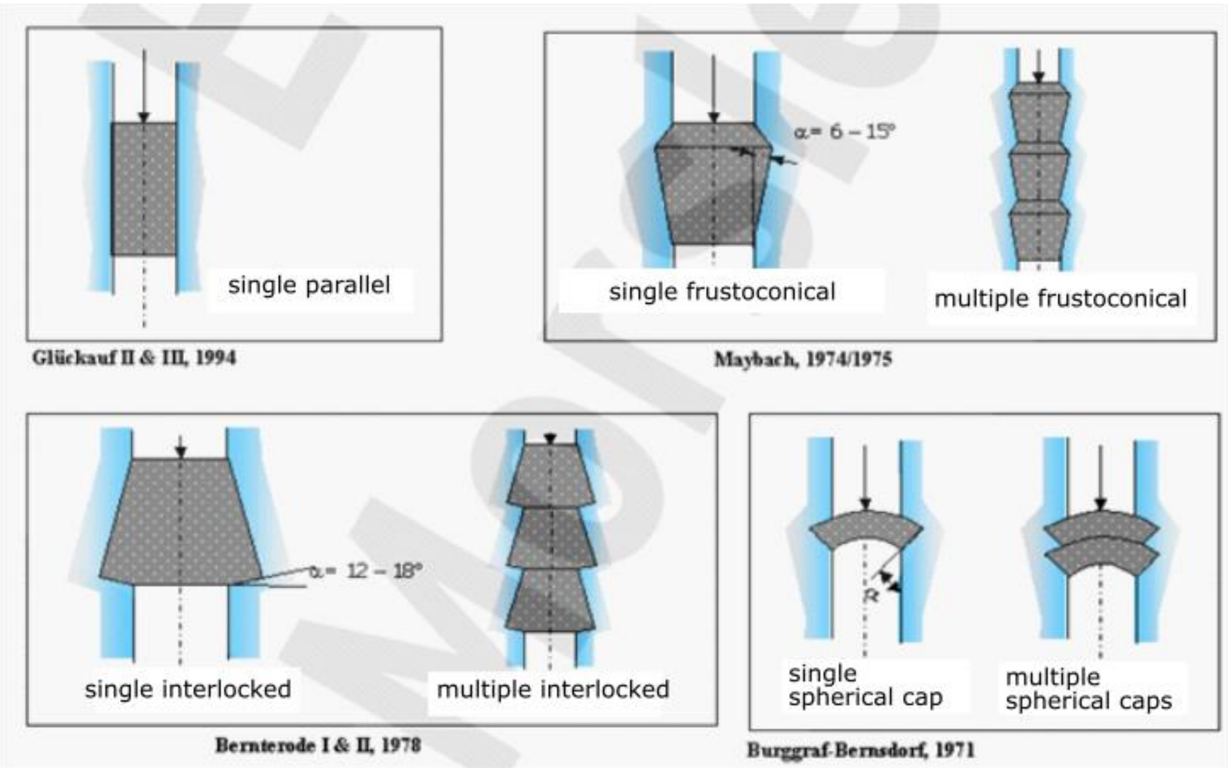

Fig. 6.4: Layout of salt mine shaft sealings (modified after Sitz, 1981)

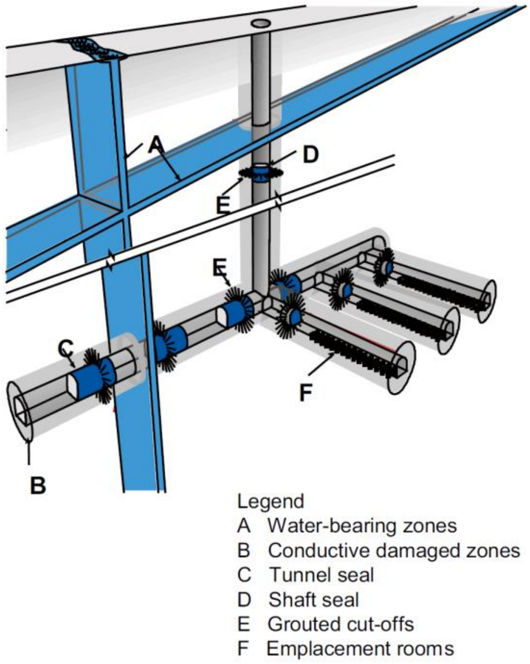

Fig. 6.5: General radioactive waste repository layout with indication of sealing constructions (Dixon et al., 2009)

