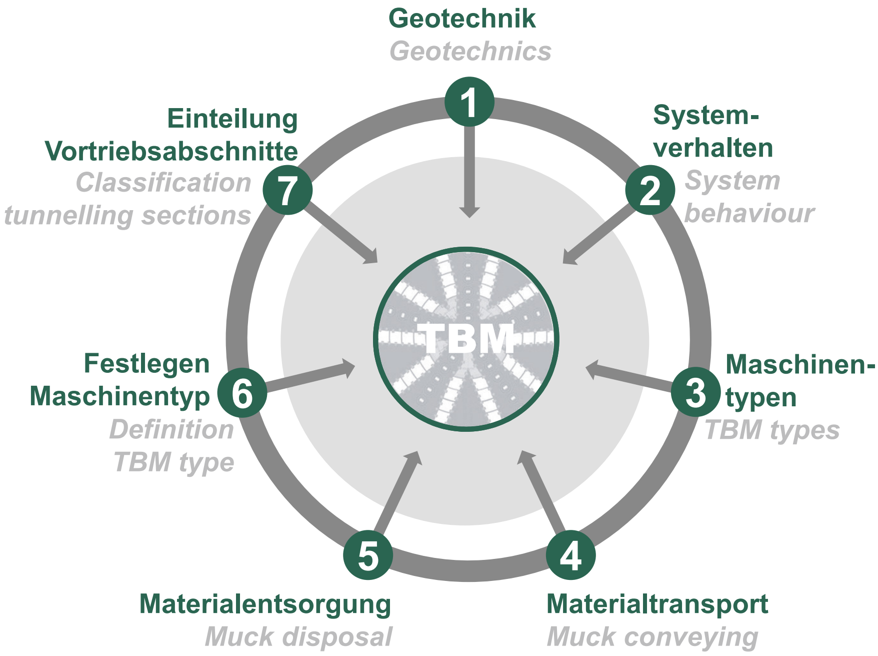

Recommendations for the Selection of Tunnel Boring Machines

DAUB-Working Group

Deutscher Ausschuss für unterirdisches Bauen e. V.
German Tunnelling Committee (ITA-AITES)

Recommendations for the Selection of Tunnel Boring Machines

Publisher
Deutscher Ausschuss für unterirdisches Bauen e. V. (DAUB)
German Tunnelling Committee (ITA-AITES)
Mathias-Brüggen-Str. 41, 50827 Köln/Cologne, Germany
Tel. +49 - 221 - 5 97 95-0
Fax +49 - 221 - 5 97 95-50
E-Mail: info@daub.de
www.daub-ita.de

Developed by the Working Group „Recommendations for the Selection of Tunnel Boring Machines"

Members of the Working Group:

Dr.-Ing. Ulrich Maidl (Lead)	MTC – Maidl Tunnelconsultants, Duisburg
Prof. Dr.-Ing. Dieter Kirschke	Consulting Engineer for Rock Mechanics and Tunnelling, Ettlingen
Prof. Dr.-Ing. Roland Leucker	Research Association for Tunnels and Underground Facilities e.V. (STUVA), Cologne
Dr. techn. Klaus Rieker	Wayss & Freytag Civil Engineering AG, Frankfurt/ Main
Prof. Dr.-Ing. Ludger Speier	ZPP Engineers AG, Bochum
Prof. Dr.-Ing. Markus Thewes	Institute for Tunnelling and Construction Management, Ruhr University Bochum
Dr.-Ing. Gerhard Wehrmeyer	Herrenknecht AG, Schwanau

External collaborators with the Working Group:

Prof. Dr.-Ing. Christoph Budach	Geotechnics and Tunnelling, TH Köln, formerly ELE Consulting Engineers, Essen
Dipl.-Ing. Jens Classen	Implenia Construction GmbH, München
Dr.-Ing. Britta Schößer	Institute for Tunnelling and Construction Management, Ruhr University Bochum
Dr.-Ing. Janosch Staschelt	MTC – Maidl Tunnelconsultants, Duisburg

January 2022 (revised version August 2025)

Title picture: Dr.-Ing. Gerhard Wehrmeyer, Herrenknecht AG

Inhalt

1 Preface

The purpose of these recommendations is to outline the process for the selection of tunnel boring machines for use in different ground types (rock and soil), on the basis of the procedural and geotechnical criteria that are to be satisfied. Existing relationships between the geotechnical, local and environmental boundary conditions as well as the process and machine technology are also taken into account. Thus, the document is intended as an aid for project-specific analysis and decision making in the process of selecting a suitable tunnel boring machine.

In particular, these recommendations supplement the existing regulations for „Underground Construction Work" DIN 18312 [18]. Regarding the selection of jacking machines for pipe jacking, additional reference is made to the guideline DWA-A 125 [3] of the German Association for Water Management, Sewage and Waste (DWA e. V.).

2 Rules, Regulations, Recommendations and Literature

When selecting a tunnel boring machine, the following documents in particular shall be considered.

2.1 National Rules, Regulations, Legislation and Recommendations

[1] Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTV-ING) der Bundesanstalt für Straßenwesen, Teil 5 Tunnelbau Abschnitt 3 Maschinelle Schildvortriebsverfahren, Stand 2018/01 (Supplementary Technical Conditions of Contract and Guidelines for Engineering Structures (ZTV-ING), Part 5 Tunnelling, Section 3 "Mechanised Shield Tunnelling"; BASt (German Federal Agency for Road Construction); Status 2018/01).

[2] Richtlinie 853 „Eisenbahntunnel planen, bauen und instand halten" der DB Netz AG, 9. Aktualisierung vom 01.09.2018 (Guideline 853 "Design, Construction and Maintenance of Rail Tunnels" DB Netz AG 9th Version; 01.09.2018):

a. Modul 853.2001 „Standsicherheitsuntersuchungen" (mit Regelungen zu den Einwirkungen aus Pressenkräften von TVM) (Module 853.2001 "Structural Stability Calculations" (including regulations concerning the actions from thrust cylinders of tunnel boring machines).
b. Modul 853.4001 „Allgemeine Grundsätze für Vortrieb, Sicherung und Ausbau" (Module 853.4001 "General rules for tunnelling, support and lining").
c. Modul 853.4005 „Tübbingausbau" (u. a. mit Regelungen zur Ringspaltverpressung) (Module 853.4005 "Segmental Lining" (including regulations concerning annular gap grouting).
d. Modul 853.6001 „Baudurchführung, bautechnische Unterlagen und Dokumentation" (mit Regelungen zur Kontrolle von Schildvortriebsarbeiten) (Module 853.6001 "Construction, technical documents and documentation" (including regulation concerning the control of shield tunnelling works).

[3] Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.: Arbeitsblatt DWA-A 125: Rohrvortrieb und verwandte Verfahren (German Association for Water, Wastewater and Waste e.V.: Standard DWA-A 125: Pipe Jacking and Related Techniques).

[4] Verordnung über Arbeiten in Druckluft (Druckluftverordnung) (Regulations for Working under Compressed Air (Compressed Air Regulations).

[5] Regeln zum Arbeitsschutz auf Baustellen (RAB 25): Konkretisierung zur Druckluftverordnung (Regulations for Health and Safety on Construction Sites (RAB 25): Further details to the Compressed Air Regulations).

[6] DIN EN 16191:2014-09: Tunnelbaumaschinen – Sicherheitstechnische Anforderungen; Deutsche Fassung EN 16191:2014 (DIN EN 16191:2014-09: Tunnelling machinery – Safety requirements; German Version EN 16191:2014).

[7] DIN EN 12110:2014-10: Tunnelbaumaschinen – Druckluftschleusen – Sicherheitstechnische Anforderungen; Deutsche Fassung EN 12110:2014 (DIN EN 12110:2014-10: Tunnelling machines – Air locks – Safety requirements; German version EN 12110:2014).

[8] DIN 4020:2010-12: Geotechnische Untersuchungen für bautechnische Zwecke – Ergänzende Regelungen zu DIN EN 1997-2 (DIN 4020:2010-12: Geotechnical investigations for civil engineering purposes – Supplementary rules to DIN EN 1997-2).

[9] DIN EN ISO 14688-1:2018-05): Geotechnische Erkundung und Untersuchung – Benennung, Beschreibung und Klassifizierung von Boden – Teil 1: Benennung und Beschreibung (ISO 14688-1:2017); Deutsche Fassung EN ISO 14688-1:2018 (DIN EN ISO 14688-1:2018-05: Geotechnical investigation and testing - Identification and classification of soil – Part 1: Identification and description (ISO 14688-1:2017); German version EN ISO 14688-1:2018).

[10] DIN EN ISO 14689:2018-05: Geotechnische Erkundung und Untersuchung – Benennung, Beschreibung und Klassifizierung von Fels (ISO 14689:2017); Deutsche Fassung EN ISO 14689:2018 (DIN EN ISO 14689:2018-05: Geotechnical investigation and testing – Identification, description and classification of rock (ISO 14689:2017); German version EN ISO 14689:2018).

[11] DIN EN ISO 17892-12:2018-10: Geotechnische Erkundung und Untersuchung – Laborversuche an Bodenproben – Teil 12: Bestimmung der Fließ- und Ausrollgrenzen (ISO 17892-12:2018); Deutsche Fassung EN ISO 17892-12:2018 (DIN EN ISO 17892-12:2018-10: Geotechnical investigation and testing – Laboratory testing of soil – Part 12: Determination of liquid and plastic limits (ISO 17892-12:2018); German version EN ISO 17892-12:2018).