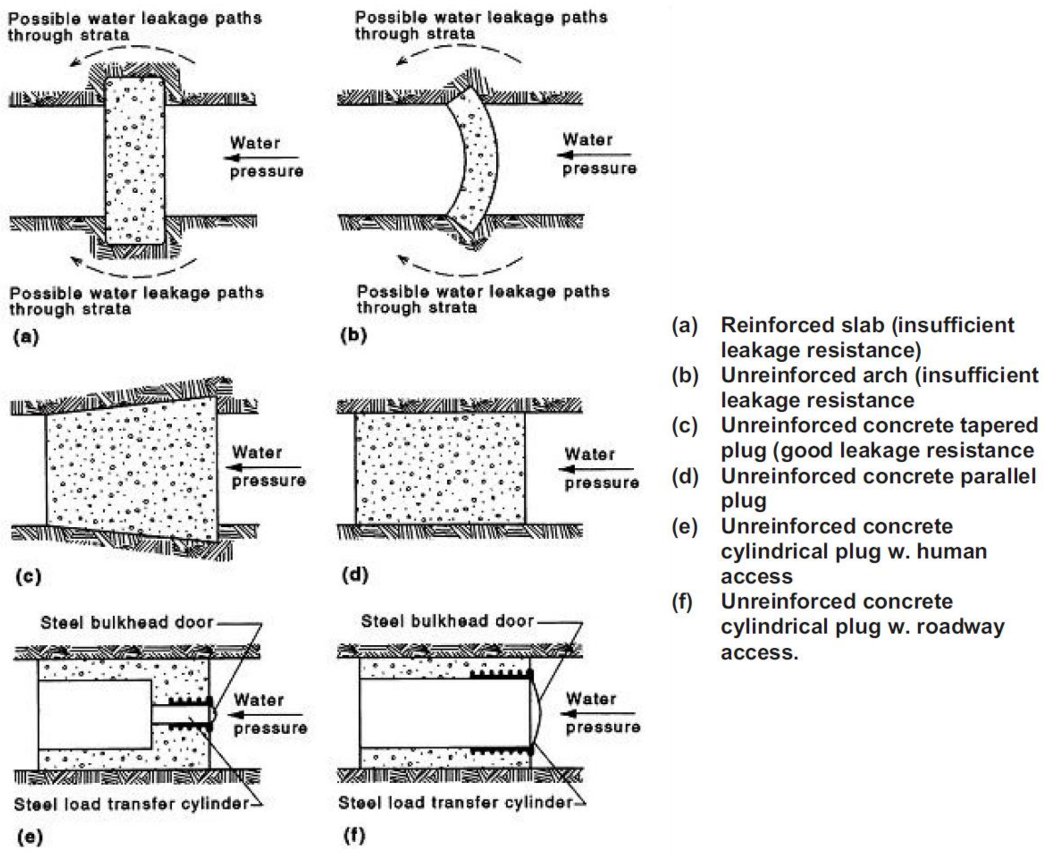

Fig. 6.6: Different plug types for tunnel (drift) sealings (Dixon et al., 2009)

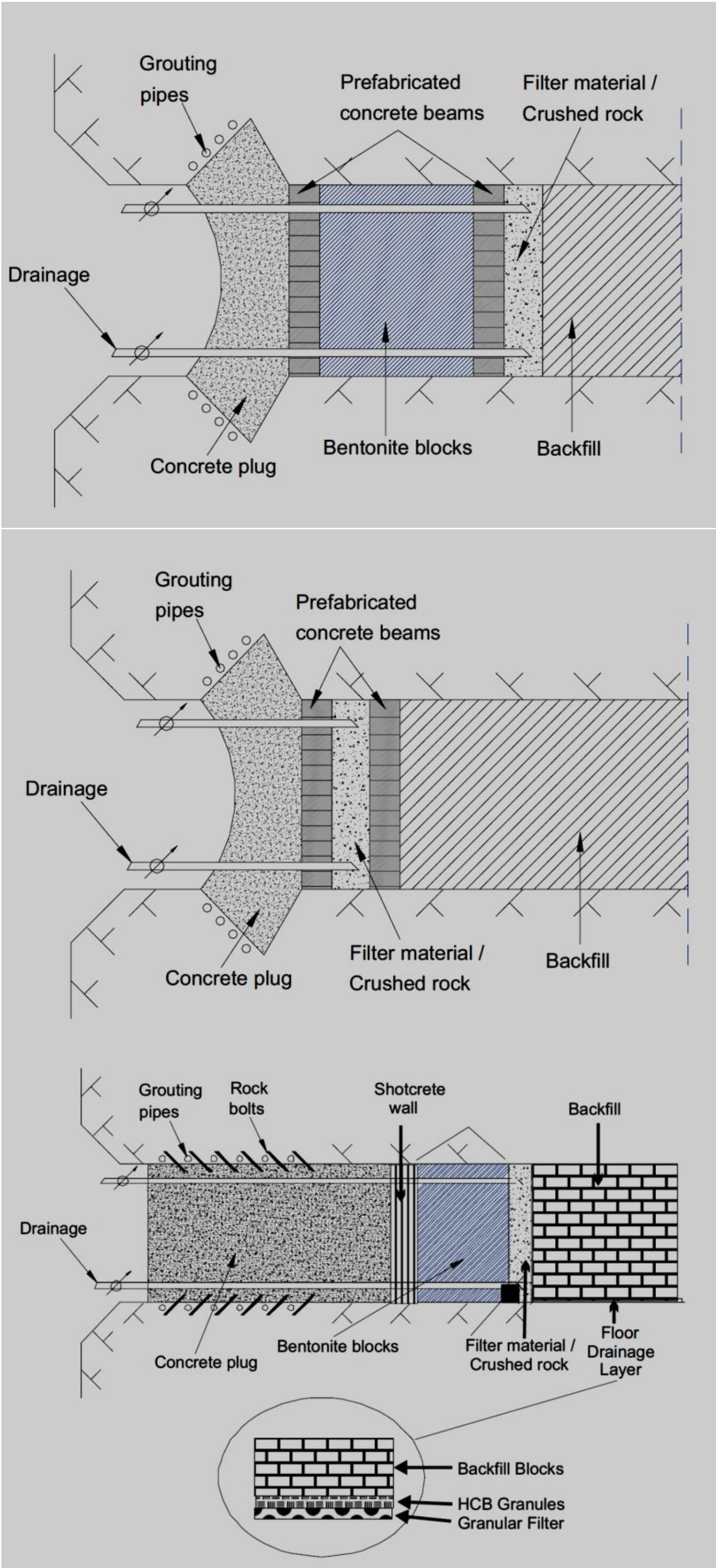

Fig. 6.7: Different tunnel (drift) sealing concepts (Dixon et al., 2009)

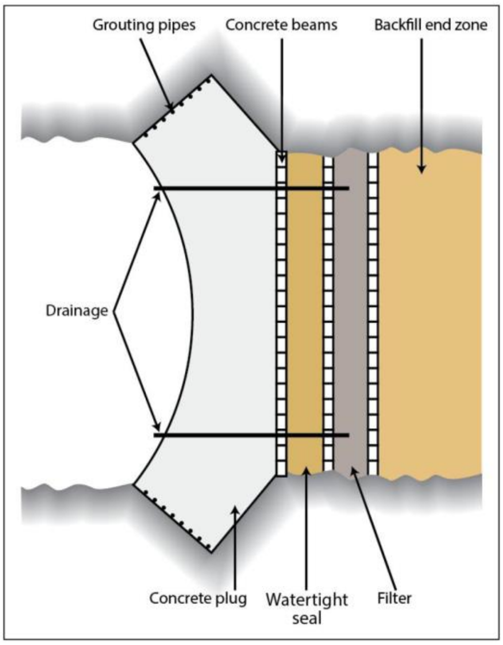

Fig. 6.8: SKB reference conceptual design for tunnel sealing (Hansen et al., 2016)

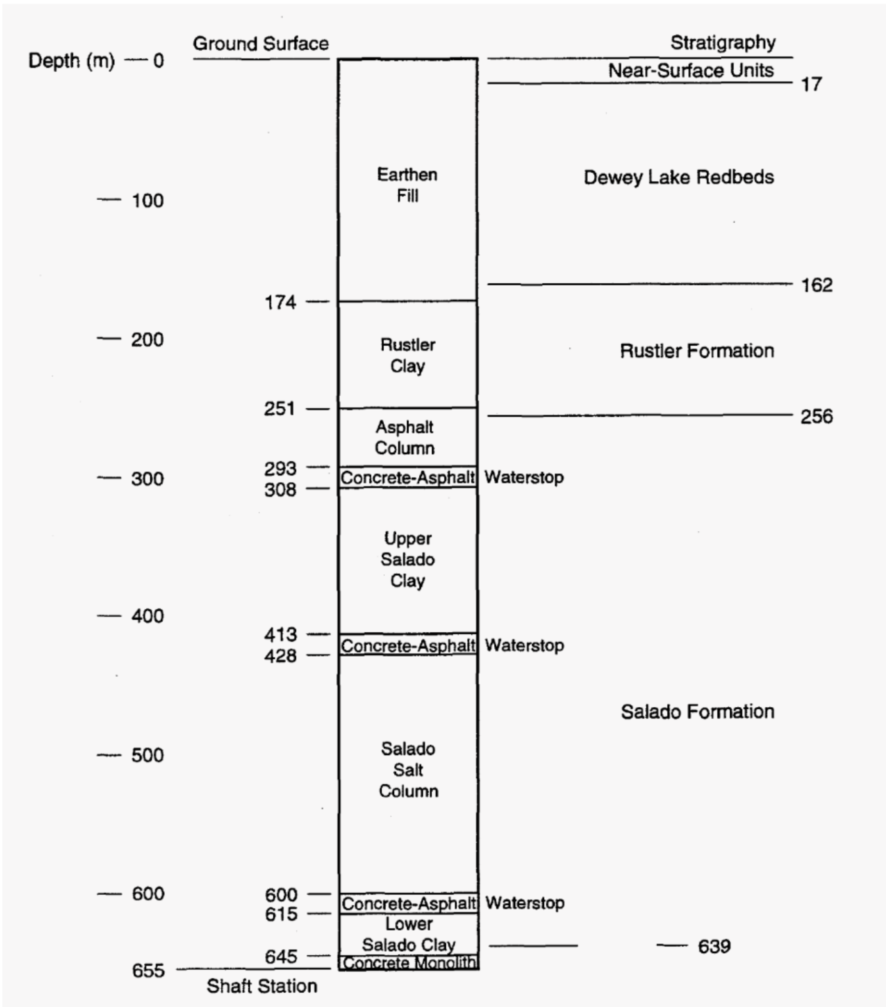

Fig. 6.9: Layout of the WIPP site air intake shaft sealing (Sandia, 1997)