[12] DIN EN ISO 17892-11:2019-05: Geotechnische Erkundung und Untersuchung – Laborversuche an Bodenproben – Teil 11: Bestimmung der Wasserdurchlässigkeit (ISO 17892-11:2019); Deutsche Fassung EN ISO 17892-11:2019 (Geotechnical investigation and testing – Laboratory testing of soil - Part 11: Permeability tests (ISO 17892-11:2019-05); German version EN ISO 17892-11:2019).

[13] DIN 18130-2:2015-08: Baugrund, Untersuchung von Bodenproben – Bestimmung des Wasserdurchlässigkeitsbeiwerts – Teil 2: Feldversuche (DIN 18130-2:2015-08: Soil, investigation and testing – Determination of the coefficient of water permeability - Part 2: Field tests).

[14] DIN 18196:2011-05: Erd- und Grundbau – Bodenklassifikation für bautechnische Zwecke (DIN 18196:2011-05: Earthworks and foundations – Soil classification for civil engineering purposes).

[15] DIN 1054:2010-12: Baugrund – Sicherheitsnachweise im Erd- und Grundbau – Ergänzende Regelungen zu DIN EN 1997-1 (DIN 1054:2010-12: Subsoil – Verification of the safety of earthworks and foundations – Supplementary rules to DIN EN 1997-1).

[16] DIN EN 1997-1:2014-03: Eurocode 7 – Entwurf, Berechnung und Bemessung in der Geotechnik – Teil 1: Allgemeine Regeln; Deutsche Fassung EN 1997-1:2004 + AC:2009 + A1:2013 (DIN EN 1997-1:2014-03: Eurocode 7: Geotechnical design – Part 1: General rules; German version EN 1997-1:2004 + AC:2009 + A1:2013).

[17] DIN EN 1997-1/NA:2010-12: Nationaler Anhang – National festgelegte Parameter – Eurocode 7: Entwurf, Berechnung und Bemessung in der Geotechnik – Teil 1: Allgemeine Regeln (DIN EN 1997-1/NA:2010-12: National Annex – Nationally determined parameters – Eurocode 7: Geotechnical design – Part 1: General rules).

[18] DIN 18312:2019-09: VOB Vergabe- und Vertragsordnung für Bauleistungen – Teil C: Allgemeine Technische Vertragsbedingungen für Bauleistungen (ATV) – Untertagebauarbeiten (DIN 18312:2019-09: German construction contract procedures (VOB) – Part C: General technical specifications in construction contracts (ATV) – Underground construction work).

[19] Recommendations for Face Support Pressure Calculations for Shield Tunnelling in Soft Ground, Deutscher Ausschuss für unterirdisches Bauen e. V. (DAUB), 2016 (German Tunnelling Committee (DAUB) e. V.).

2.1.1 Laws and regulations concerning the use of Conditioning Agents

[20] Allgemeine Verwaltungsvorschrift zum Wasserhaushaltsgesetz über die Einstufung wassergefährdender Stoffe in Wassergefährdungsklassen (VwVwS), 1999 (General administrative regulations to the water supply law with the categorisation of potential water pollutants into water risk classes (VwVwS), 1999).

[21] Allgemeine Verwaltungsvorschrift zur Änderung der Verwaltungsvorschrift wassergefährdender Stoffe, 2005 (General administrative regulations for the revision of the administrative regulations concerning potential water pollutants, 2005).

[22] Gesetz über die Umweltverträglichkeit von Wasch- und Reinigungsmitteln (WRMG), 2007 (Law concerning the environmental acceptability of washing and cleaning agents (WRMG), 2007).

2.1.2 Laws and regulations concerning Landfill

[23] Länderarbeitsgemeinschaft Abfall (LAGA); Mitteilung M20; Anforderungen an die stoffliche Verwertung von mineralischen Reststoffen/Abfällen – Technische Regeln (Stand 6. November 2003) (Federal States of Germany Working Group for Waste (Länderarbeitsgemeinschaft Abfall – LAGA); Note M20; Requirements for the material recycling or mineral residues/wastes – technical rules (version 6 November 2003).

[24] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit: Verordnung zur Vereinfachung des Deponierechts, 2009 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; Regulations for the generalisation of landfill law – 2009).

[25] Deutscher Bundestag: Verordnung zur Umsetzung der Ratsentscheidung vom 19.12.2002 zur Festlegung von Kriterien und Verfahren für die Annahme von Abfällen auf Abfalldeponien, 2006 (German Bundestag: Regulation implementing the Council Decision of 19.12.2002 establishing criteria and procedures for the acceptance of waste at landfills, 2006).

[26] Kreislaufwirtschaftsgesetz (KrWG) (Recycling Management Act).

[27] Bundesbodenschutzverordnung (BBodSchV) (Federal Soil Protection Regulations).

[28] Deponieverordnung (DeponieV) (Landfill Regulations).

[29] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV), Arbeitsgruppe Erd- und Grundbau: Merkblatt zur Herstellung, Wirkungsweise und Anwendung von Mischbindemitteln, R 2, Ausgabe 2012 (Research Society for Road and Traffic Engineering (Forschungsgesellschaft für Straßen- und Verkehrswesen - FGSV) Working Group Earthworks and Foundation Engineering: Leaflet on the production, effect of action and application of mixed binders, R 2, 2012 edition).

[30] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV), Arbeitsgruppe Erd- und Grundbau: Hinweise für die Herstellung und Verwendung von zeitweise fließfähigen, selbstverdichtenden Verfüllbaustoffen im Erdbau, W1, Ausgabe 2012 (Research Society for Road and Traffic Engineering (Forschungsgesellschaft für Straßen- und Verkehrswesen – FGSV) Working Group Earthworks and Foundation Engineering: Guidance for the production and use of temporarily flowable, self-compacting backfill materials in earthworks, W1, edition 2012).

2.1.3 Recommendations

[31] „Mindestmaßnahmen zur Vermeidung von Personenschäden bei den wesentlichen Gefährdungen Brand, Gaseintritt, Wassereinbruch sowie Verbruch/Niederbruch“ (Anhang A des Leitfadens für Planung und Umsetzung eines Sicherheits- und Gesundheitsschutzkonzeptes auf Untertagebaustellen, erarbeitet vom DAUB-Arbeitskreis „Ereigniskonzepte“), Stand 09.02.2007 (Minimum required measures for preventing damages to persons in case of the site-relevant hazards of fire, gas ingress, water rush-in and rock-burst (Appendix A of the Recommendations for planning and implementation of occupational health and safety concept on underground worksites, developed by the DAUB working group “Emergency concepts”), status 09.02.2007).

[32] DAUB-Empfehlung „Konfliktarmer Bauvertrag im Tunnelbau“, April 2020 (Discussion paper on the preparation of conflict-free construction contracts in tunnel construction”, prepared by the DAUB working group “Conflict-free contract”, status 2015).

2.2 International Rules, Regulations, and Recommendations

[33] Leitfaden für Planung und Umsetzung eines Sicherheits- und Gesundheitsschutzkonzeptes auf Untertagebaustellen. Herausgeber: DACH; DAUB; FSV; SIA/FGU, 2007 (Recommendations for planning and implementation of occupational health and safety concept on underground worksites. Publisher DACH; DAUB (German Tunnelling Committee), FSV (Österreichische Forschungsgesellschaft Straße Schiene Verkehr – Austrian Research Institute for Road and Rail Transport), SIA (Swiss Society of Engineers and Architects)/FGU (Fachgruppe für Untertagebau – Swiss Tunnelling Society), 2007).

[34] SIA 198:2007 (SN 507198) Allgemeine Bedingungen Untertagebau; Schweizerischer Ingenieur- und Architektenverein, Ausgabe 11/2007 (SIA 198:2007 (SN 507198) General conditions underground construction, Swiss Society of Engineers and Architects).

[35] ÖNORM B 2203-2:2005-01-01 Untertagebauarbeiten – Werkvertragsnorm Teil 2: kontinuierlicher Vortrieb, Ausgabe 2005 (OENORM B 2203-2:2005-01-01 Underground works – Works contract – Part 2: Continuous driving, 2005 edition).

[36] Richtlinie für die geotechnische Planung von Untertagebauten mit kontinuierlichem Vortrieb der ÖVGG, Ausgabe 2013 (Guideline for the geotechnical design of underground works with continuous excavation, ÖVGG – Austrian Society for Geomechanics, 2013 edition).

[37] Recommendations on the development process for mined tunnels Working group No. 14 Mechanized Tunnelling ITA, 2016.

[38] BS 6164:2011, Code of Practice for safety in tunnelling in the construction industry.

[39] Detergenzienverordnung, Verordnung (EG) Nr. 648/2004 des europäischen Parlamentes und des Rates (2004) (Regulation (EC) No 648/2004 of the European Parliament and of the Council of 31 March 2004 on detergents).

[40] Organisation for Economic Co-operation and Development (OECD), guidelines 201-203; 301 B und 302 B: Freshwater Alga and Cyanobacteria, Growth Inhibition Test, 2011; Daphnia sp. Acute Immobilisation Test, 2004; Fish, Acute Toxicity Test, 1992; Ready Biodegradability, CO2 Evolution Test, 1992; Inherent Biodegradability: Zahn-Wellens/EMPA Test, 1992).

[41] NF P94-430-1:2000-10-01: Gestein – Bestimmung der Schleifbarkeit von Gestein – Teil 1: Ritzprobe mittels Spitzhacke (NF P94-430-1:2000-10-01 Rock – Determination of the rock abrasivity – Part 1: scratching-test with a pointed tool).

[42] NF P18-579:2013-02-09: Gesteinskörnungen – Bestimmung der Koeffizienten der Abrasivität und Mahlbarkeit (NF P18-579:2013-02-09 Aggregate – Abrasivity and grindability tests).