Tab. 6.1: Layout of the WIPP site air intake shaft sealing (DOE, 1995)

Qualitative Design Guidance	Design Approach
The shaft sealing system shall limit:	The shaft sealing system shall be designed to meet the qualitative design guidance in the following ways:
1. the migration of radiological or other hazardous constituents from the repository horizon to the regulatory boundary during the 10,000-year regulatory period following closure;	1. brine migrating from the repository horizon to the Rustler Formation must pass through a low permeability sealing system;
2. groundwater flowing into and through the shaft sealing system;	2. groundwater migrating from the Rustler Formation to the repository horizon must pass through a low permeability sealing system ;
3. chemical and mechanical incompatibility of seal materials with the seal environment;	3. the sealing system materials are chemically and mechanically compatible with the seal environment or can be protected;
4. the possibility for structural failure of individual components of the sealing system;	4. structural analysis shows that each component is adequate to withstand the forces expected from rock creep and hydraulic pressure;
5. the possibility for subsidence of the ground surface in the vicinity of the shafts and accidental entry after sealing;	5. the shaft is completely filled with low porosity materials, and construction equipment would be needed to gain entry;
6. the need to develop new technologies or materials for construction of the shaft sealing system.	6. construction of the shaft sealing system is feasible using available technologies and materials.

Besides the static safety analyses under certain circumstances also dynamic excitation, for instance by earthquakes, have to be considered. This is especially important for permanent sealing constructions like those for radioactive waste repositories, because the time span, which has to be considered becomes very long (e.g. 1 Mio. years). That implies that the occurrence probability of larger earthquakes increases. Neubert (2014) shows a potential way to evaluate the impact of an earthquake on the safety of a shaft sealing system. The assumed parameters for a design earthquake are given in Tab. 6.2. In conjunction with the response spectrum (Fig. 6.10) an artificial accelerogram was produced and the corresponding vibration velocity was deduced (Fig. 6.11). Tab. 6.3 shows the key parameters of the synthetic input wave, which was applied to the 3-dimensional numerical model show in Fig. 6.12.

Tab. 6.2: Assumed earthquake parameters (Neubert, 2014)

Parameter	Symbol	Value
Macroseismic intensity	I_0	7.3 (MSK-scale)
Acceleration, horizontal	a_h	1.4 m/s²
Acceleration, vertical	a_v	0.7 m/s²
Probability of occurrence per year	$W_ü$	0.5 10^{-6} - 1.0 10^{-6}
Subsurface strong ground motion duration	t_{0u}	3.0 s

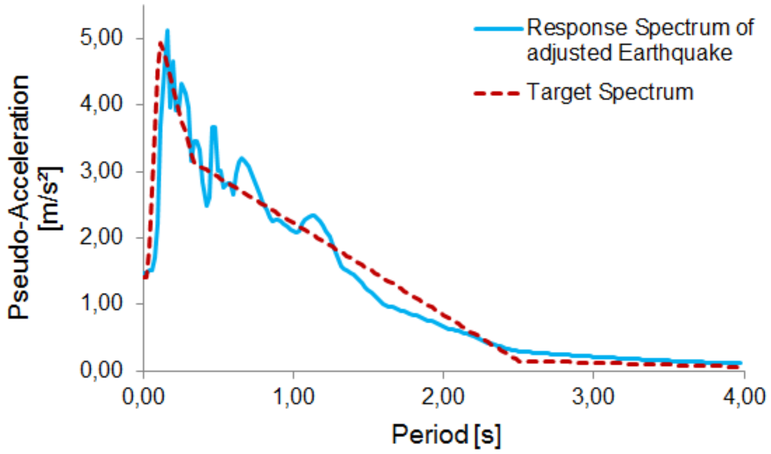

Fig. 6.10: Response spectrum for design earthquake (Neubert, 2014)

Tab. 6.3: Key design parameters of the synthetic input wave (Neubert, 2014)

Parameter	Symbol	Value
Maximum acceleration	a_{max}	1.486 m/s²
Maximum velocity	v_{max}	0.126 m/s
Maximum displacement	u_{max}	0.029 m
Maximum frequency	f_{max}	9.0 Hz
Duration	t_{Dg}	5.20 s