[43] ASTM D6032/D6032-17: Standard Test Method for Determining Rock Quality Designation (RQD) of Rock Core (2017).

[44] Richtlinien zum Risikomanagement von Tunnelprojekten („The Code of Practice for Risk Management of Tunnel Works") der International Tunnelling Insurance Group (ITIG) (2006).

[45] Bewirtschaftung und Wiederverwertung von Ausbruchmaterial – Inventar Schweizer Großprojekte, FGU Fachgruppe für Untertagebau, Esslingen (CH) 2016 (Management and recycling of tunnel spoil – Inventory of major swiss projects, FGU – Swiss Tunnelling Society).

[46] Forschungsgesellschaft Straße – Schiene – Verkehr (FSV): RVS 09.01.51 Sicherheit und Gesundheitsschutz auf Untertagebaustellen, 2017 (Austrian Research Institute for Road and Rail Transport (FSV): Health and Safety on underground construction sites, 2017).

2.3 Additional References

[47] Thewes, M.; Hollmann, F. (2016): Assessment of clay soils and clay-rich rock for clogging of TBMs. Tunnelling and Underground Space Technology, Vol. 57, pp. 122-128.

[48] Anagnostou, G.; Kovari, K. (1994): The Face Stability of Slurry-shield-driven Tunnels. In: Tunnelling and Underground Space Technology, Vol. 9, No. 2, p. 165–174.

[49] Bayer, L.; Diete, P.; Thewes, M.; Schößer, B.; Seegers, J.; Tirpitz, E.-R.; Fahlbusch, D.; Wehrmeyer, G. (2016): Suspensionen mit erhöhter Dichte anstelle von Ballastierung beim Hydroschildvortrieb U5 Berlin. In: Taschenbuch für den Tunnelbau 2016, Deutsche Gesellschaft für Geotechnik e.V. (Hrsg.), Verlag Ernst & Sohn, Berlin, S. 39-80 (Suspensions with increased density instead of ballasting during slurry shield excavation U5 Berlin. Tunnelling handbook 2016, German Geotechnical Society e.V., Ernst & Sohn publishing, Berlin, p. 39-80).

[50] Burger, W.; Straesser, M.; Schößer, B. (2015): Variable Density Maschine: Eine hybride Schildmaschine aus Erddruck- und Flüssigkeitsschild. In: Taschenbuch für den Tunnelbau 2015, Deutsche Gesellschaft für Geotechnik, S. 188-229 (Variable Density Machine: A Hybrid Shield Machine of earth pressure balance and slurry shield. Tunnelling handbook 2015, German Geotechnical Society, p. 188-229).

[51] Kilchert, M; Karstedt, J. (1984): Schlitzwände als Trag- und Dichtungswände – Standsicherheitsberechnungen von Schlitzwänden nach DIN 4126. Volume 2. DIN Deutsches Institut für Normung e.V., Beuth Verlag, Berlin/Köln (Diaphragm walls as load-bearing and sealing walls – stability calculations of diaphragm walls according to DIN 4126, Volume 2, DIN German Institute for Standardization, Beuth Verlag, Berlin/Cologne).

[52] Praetorius, S.; Schößer, B. (2016): Bentonithandbuch – Ringspaltschmierung für den Rohrvortrieb. Verlag Wilhelm Ernst und Sohn, Berlin (Bentonite handbook – Annular gap lubrication for pipe jacking, Wilhelm Ernst & Sohn publishing, Berlin).

[53] Straesser, M.; Klados, G.; Thewes, M.; Schößer, B. (2016): Entwicklung des LDSM und HDSM Konzepts für die Variable Density-TBM. In: Fachzeitschrift Tunnel 7, S. 18-37 (Development of LDSM and HDSM concepts for Variable Density TBM, Tunnel Journal 7, p. 18-37).

[54] Maidl, B.; Herrenknecht, M.; Maidl, U.; Wehrmeyer, G. (2011): Maschineller Tunnelbau im Schildvortrieb, Verlag Ernst & Sohn, Berlin (Mechanised Shield Tunnelling, Ernst & Sohn publishing).

[55] Thuro, K.; Singer, J.; Käsling, H.; Bauer, M. (2006): Abrasivitätsuntersuchungen an Lockergesteinen im Hinblick auf die Gebirgslösung, Beiträge zur 29. Baugrundtagung 2006, S. 283-290 (Abrasivity testing for soils with a view to the excavatability of the soil mass).

[56] Thuro, K.; Käsling, H. (2009): Klassifizierung der Abrasivität von Boden und Fels, Geomechanik und Tunnelbau, 2, S.179-188 (Classification of the abrasivity of soil and rock, Geomechanics and Tunnelling 2, p. 179-188).

[57] Zum Gahr, K.-H. (1987): Microstructure and Wear of Materials, Elsevier.

3 Definitions und Abbreviations

3.1 Definitions

Abrasivity	Abrasivity describes the geologically induced influence on the wear of tools. To characterise abrasivity in rock, the CAI test (CERCHAR Abrasivity Index) is often used in addition to the mineralogical composition and strength. In soils, the test of the „Laboratoire Central des Ponts et Chaussées" (LCPC test) is often used. In the revised DIN 18312, the values A_{IN}, A_{BR} and B_R from the aforementioned tests have to be stated for underground construction work in the Geotechnical Report.
Active Face Support	Measured and monitored support of the tunnel face through a suitable medium (e.g. slurry or (conditioned) remoulded earth) on the basis of a support pressure calculation.
Air Pressurisation	In order to balance the groundwater pressure, the excavation chamber is pressurised with compressed air. Support of the tunnel face against earth pressure is only possible in almost impermeable soils or if the tunnel face is sealed, e.g. by forming a filter cake on the face.
Annular gap	Cavity between the intrados of the excavated section and the extrados of the lining segments.
Annular gap backfill	Backfill or grouting of the annular gap with a suitable material to ensure force-locked bedding of the lining segments and to reduce surface settlement.
Blowout	Uncontrolled escape of compressed air to the ground surface or riverbed associated with loss of face support.
Boreability	The ability for a rock mass to be bored. Depending on the rock properties, it is possible to loosen rock in full section with a tunnel boring machine (TBM). Important technical parameters for the quantitative description of the boreabilty are penetration and contact pressure.
CAI (CERCHAR Abrasivity Index)	Value derived from the CERCHAR tests for the characterisation of the abrasivity of rock. The test is carried out according to NF P94-430-1:2000-10-01. The abrasivity index A_{IN} is determined in the course of the standard-compliant tests.
Clogging	Blockage of tools or openings with sticky material.
Closed mode	In closed mode, the excavation chamber of a tunnel boring machine is held under a measured and monitored positive pressure. The pressure is applied by slurry, remoulded earth or compressed air.
Cutterhead	A tool carrier equipped with disc cutters for full-face mining in rock machines. The excavated material is transported via muck chutes to the cutterhead centre with transfer to a conveyor belt.
Cutting wheel	Appliance for the full-face excavation of a tunnel cross-section in soils. The ground is excavated as the wheel rotates and the design and tool equipment of the wheel are suited to the relevant ground properties. In rock, the term cutterhead is normally used.
Cutting wheel opening ratio	Percentage ratio of the openings in the cutting wheel on the total area of the tunnel face.
Disc cutter (disc)	Rock cutting tool with a rotating, hardened cutter ring, for excavation of the rock at the tunnel face through destruction of the structure of the rock.
Disposal	Part of the spoil management process. Material that is not suitable for recycling is often deposited in accordance with the local waste regulations (in Germany: DepV).

Equivalent Quartz Content	A measure of the mineral hardness of a soil that is decisive for determining the abrasivity.
Excavation class	Classification based on the type of face support (according to DIN 18312:2019). In a broader sense, the term is sometimes used within the project to classify certain tunnelling scenarios (e.g. different support pressure levels or conditioning requirements). This extended meaning is not used in this document as the term tunnelling section has been defined for this purpose.
Factor of Safety against Break-up	Safety against the break-up of the overlying ground, due to the support pressure of the tunnel face causing surface heave.
Finger shield	Partially open shield casing located behind the cutterhead
Geotechnical report	Description of the site investigation with characteristic values for the soils and rock parameters.
Gripper	Lateral, radially acting bracing apparatus in rock tunnel boring machines, intended to transfer the thrust forces into the surrounding rock mass, resist roll and stabilise the TBM.
Ground behaviour	Behaviour of the unsupported ground at the tunnel face as well as the sides of a tunnel without consideration of the construction process. The ground behaviour is determined by consideration of the mechanical, hydraulic and chemical properties of the material as well as its structure. In rock, ground behaviour is described as rock mass behaviour. The rock mass behaviour is determined by the properties of the rock and the structure of the joints, the stresses in the rock and groundwater situation as well as the shape and size of the excavated cavity.
Ground profile	Geometric interpretation of the profile of natural formations or strata (DIN 4020) of homogeneous zones
Homogeneous zone	A limited zone, consisting of single or several ground types, which comprise comparable properties for underground construction work (DIN 18312). The tunnel project is divided into homogeneous zones along its route.
Landfill	One option for the disposal of excavated tunnel material
LCPC – Abrasivity Coefficient (LAK)	Value of the test method of the LCPC test for characterising the abrasivity of soils or crushed rock. It is named after the „Laboratoire Central des Ponts et Chaussées". The test is carried out according to NP-P18-579:2013-02-09 and determines the abrasivity value A_{BR} and the breakability coefficient BR.
Mechanical face support	Support of the face with support plates.
Open mode	Operation mode of an earth pressure balance TBM. In open mode, the excavation chamber is not pressurised.
Overcut	Differential dimension between the cutterhead radius and the shield radius measured at the cutting edge of the shield. The overcut serves to improve driving curves, to reduce the skin friction and to relieve stress in the ground.
Penetration	Penetration depth of the cutting tools into the ground per rotation of the cutting wheel.
Primary wear	Wear of the excavation tools solely due to the excavation of the tunnel face; influenced by the strength, jointing and abrasivity of the rock mass.