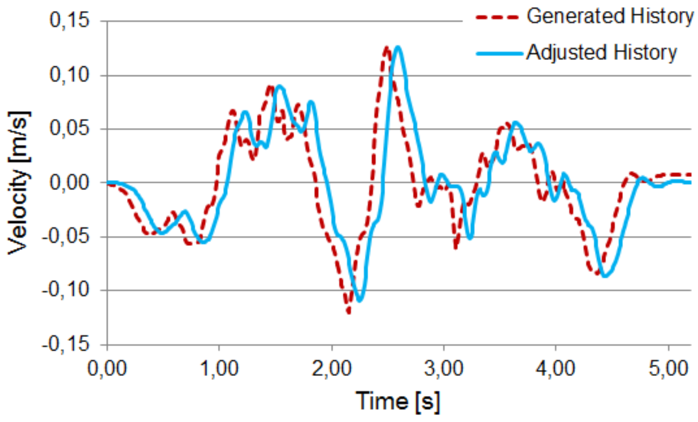

Fig. 6.11: Artificial time series deduced from response spectrum (Neubert, 2014)

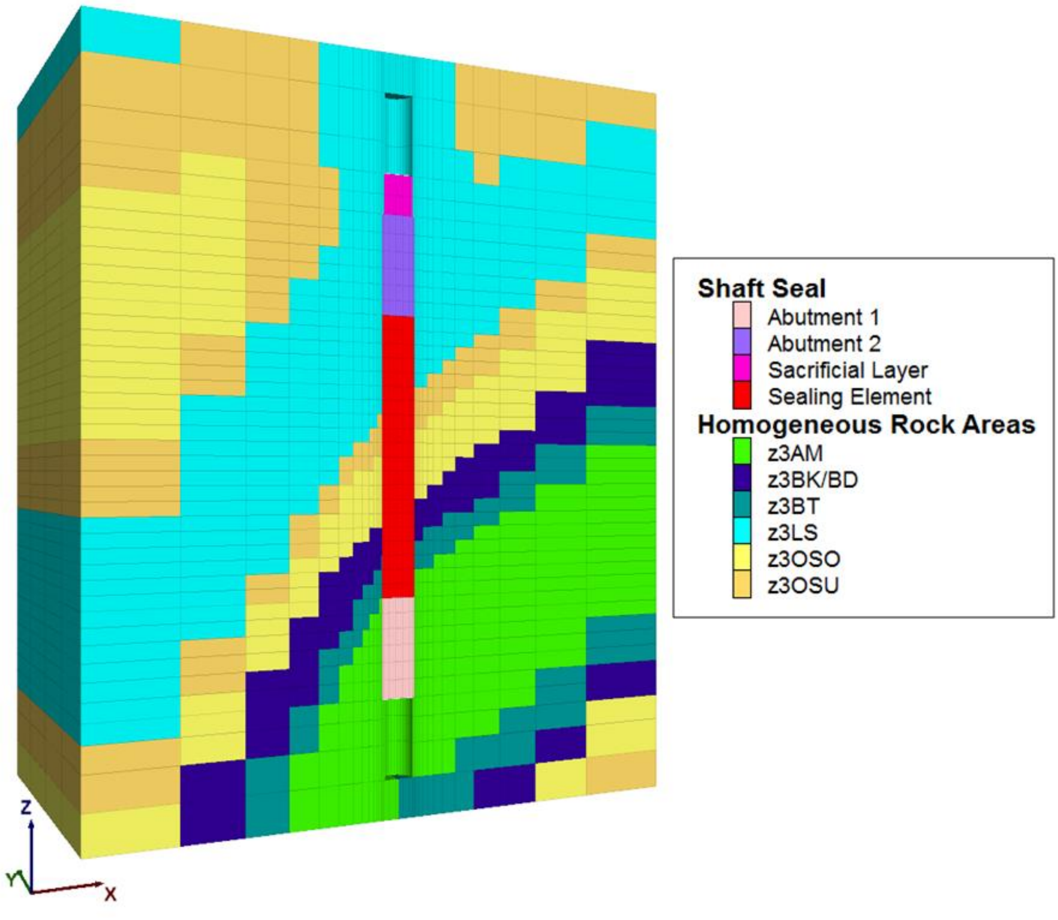

Fig. 6.12: 3-dimensional numerical model for dynamic visco-elasto-plastic simulations (Neubert, 2014)