Re-use	Possibility of disposing of the excavated material by integration of the material within suitable constructions. The classifications and geotechnical properties specified within the relevant local regulations (LAGA in Germany) shall be observed.
RMR (Rock Mass Rating)	Value for the classification of rock mass based on 6 rock mass parameters.
Rock mass behaviour	See ground behaviour.
RQD Index (Rock Quality Designation Index)	Value for the characterisation of rock quality based on the sum of the lengths of drill core pieces larger than 10 cm out of the total length of core taken according to ASTM D6032-02.
Secondary wear	Secondary wear results from the rubbing and grinding action of the already excavated ground. Poor material flow and stickiness increase the secondary wear.
Separation	Description for the separation of fluids and solids in hydraulic material transport.
Shield machine	A tunnel boring machine with a complete shield, within the protection of which the tunnel lining is constructed.
Spoil Management	Generic term for recycling and disposal of the excavated material
Stability	Stability describes how stable/instable the ground is, including consideration of the effect of the construction process. The stability is verified through corresponding calculations.
Stand-up time of the ground	The length of time the ground can stand up without support. However, the final assessment and selection of the tunnel boring machine is still based on the calculation of the stability of the tunnel face and the stability of the excavated tunnel profile.
Stickiness	Tendency of adhesion of excavated material to excavation tools leading to clogging of material removal passages and equipment in clayey soil through adhesion, bridging, cohesion and insufficient dispersion capability.
Support plates	Additional mechanical support applied to the face through the use of extendable plates.
Surcharge	Creation of additional load on the ground above the tunnel alignment with insufficient overburden e.g. placing of soil/fill material.
System behaviour	Behaviour of the overall system of ground/rock mass and tunnelling machine.
TBM (Tunnel boring machine)	For tunnelling in soil or rock
Temporary Stability	In the construction state, the verification of the temporary stability can be carried out with reduced factors of safety applied to the loads.
Tunnelling section	A section or sub-section of tunnel that forms a unit from a design point of view. A tunnelling section can correspond to a homogeneous zone, but can also be part of a homogeneous zone. For each individual tunnel section, an excavation class forecast is determined.
Wear	Generic term for primary and secondary wear.
Wear prediction	Estimation of the primary wear usually carried out prior to tunnelling.

3.2 Abbreviations

A_{BR}	Abrasivity coefficient according to LCPC
A_{IN}	Abrasivity index
B_{R}	Breakability coefficient
CAI	CERCHAR Abrasivity Index
DepV	Deponieverordnung - Landfill Regulations
DOS	Double Shield Machine
EPB	Earth Pressure Balance
EXS	Partial excavation machine with excavator
GRT	Gripper-TBM
HYS	Hybrid shield machine
LAGA	Länderarbeitsgemeinschaft Abfall: Working Group of the German Federal States on Waste
LAK	LCPC – Abrasivity coefficient
LCPC	Laboratoire Central des Ponts et Chaussées
OPS	Open shield
RHS	Roadheader Shield
RMR	Rock Mass Rating
RQD	Rock Quality Designation
SLS	Slurry Shield Machine
TBM	Tunnel Boring Machine
VDS	Variable Density Shield Machine
XTS	Extension Tunnel Boring Machine
ZFSV	Temporarily Flowable, Self-Compacting Backfill Material

4 Application and structure of the recommendations

For the selection of a tunnel boring machine (TBM), a seven-step procedure according to **Figure 1** is recommended. The steps and the respective results are explained below.

4.1 Geotechnical report analysis

The geotechnical report (according to DIN EN 1997 **[16]**, **[17]** or DIN 4020 **[8]**) contains a proposal for the division of the ground into homogeneous zones and should include a representation of the homogeneous zones in the geotechnical longitudinal section. A homogeneous zone consists of one or more soil or rock layers which possess comparable properties for underground construction. Decisive for a TBM drive is the situation at the tunnel face. In this case, layers with different properties that are to be excavated together in the tunnel cross-section can also form a homogeneous zone. If necessary, properties other than the mechanical properties shall also be taken into account when defining the homogeneous zones.

Potential excavation classes (according to DIN 18312 **[18]**) and/or preliminary tunnelling sections can be determined from the analysis of the geotechnical report. However, the final tunnelling sections will only be finalised in the course of determining the type of machine to be used.

4.2 System behaviour analysis

The system behaviour comprises the interaction between the tunnel boring machine and the ground. This includes, in particular, proof of the stability of the tunnel face and the tunnel excavation as well as settlement calculations. Further aspects of the subsoil, which are important, are the boreability, wear potential, assessment of stickiness and material flow.

In addition to the properties of the ground, surface and underground infrastructure and structures, in the

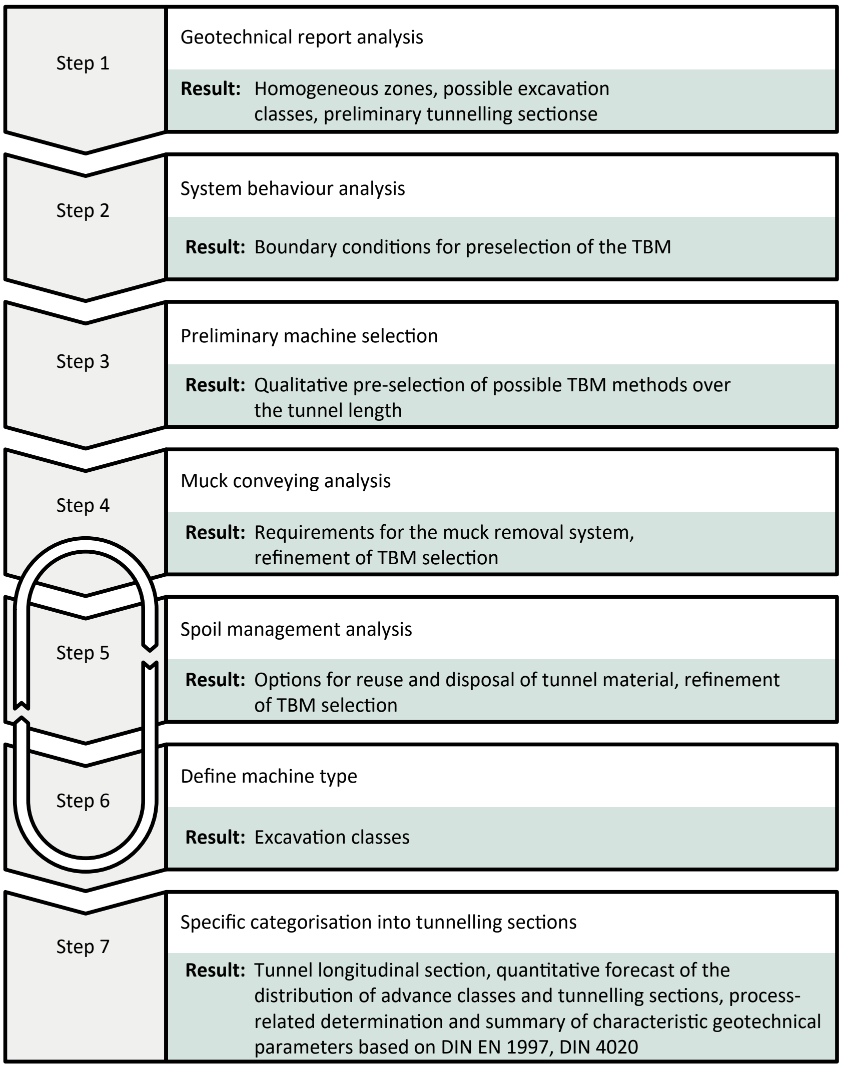

Figure 1 *Flow diagram for application of the recommendations*

zone of influence of the tunnel also have a significant impact on the overall system behaviour. The presence of such structures can result in additional safety requirements and, possibly, restrictions regarding the use of certain types of machines. Following the analysis of the system behaviour, basic requirements for the machine type can be formulated. Guidance on this process is given in **Chapters 6.2 to 6.5** of this recommendation.

4.3 Preliminary TBM selection

Based on the process of elimination method set out above, suitable machine types can be assigned to individual homogeneous zones, so that a qualitative pre-selection of possible TBM types along the tunnel length is possible. **Chapter 5** and the **appendices** of this recommendation provide guidance in relation to the designation and selection of machine types.

4.4 Muck conveying analysis

For the pre-selected machine types, the transport of the excavated material has to be examined under consideration of a number of factors, including the technical process, tool wear, stickiness, conditioning and material disposal. Further guidance on material transport is contained in **Chapter 6.6**.

4.5 Spoil management analysis

For the pre-selected machine types and taking into consideration the muck conveying analysis, the spoil management (recycling or disposal) shall be investigated. Environmental and economic aspects shall be included in the investigations. Guidance is given in **Chapter 6.7**.

4.6 Definition of machine type

On the basis of the previously performed analyses of muck conveying and spoil management, follows a determination of the optimal machine type under consideration of project-specific and economic factors or risks. As a result of this step, the excavation classes according to DIN 18312 **[18]** are also determined.