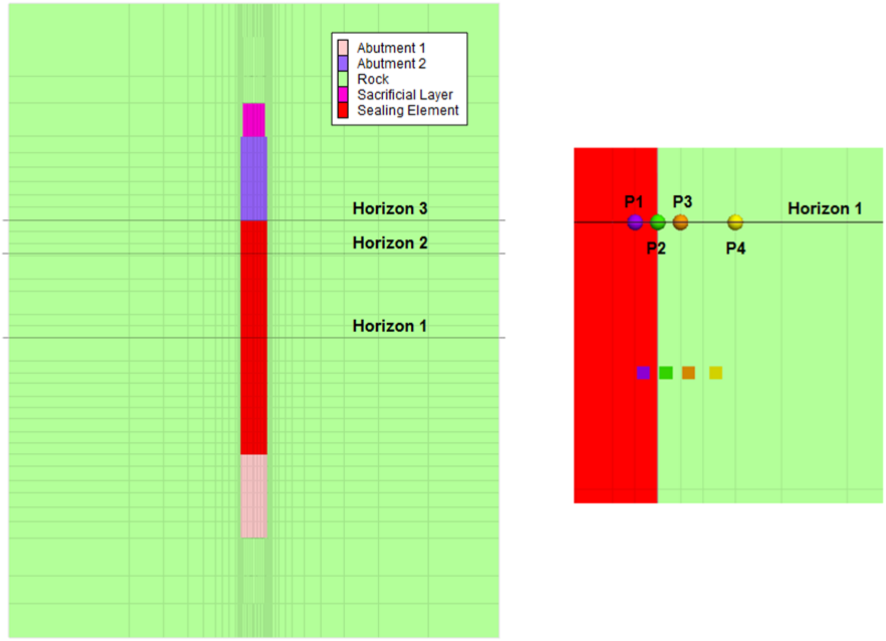

Fig. 6.13: Vertical cross section through numerical model with indication of observation points (Neubert, 2014)

Fig. 6.13 shows a vertical cross section through the model with the sealing construction in the centre incl. observation points. Fig. 6.8 shows the utilization factor for the observation points P2, P3 and P4 during the earthquake impact for two different points in time. It can be seen, that the dynamic impact increases the utilization factor, or with other words, reduces the safety of the sealing system. However, in this case the increase in utilization is marginal. Time point 1 is 2 years after completion of the sealing, time point 2 is twenty years after completion of the sealing.

Extensive lab tests and in-situ experiments (especially in underground labs) are performed to investigate the functionality of sealing constructions under different conditions and for different time spans (see for instance Huertas et al., 2000; Hansen et al., 2016 or Van Geet et al., 2009).

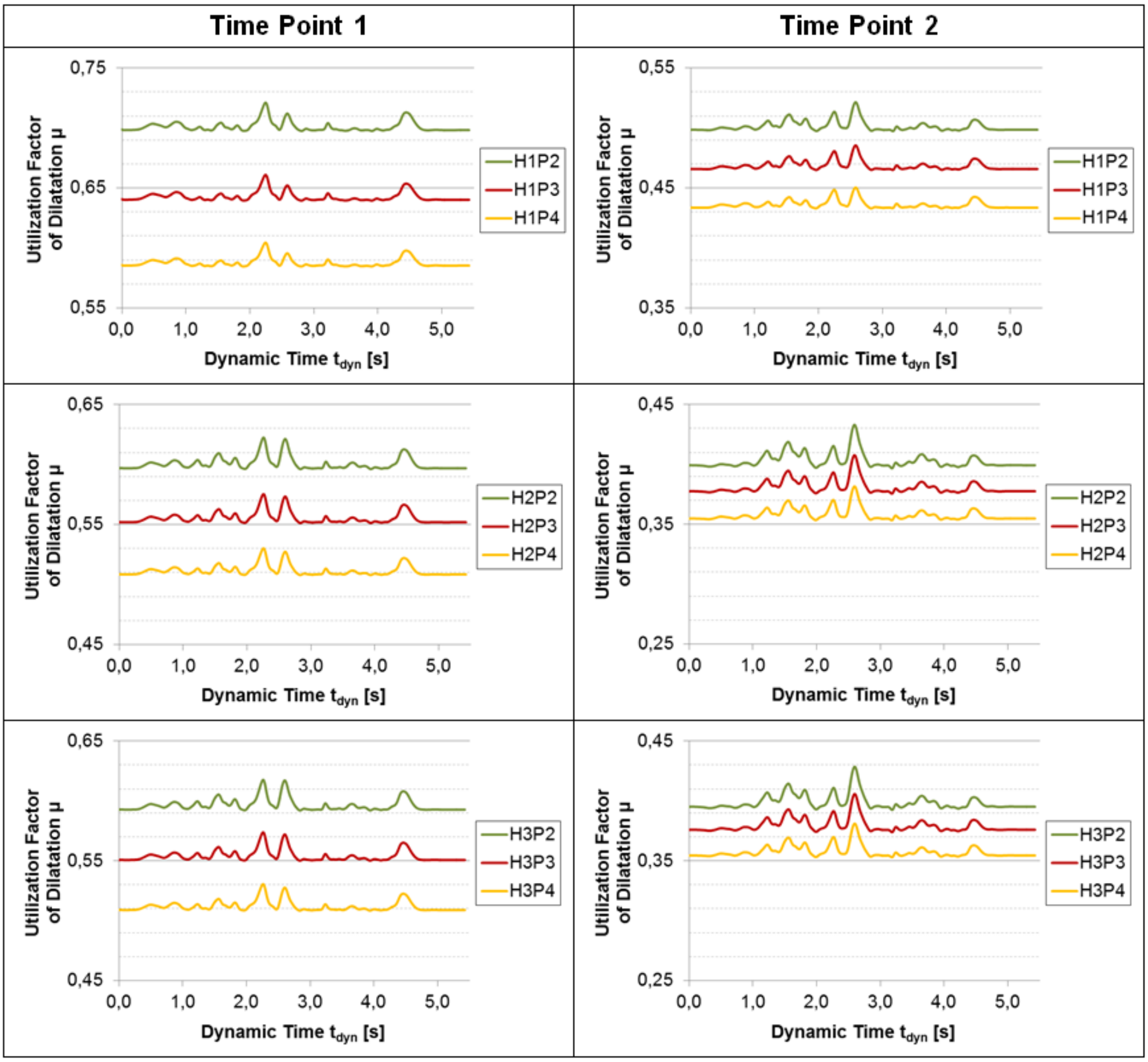

Fig. 6.14: Utilization factor according to Fig. 6.13 during earthquake impact 2 (time point 1) and 20 years (time point 2) after installation of the shaft sealing (Neubert, 2014)