4.7 Process-specific categorisation into tunnelling sections

To conclude the selection of tunnel boring machines, the tunnel longitudinal section is to be divided into tunnelling sections based on the analyses carried out and the definition of the excavation classes (according to DIN 18312:2019 **[18]**). These homogeneous zones differ according to machine operation modes, pricing mechanism, and other project specific boundary conditions. For each tunnelling section, the machine type and the operation mode are to be determined. For the closed mode, the operating pressure range shall be specified. Detailed information regarding this topic can be found in **Chapter 6**.

For the representation of the tunnelling sections, the tunnel longitudinal section is particularly suitable. The longitudinal section can also be used as the technical and estimate basis for contracts and therefore should contain all geotechnical and contract relevant parameters. In the case of BIM-based planning, the corresponding parameters should be linked to the model. As a result of this step, the longitudinal section, the quantitative forecast across the excavation classes, the tunnelling sections, as well as a process-related determination and summary of the characteristic parameters of the ground according to DIN EN 1997 **[16]**, **[17]** as well as DIN 4020 **[8]** should be combined.

5 Categorisation of tunnel boring machines

5.1 Classification of tunnel boring machines

Tunnel boring machines (TBMs) excavate either the entire tunnel cross-section with a cutterhead or cutting wheel, or partially through specific excavation tools. **Table 1** shows a systematic classification of the various tunnel boring machines.

5.2 TBMs for full face excavation

5.2.1 Gripper tunnel boring machine (GRT)

Gripper tunnel boring machines (**Figure 2**) are utilised in rock with a medium to long stand-up time.

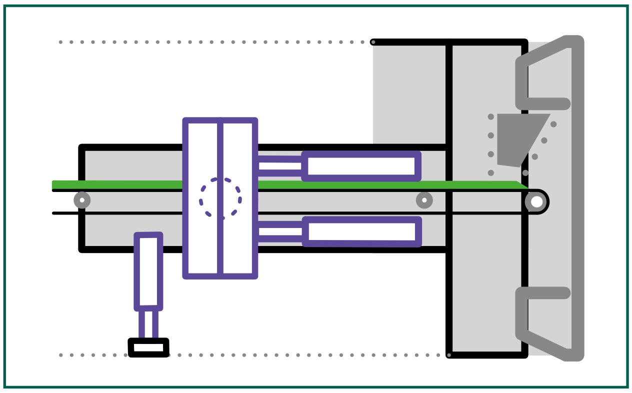

Figure 2 *System Layout GRT*

Table 1 Classification of tunnel boring machines

Name			Operation Mode			Standard excavation classes according to DIN 18312:2019*
German	**English**	**Short**	**Open (OM)**	**Closed (CM)**	**Transition (TM)**	
Full-face machines types						
Gripper-TBM	Gripper TBM	GRT	X	–	–	TBM1/TBM2/TBM3
Einfachschild	Single Shield/ Open Shield	OPS	X	–	–	TBM3 or VS1
Doppelschild	Double Shield	DOS	X	–	–	TBM2/TBM3 or VS1
Flüssigkeitsschild	Slurry Shield	SLS	–	X	–	VS2
Erddruckschild	Earth Pressure Balance Shield	EPB	–	X	–	VS3
Variable-Density-Schild	Variable Desity Shield	VDS	–	X	X	VS2/VS3
Hybrid-/Multimodeschild	Hybrid Shield	HYS	X	X	X	VS2/VS3
Erweiterungs-TBM	Extension TBM	XTS	X	–	–	TBM1/TBM2/TBM3
Partial-face machine types						
TS-Schilde mit Bagger	Excavator Shield	EXS	X	(X)	–	TS1/TS2
TS-Schilde mit Schräme	Roadheader Shield	RHS	X	(X)	–	TS1/TS2

*Due to the complex and intergrading technologies of the different tunnel boring machines, especially of the shield machines, the advance classes of the shield machines are defined according to DIN 18312:2019. A specification of advance classes of the tunnel boring machines according to DIN 18312:2019 has to be performed on a project-specific basis.

There is no active support of the tunnel face and excavation profile. They do not possess a full shield. In the immediate area behind the cutterhead, a short cutterhead shield with hood, side panels and invert plate is utilised. In the case of an unfavourable deviation from the predicted rock mass prognosis, an economical operation can be significantly affected and limited by the need for complex conventional ground support measures and increased costs due to additional wear of the mining tools.

In order to apply the contact pressure to the cutterhead, the machine is braced radially by bracing plates (gripper plates), which are hydraulically pressed against the intrados of the tunnel. When the maximum stroke of the thrust cylinders is reached, the advance is stopped and the machine is stabilised by an additional rear support before the gripper plates are released from the excavation intrados. With the retracted gripper plates, the force plane is moved in the direction of advance and then the advance is continued.

Rock is excavated precisely and to the exact excavation profile by disc cutters mounted on the cutterhead. Depending on the diameter, the machine fills a large part of the cross-section with the cutterhead shield or the machine frame. Systematic support of the tunnel profile is normally carried out in the protection of the finger shield or directly behind the cutterhead shield (5 m to 10 m behind the tunnel face) and supplemented in the trailing gantry areas if required. In order to cope with fault zones that consist of less stable rock, particularly when there is a risk of rockfall, it shall also be possible to install steel arches, shotcrete, spiles or anchors as closely as possible behind the cutterhead.

A systematic shotcrete lining should only be installed in the trailing gantry area, in order to reduce, as much as possible, contamination of the drive and steering units in the front part of machine. The shotcrete application can be performed mechanically (shotcrete robot) or manually (hand spraying). Likewise, reinforcement of the rock support with anchors in the gantry area should also be foreseen.

In sections of unstable or heterogeneous rock conditions (high degree of fracturing, fault zones), it is recommended that the tunnel boring machine is equipped with devices to enable forward probe drilling and perhaps also rock improvement, ahead of the machine.

During tunnelling, the rock is removed by cutting of the tunnel face. This results in the production of small-sized pieces of material (chips) and generated dust. Therefore, for gripper machines, equipment for reducing the production of dust, and for dedusting are required. Methods of dust suppression can be:

a) Water spraying at the cutterhead,

b) Dust shield behind the cutterhead,

c) Dust extraction in the excavation chamber with dedusting on the backup.

5.2.2 Single shield, Open shield machine (OPS)

For stable tunnel faces, e.g. in clays with a firm consistency and sufficient cohesion or in rock, single shields (**Figure 3**) can be employed. Single shields, also known as open shields, consist of a shield that secures the tunnel profile with its shell. The tunnel lining is constructed within the shield in the form of a segmental ring. The ground is usually excavated by a cutterhead equipped with cutter discs. This extracted material is then removed via conveyor belts. The thrust forces and the cutterhead torque are transmitted via the thrust cylinders to the last constructed segmental lining ring.

In blocky rock, usually jacking shields are used, which are equipped with a mainly closed cutterhead and, in conjunction with the shield casing, protect against the ground that could potentially become displaced.

In sections of unstable or heterogeneous rock conditions (high degree of fissuring, fault zones), it is recommended that the tunnel boring machine be equipped with devices to enable forward probe drilling and rock improvement ahead of the machine.

During tunnelling, the rock is removed by cutting of the tunnel face. This results in the production of small-sized pieces of material (chips) and generated dust. Therefore, for single-shield machines, equipment for reducing the production of dust, and for dedusting are required. Methods of dust suppression can be:

a) Water spraying at the cutterhead,

b) Dust shield behind the cutterhead,

c) Dust extraction in the excavation chamber with dedusting on the backup.

5.2.3 Double shield machine (DOS)

Double shield machines (**Figure 4**) consist of two telescopic machine parts. They are used in solid rock or soils with a stable tunnel face. The front section is called the front shield and contains the cutterhead with its disc cutters, the cutterhead drive and the main thrust cylinders. The rear part of the machine is known as the gripper shield and houses the gripper plates and the auxiliary thrust cylinders. Connected to the gripper shield are the tailskin and the segment placement device (erector). The front shield can be extended forwards by a complete ring length in relation to the gripper shield through extension of the main thrust cylinders. The resulting free space between both shield parts at the tunnel reveal is called the telescopic joint and is closed by the telescopic shield.

In a stable rock mass, the grippers resist the torque and the thrust forces during advance. Through secure fixation of the rear part of the machine with the bracing plates, the segment ring can be constructed in the tailskin area while the front shield is being thrust forwards and the advance can continue. This operating mode is known as double-shield mode. In stable rock masses, segment installation may not be necessary. In subsoil in which the grippers cannot grip sufficiently, the advance can be supported from the last ring of segments. This operating mode is known as single-shield mode. In single-shield mode, the front and rear parts of the machine are advanced together, the thrust forces are applied to the tunnel segments through the auxiliary thrust cylinders.

Typically, there is no possibility for active support of the tunnel face. In double-shield mode, the excavation intrados is not protected by a shield. Therefore, the rock shall exhibit a sufficient stand-up time in or-

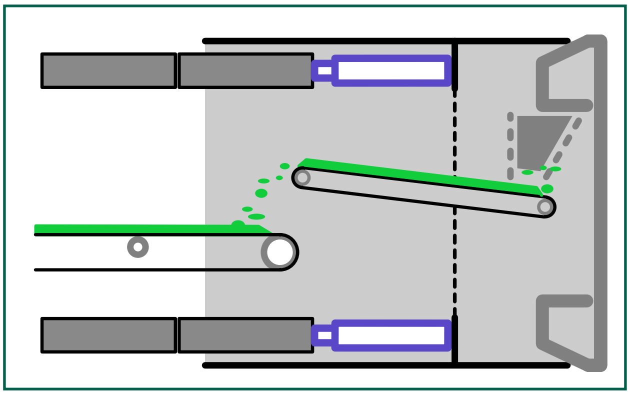

Figure 3 System layout OPS

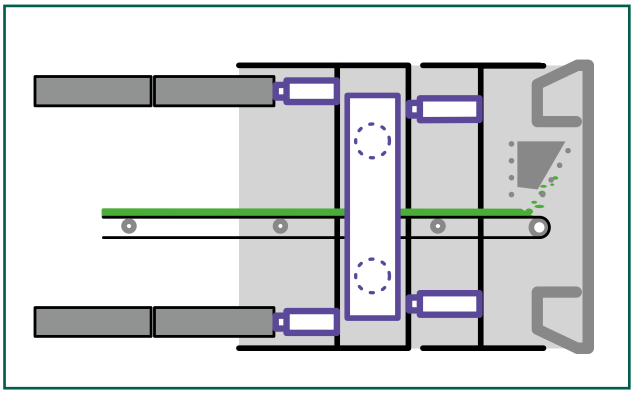

Figure 4 System layout DOS

der for the intended support to be installed. In the single-shield mode, areas of rock with a shorter stand-up time can also be excavated. If there is a possibility that sections of unstable or heterogeneous rock conditions (high degree of fissuring, fault zones) can be encountered, it is recommended that the tunnel boring machine be equipped with devices to enable forward probe drilling and perhaps also ground improvement, ahead of the machine.

During tunnelling, the rock is removed by cutting of the tunnel face. This results in the production of small-sized pieces of material (chips) and generated dust. Therefore, for double-shield machines, equipment for reducing the production of dust, and for dedusting are required. Methods of dust suppression can be:

a) Water spraying at the cutterhead,

b) Dust shield behind the cutterhead,

a) Dust extraction in the excavation chamber with dedusting on the backup.

5.2.4 Slurry shield machine (SLS)

In tunnel boring machines with fluid support (**Figure 5**), the tunnel face is actively supported by a pressurised medium (slurry). The excavation chamber is sealed off from the tunnel by a pressure wall. In addition to the active support of the tunnel face, the closed shield machines offer the advantage of sealing against the formation of dust when the material is loosened at the tunnel face. Slurry shields are usually used under conditions in which the tunnel face has to be actively supported and the inside of the machine protected against soil and water penetration.

The tunnel lining is built within the protection of the shield casing through erection of segmental rings. The properties of the support medium shall be determined in accordance with the permeability of the existing subsoil. It shall be possible to vary the density and viscosity of the slurry. Bentonite suspensions have proven to be particularly suitable for this purpose. The required support pressure can be controlled very precisely via an air bubble behind an integrated submerged wall and via the coordinated output rates of the feed and slurry pumps. Prior to the start of tunnelling, the required and maximum support pressures shall be calculated over the entire length to be tunnelled (support pressure calculation). Removal of the soil takes place through full-face excavation by a cutting wheel equipped with tools. The soil is then removed via the suspension. Subsequent separation of the removed suspension is essential.

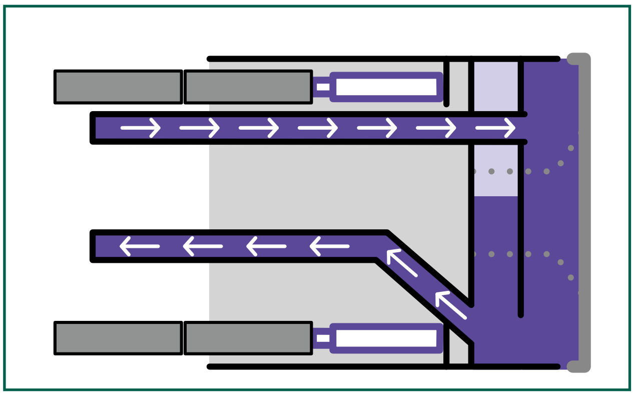

Figure 5 *System layout SLS*

If it is necessary to enter the mining chamber, e.g. to change tools, for repair work, or to remove obstructions, the support fluid shall be partially or completely replaced by compressed air. The support slurry then forms a low-permeability membrane on the face; however, the durability of this membrane is limited (risk of drying out). The membrane permits the support of the face by compressed air and may need to be renewed regularly. The support slurry can be completely (empty) or only partially (lowering) removed and replaced by compressed air. The required level of lowering is determined in particular by the required size of the working space or the permissible maximum lowering height. This decision should be taken so that sufficiently safe working is possible at all times and an adequately large space is available for the workers to retreat in the case of face instability. Partial lowering of less than half the diameter of the cutting wheel does not allow access to all tools.

If an open cutting wheel is used, shutter segments in the cutting wheel or plates that can be extended from the rear can be used to mechanically close the face in order to protect the personnel working in the excavation chamber while the machine is stopped. Such measures can be considered prudent due to the limited duration of the membrane effect. Possible additional mechanical support of the tunnel face by the cutting wheel or by safety plates is only to be considered as an additional safety measure. Consideration of these measures within the calculated approach for the supporting effect is not permissible.

Stones or rock benches can be reduced to a conveyable size by cutter discs on the cutting wheel and/or crushers in the working chamber. In stable ground, the slurry shield can also be operated without pressurisation, with the excavation chamber partially filled with water, which is then used as the conveying medium. In terms of the machine technology, it may be necessary to maintain a minimum operating pressure to avoid cavitation and pressure fluctuations of the feed pumps, as well as blockages in the suction area. However, these minimum operating pressures required for machine processes are usually not taken into account in the calculation of the support pressure.

5.2.5 Earth pressure balance machine (EPB)

For the tunnelling machines with earth pressure balance face support (**Figure 6**), the tunnel face can be actively supported through remoulded earth formed from the excavated material. In this case, the excavation chamber is completely or partially closed off from the tunnel by a pressure bulkhead. The mode of operation where the excavation chamber is completely filled with the soil paste is called closed mode.

A cutting wheel with a relatively low opening ratio, fitted with cutting tools, excavates the soil. Mixing vanes on the back of the cutting wheel (rotors/back buckets) and on the pressure bulkhead (stators) help to give cohesive soil a suitable and uniform consistency, and for mixed and coarse-grained soil, to ensure adequate workability. The support pressure is monitored with earth pressure cells that are distributed on the front of the pressure bulkhead. A pressurised screw conveyor removes the soil from the working chamber.

The support pressure is controlled by the speed of the screw conveyor and the advance rate of the TBM as well as the pressure-volume controlled injection of suitable conditioning agents. The pressure reduction between the excavation chamber and the tunnel is achieved by friction in the screw conveyor. The soil material in the screw conveyor or additional mechanical devices shall ensure the tightness in the respective device. Complete support of the tunnel face, especially in the upper area, is only possible if the soil is conditioned in such a way that it possesses suitable properties to operate as a support medium. Here the proportion of fine grain with a grain diameter of less than 0.06 mm has a significant influence. By conditioning the soil, e.g. with bentonite, polymers or foam, the field of application of the earth pressure balance shields can be extended, however, attention needs to be paid to sustainable disposal of the material.

In stable ground, the earth pressure balance machine can also be operated without pressurisation with a partially filled excavation chamber. This operating mode without active support of the tunnel face is called open mode. In stable ground with water ingress, operation is also possible with partially filled excavation chamber and compressed air (transition mode).

In the event of high groundwater pressure and if the ground tends to liquefy, the – in this case critical – material transfer from the screw to the conveyor belt can be replaced by a closed system (pump feed). See **Section 5.2.7** “Hybrid/Multi-mode machines”.

5.2.6 Variable Density Machine (VDS)

The closed machines based on the variable density principle (**Figure 7**) combine the principles of the active tunnel face support of a slurry machine and that of an earth pressure balance machine in one tunnel boring machine. Therefore, the VDS machine has two chambers connected to each other by communication pipes with an air cushion for precise regulation of the support pressure. Extraction of the material from the excavation chamber takes place via a screw conveyor, in both slurry and earth pressure support modes. Depending on the mode, the support pressure is regulated either by screw speed and advance rate or by an automatically controlled compressed air cushion.

The supporting and conveying principle of a variable density machine is provided in the basic equipment behind the screw conveyor – a closed, pressurised hydraulic conveying circuit with a separation plant above ground. In slurry mode, either a normal low-density bentonite suspension can be used or alternatively a high-density suspension can be pumped into the excavation chamber. Similarly, for earth pressure operation in closed mode, both with or without the addition of bentonite suspension, this pumping principle can also be used. The flow rate of the share of the complete circuit that is directed through the excavation chamber can be adjusted as required. Thus, the density in the excavation chamber can be continuously altered between that of a slurry shield

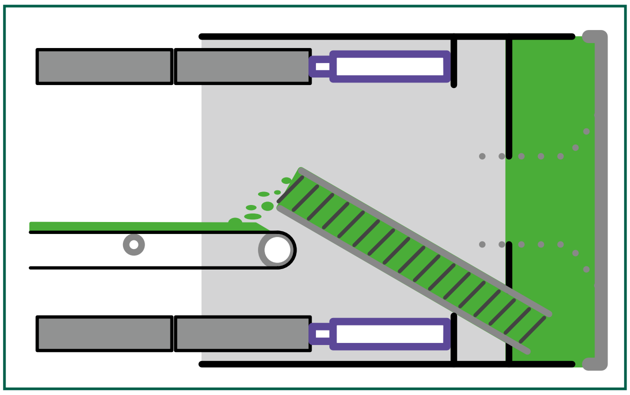

Figure 6 *System layout EPB*

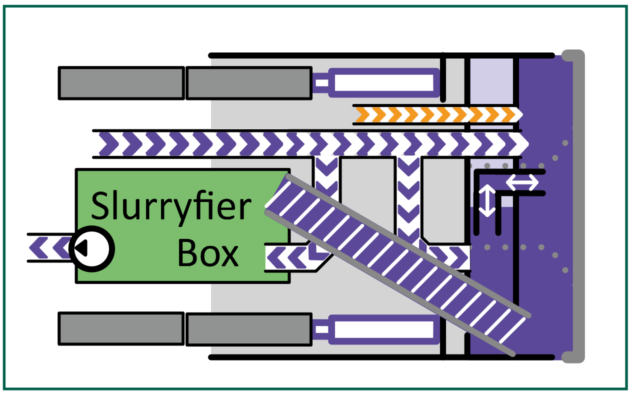

Figure 7 *System layout VDS*

and that of an earth pressure balance shield. The tunnel face is continuously supported and the excavation modes can be switched without conversion works in the excavation chamber.