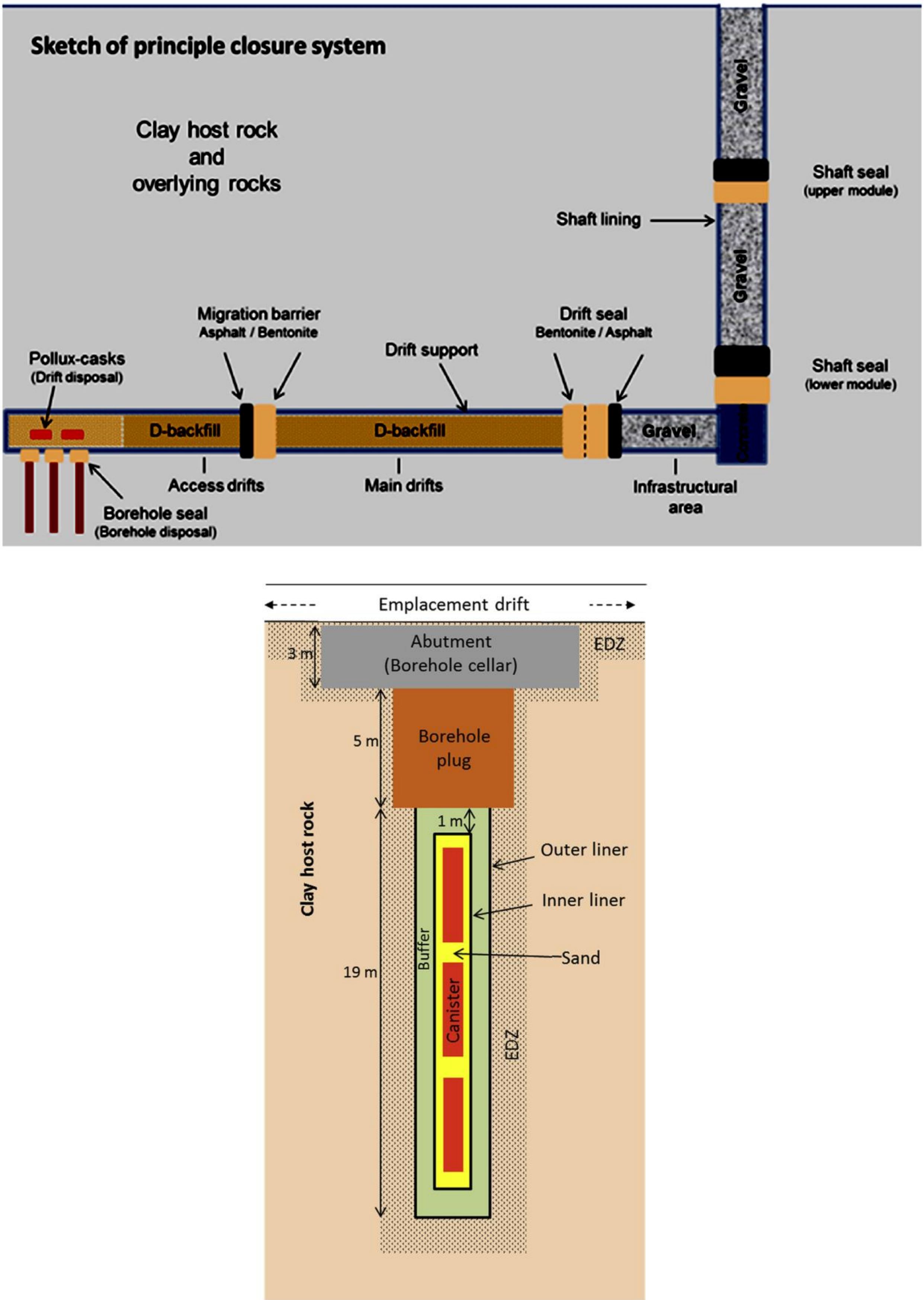

Fig. 6.15: Sealing concept for radioactive waste repository in clay (top: overview, bottom: sealing concept for emplacement borehole) (Jobmann et al., 2017)

7 References

Bartl, H.; Döring, G.; Hartung, K.; Schilder, C. & Slotta, R. (2003): Kali im Südharz-Unstrut-Revier, Deutsches Bergbaumuseum Bochum, Vol. I and II

Bertrand, F.; Charlier, R.; Collin, F. & Dieudonné, A.C. (2015): Efficiency of shaft sealing for CO_2 sequestration in coal mines, *Proc. 2nd EAGE Workshop*, 4 p.

Bhowan, T. (2019): Shaft capping prevents illegal mining, improves ground safety, *Mining Weekly*, 2019-11-15

Biegler, J & Gruner, M. (2020): Grube Teutschenthal: 20 Jahre in-situ-Forschungsarbeiten, *Bergbau*, 11: 498-503

Bock, S. & Prusek, S. (2015): Numerical study of pressure on dams in a backfilled mining shaft based on PFC3D code, *Computers and Geotechnics*, 66: 230-244

Dieudonne, A.C.; Cerfontaine, B.; Collin, F. & Charlier, R. (2015): Hydromechanical modelling of shaft sealing for CO2 storage, *Engineering Geology*, 193: 97-105

Dixon, D.A.; Börgesson, L.; Gunnarsson; L. & Hansen, J. (2009): Plugs for deposition tunnels in a deep geological repository in granitic rock – Concepts and experience, SKB report R-09-05

DOE (1995): Waste isolation pilot plant sealing system design report, US Department of Energy, DOE/WIPP-95-3117

Hansen, J.; DOPAS consortium & Posiva Oy (2016): DOPAS Project Final Summary Report, EU-Report No. 323373

Hausdorf, A.; Konietzky, H.; Fliss, T. & Dengel, A. (2009): Druckluftspeicherung in stillgelegten Bergwerken – Bewertung wesentlicher Einflussgrößen auf die Dichtheit mit Hilfe numerischer Untersuchungen, *Erdöl-Erdgas-Kohle*, 125(4): 144-151

Heath, G.J. (2009): The location, hazard assessment and sealing of unsafe mine openings in the Central Witwatersrand Gold Mining Basin, PhD Thesis, University of the Witwatersrand, South Africa

Huertas, F.; Fuentes-Cantillana, J.L. & Jullien, F. (2000): Full-scale engineered barriers experiment for a deep geological repository for high-level radioactive waste in crystalline host rock (FEBEX project), EU-Report No. FI4W-CT95-0006

IfBS (1976): Grundsätze für die Verwahrung von Tagesschächten, Institut für Bergbausicherheit, Forschungsabteilung Geomechanik, Leipzig, August 1976

Jobmann, M.; Bebiolka, A.; Burlake, V.; Herold, P.; Jahn, S.; Lommerzheim, A.; Maßmann, J.; Meleshyn, A.; Mrugalla, S.; Reinhold, K.; Rübel, A.; Stark, L. & Ziefle, G. (2017): Safety assessment methodology for a German high-level waste repository in clay formations, *J. Rock Mechanics and Geotechnical Engineering*, 9(5): 856-876

Kamlot, P.; Weise, D.; Gärtner, G. & Teichmann, L. (2012): Drift sealing elements in the Asse II mine as a component of the emergency concept – assessment of the hydro-mechanical functionality, *Proc. 41. Geomechanics Colloquium* (ed. H. Konietzky), Geotechnical Institute, TU Bergakademie Freiberg, Heft 2012-1: 127-152

Konietzky, H. et al. (2014): Abschlussbericht Verwahrung Schürfe, Geotechnical Institute, TU Bergakademie Freiberg, unpublished report

Lecomte, A.; Salmon, R.; Yang, W.; Marshall, A.; Purvis, M.; Prusek, S.; Bock, S.; Gajda, L.; Dziura, J. & Niharra, A.M. (2014): Case studies and analysis of mine shaft incidents in Europe, ineris-00973661

Nguyen, Q.T. (2016): Shafts backfilled with ballast: stability and settlement predictions via DEM simulations, PhD thesis, Geotechnical Institute, TU Bergakademie Freiberg, Heft 2016-1 (ed. H. Konietzky)

Koski, J.A. (1994): Sealing abandoned mine shafts with concrete, *Concrete Construction*, J941015

Neubert, N. (2014): Stability and integrity of geotechnical barriers under earthquake loading, Proc. 43. Geomechanics Colloquium (ed. H. Konietzky), Geotechnical Institute, TU Bergakademie Freiberg, Heft 2014-2: 227-239

Salmon, R.; Marshall, A.; Bock, S.; Madrza, A.; Rapp, S.; Munos Niharra, A. & Bedford, M. (2015): Mine shafts: improving security and new tools for the evaluation of risks (MISSTER), Luxembourg European Commission, EUR 27086

Sandia (1997): WIPP shat sealing system parameters recommended to support compliance calculations, SAND97-1287, UC-721

SITZ, P. (1981): Querschnittsabdichtungen untertägiger Hohlräume durch Dämme und Pfropfen, Dissertation B, TU Bergakademie Freiberg

Van Geet, M. et al. (2009): A large-scale in situ demonstration test for repository sealing in an argillaceous host rock – Phase II (RESEAL II), EU-report No. FIKW-CT-2000-00010