If the slurry-supported operating modes are not required, a belt conveyor system can be installed in the tunnel in place of hydraulic conveyance through slurry pipes with an above-ground separation plant. In this case, it is also possible to utilise foam conditioning of the excavated soil, which otherwise could not be hydraulically conveyed.

5.2.7 Hybrid-/Multi-mode machine (HYS)

A large number of tunnels run through highly variable ground conditions, which can range from rock to loosely consolidated soil. Therefore, in order to adapt the process technology to the geotechnical conditions, corresponding shield machines have to be used. Here, shield machines are used where a change of the process technology is possible by a modification of the excavation system. These machines are called hybrid or multimode machines (**Figure 8**).

The mucking is divided into primary mucking within the machine and secondary mucking in the tunnel. Depending on the possible change of the process technology, the multimode machines are differentiated as the following:

- Alteration of the primary mucking within the machine (see **Figure 8**):
  a) Alteration between screw conveyance and belt conveyance
  b) Alteration between hydraulic conveyance and belt conveyance with chutes at the back of the cutterhead
- Alteration of the secondary mucking in the tunnel between hydraulic and belt conveyance

In the case of multimode machines for switching between hydraulic and belt conveyance in the tunnel, the primary conveyance in the machine and the tunnel face support are not directly affected. Here, the consistency of the excavated material is decisive. If suspensions or water are used for conditioning or assisting the supporting effect, hydraulic conveying or separation on the machine may be necessary. Foam-conditioned or higher viscosity spoil can be transported in the tunnel on conveyor belts. When changing the primary conveying system from screw conveyors to chutes and conveyor belts, active face support is omitted. The tunnel is then driven according to the single shield principle (OPS). The alteration work usually takes several shifts.

5.2.8 Extension TBM (XTS)

Extension tunnel boring machines (widening machines, **Figure 9**) are used in hard rock to enlarge a previously constructed continuous pilot tunnel to

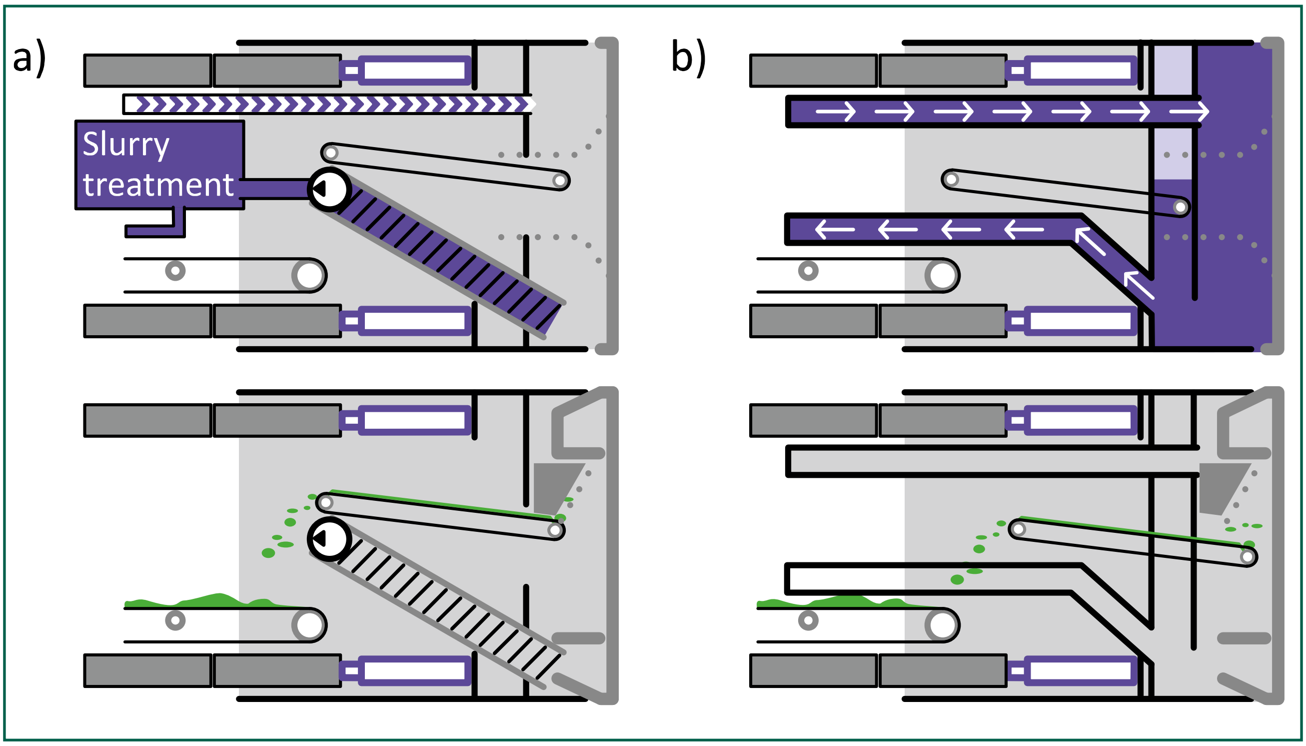

Figure 8 *System layout HYS*

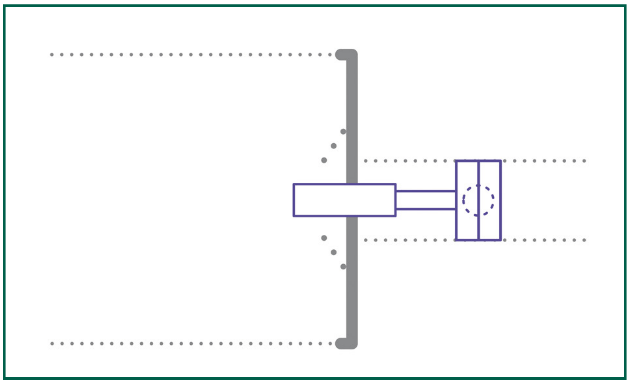

Figure 9 System layout XTS

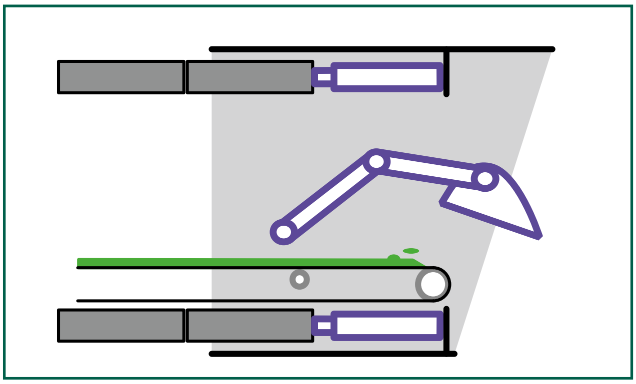

Figure 10 System layout EXS

the planned final diameter. The expansion to the full cross-section is carried out in one or two operations by a suitably designed cutterhead.

The main elements of this machine are the cutterhead, the bracing and the advance mechanism. Bracing of this special machine is located in front of the cutterhead and is supported by grippers in the pilot tunnel. The cutterhead of the machine is drawn towards the bracing during the boring process. In disturbed rock formations, measures can be undertaken to stabilise fault zones from the previously bored pilot tunnel, thus minimizing the risks when drilling the main tunnel. The systematic securing of the tunnel soffit is carried out behind the expansion cutterhead with support arches, anchors and shotcrete. Special attention is to be paid regarding the removal of the dust produced during the drilling process.

5.3 Partial-face excavation machine

These shield types can be utilised on vertical or steep slopes of a stable tunnel face. Partial-face excavation machines consist of a shield casing, a specific excavation device, the thrust cylinders, the tailskin, and the segment erector. Excavated material is then discharged via conveyor belts or scraper belts.

In some cases, partial-face excavation machines have an arrangement of platforms and/or breasting plates which are intended to provide mechanical support for the face. However, as such support cannot be accurately regulated and controlled, it is not considered a reliable method for preventing major settlement.

In partial-face excavation machines, groundwater can be retained by compressed air. For this purpose, either the entire tunnel is pressurised with compressed air, or the machine possesses a pressure wall. The excavated material is either conveyed hydraulically or discharged dry.

5.3.1 Partial-face excavation machine with excavator (EXS)

This machine (**Figure 10**) consists of a shield, an excavation device (excavator or ripper tooth), the conveyor system, the thrust cylinders, the tailskin and the segment erector. The spoil is then discharged via conveyor belts or scraper belts.

5.3.2 Partial-face excavation machine with roadheader (RHS)

The partial-face excavation machine with a roadheader consists of a shield, a roadheader excavation tool, the conveyor system, the thrust cylinders, the tailskin and the segment erector. The spoil is then discharged via conveyor belts or scraper belts.

6 Ground and system behaviour

6.1 Preliminary Remarks

The system behaviour is of critical importance for the selection of a tunnel boring machine, i.e. the behaviour of the overall system that consists of ground and selected tunnelling method **[35]**. When a tunnel boring machine is used, the ground behaviour criteria (see **Appendix 2**) are fundamentally different from those in conventional tunnelling.

The foundation for the necessary knowledge of the system behaviour are the geotechnical investigations, which are generally to be undertaken in accordance with local codes and standards (in Germany: DIN 4020 **[8]**). Determination of the characteristic values, the display and evaluation of the results of the geotechnical investigation as well as the conclusions, recommendations and advice drawn from them should already be aligned with the (anticipated) subsequent tunnelling method determined early in the design phase.

The more extensive and meaningful the preliminary investigations are, the better the conditions for the selection of the process technology and the tunnel boring machine. In this regard, it is recommended to consider the entire process, from excavation of the tunnel face, via mucking and material transport, to the final disposal or recycling of the excavated material in the planning of the geotechnical investigation.

The essential geotechnical parameters are summarised in **Appendix 2** for each process and can serve as a rule of thumb for the selection of the tunnel boring machine. They should be determined specifically for each project for the relevant ground conditions. It should be noted that deviations of these ground parameters from the assumed values can result in complex and irregular consequences for the process chain. It is therefore recommended to include appropriate provisions within the contract.

It is helpful and practical to display the expected ground conditions in a geotechnical longitudinal section and assign sections to relevant tunnelling sections.

In the following sections, basic advice and recommendations for a process-oriented analysis of system behaviour are given. A summary of the required characteristic values – split into soft ground and hard rock – is given in **Appendices 2.1 and 2.2**.

6.2 Stability and Face Support

Ground behaviour as well as any necessary support of the tunnel lining and the tunnel face are the primary criteria for the selection of the tunnel boring machine. The basis for this is the proof of the global and local stability of the tunnel face.

In a first step, it can be examined whether the ground is inherently stable or whether active support of the tunnel face is required. For an approximate assessment of the stability, for example according to **[35**, see Table 1 there**]**, the classifications according to **Table 2** can be used in hard rock on the basis of the RMR classification.

Especially in the case of larger excavation cross-sections, more thorough investigations of rock stability are required.

In soils, depending on the geotechnical boundary conditions, various analytical or numerical methods are used with which – again depending on the method – the necessary measures for the tunnel face support can be determined. In this context, reference is made to the relevant guidelines **[1]**, **[2]**, **[19].**

In addition, criteria regarding expected ground deformations and surface settlements shall be taken into account, if necessary. This is often decisive for the choice of a tunnelling method, particularly in urban tunnelling. In this case, corresponding verification calculations, e.g. of the hazard to existing buildings, shall be provided.

6.3 Soil and rock excavation

The efficiency of soil and rock excavation depends not only on the ground properties but also on the choice of excavation tools, the geometry and design of the cutting wheel or cutterhead, and the advance parameters of the TBM. Changes in the geotechnical parameters can make driving more difficult or even easier. Extremely complex interactions between the ground and the process technology therefore require detailed analyses to increase efficiency.

In particular, clogging in the excavation chamber, high wear and tear of the excavation tools and unstable tunnel face conditions are the most frequent causes for a reduction of excavation performance which in turn leads to increased costs. These factors are important criteria for the determination of a suitable TBM.

6.3.1 Clogging

The stickiness of the soil can have a decisive effect on the advance rate in mechanised tunnelling. Clogging reduces the advance rate because, for example, the excavation chamber of slurry-support machines has to be flushed, or time-consuming manual cleaning leads to unplanned stoppages. In addition, stickiness in combination with a high content of certain minerals liable to cause wear can lead to heavy wear on the cutting wheel, excavation chamber or conveyor equipment. Any propensity for the ground to stick should therefore always be described in geotechnical reports.

Soft ground with clay content, but also solid rock containing clay minerals, can result in considerable delays through clogging. Clays with pronounced plasticity and sedimentary rocks containing clay, like for example, conglomerates/breccias with clay mineral content, siltstones and specifically mudstone have exhibited a particularly high degree of stickiness. Clog-

Table 2 *RMR Classification*

A1	stable	RMR 81-100
A2	loose	RMR 61-80
B1	brittle	RMR 51-60
B2	very brittle	RMR 41-50
B3	non-cohesive	RMR 21-40
C	squeezing rock	RMR < 20

ging often occurs in combination with water, which can originate from groundwater with open and earth pressure balance machines or process water (support suspension, soil conditioning, cutterhead jetting in hard rock).

Hindrance of progress through clogging can be most effectively countered by identifying the stickiness of the ground prior to the start of construction, and appropriately adapting the equipment of the complete tunnelling system and the planned advance rate to take the problem into consideration. Geotechnical reports should provide the following information in this regard:

- Determination of the Atterberg limits and the consistency of the soil as an indication of the stickiness according to DIN 18122 for soft ground,
- Clay mineralogical analyses for the determination of the content of the most significant minerals (montmorillonite, kaolinite, illite, smectite, quartz etc.),
- Closer pattern of investigation in areas containing clay minerals for the more precise determination of the affected sections and the content of clay constituents at the face.

6.3.2 Wear

The wear on the excavation and mucking components depends on the abrasivity of the ground, the type of mechanical loading, the selection of tool materials and the operating parameters of the machine. The interactions in the so-called tribological system include the four basic mechanisms adhesion, abrasivity, surface fatigue and tribochemical reactions **[55]**, **[56]**, **[57]**. **Appendix 2** contains tabular compilations of the most important characteristic values for wear in soil and rock, among others.

In coarse-grained and mixed-grained soils, the breakability and strength of the coarse-grained fractions, stones and blocks as well as the equivalent quartz content (EQC %) decisively determine the primary wear. Secondary wear increases with increasing equivalent quartz content and a deterioration of the material flow and detachability, especially in broadly-graded granular mixtures. Depending on the TBM and tooling used, it is therefore necessary to investigate whether fracturing, crushing or grinding processes occur during loosening and conveying of the soil in order to predict the wear.

For the estimation of the abrasivity of soil, ranges for the abrasivity coefficient A_{BR} according to DIN 18312:2019 and for the breakability coefficient B_R according to NF P18-579:2013-02-09 are to be specified in the geotechnical report. The test, commonly known as the „LCPC test", developed by the Laboratoire Central des Ponts et Caussées (LCPC), only examines grains with a diameter of 4 mm to 6.3 mm that, if necessary, have been previously broken in accordance with the standards. A standardised classification of the results of the abrasivity coefficient A_{BR} does not exist. Since the test for determining the abrasivity coefficient cannot reflect the boundary conditions of wear in tunnel boring machines, this test, although its results are to be given in bandwidths in accordance with DIN 18312:2019, is disputed among industry experts and is therefore not considered a geotechnical parameter in **Appendix 3**.

For this reason, further characteristic values based on non-standardised test methods are made available in order to better describe the abrasivity of the soil or the wear of the tools.

In order to take into account larger ranges of grain size distributions, which are to be examined based on the A_{BR} abrasivity coefficient, additional tests are sometimes carried out to determine the abrasivity value, in which the abrasive effect of the sand, silt, and clay fraction with a diameter of less than 4 mm is also examined. A comparable test with the entire band width from 0 mm to 6.3 mm can be suitable in this case, which should be designated $A_{BR,\ 0\text{-}6.3}$.

Following the test for determining the abrasivity coefficient according to NF P18-579:2013-02-09, investigations can also be carried out using the test rig developed at the Technical University of Vienna, where, in contrast to the above-described test for determining the abrasivity coefficient A_{BR}, further boundary conditions of mechanised tunnelling can be taken into account. Further tests have also been developed by other national and international institutes.

Since the mineralogical composition of the soil can have a significant influence on the abrasivity or wear, it is recommended to determine and indicate the equivalent quartz content (EQC %) of the soil. To date there has been no classification for the equivalent quartz content. For the selection tables in **Appendix 3**, therefore, a division into equivalence ranges is made as listed in **Table 3** without verbal classification in accordance with **[56]**.

Table 3 *Range of the equivalent quartz content (EQC %) for tunnelling in soils*

0 % ≤ EQC% < 5 %	**5 % ≤ EQC% < 15 %**	**15 % ≤ EQC%< 35 %**	**35 % ≤ EQC%< 75 %**	**75 % ≤ EQC% ≤ 100 %**

It is to be noted that the determined index values as well as the verbal descriptions of the abrasivity cannot be used for a clear correlation analysis or analytical determination of the tool wear. The mechanical stress applied to the cutting tools is fundamentally different from the test conditions. Important geometrical and technical parameters as well as influencing factors have not yet been taken into account. Further information can be found in **[55]**, **[56]**.

In rock, wear can significantly vary depending on rock strength, mineralogical composition, jointing, and tunnel orientation to the texture of the rock mass. The Cerchar Abrasivity Index (CAI) is suited to classify the abrasivity of the rock. The CAI test can be used to determine the abrasivity index A_{IN} (according to NF P94-430-1:2000-10-01), which shall be specified according to the current standard DIN 18312:2019. There is no standardised classification of the results of the abrasivity index A_{IN}. The selection tables in **Appendix 3** are divided into the areas with classification according to **[56]**.

Other important parameters are the equivalent quartz content, the robustness of the rock, and the rock strength. High rock strength and correspondingly high abrasivity values lead to high primary wear in compact rock. In case abrasive, hard to break rocks are loosened out of the rock mass in an uncontrolled manner (unstable tunnel face), the wear can increase over-proportionately due to impermissible peak loading (shock loads). If the material flow is poor due to clogging, or the design of the cutting wheel openings is unfavourable to material flow, a further increase of wear is to be expected (secondary wear).

Further factors determining wear are: breakability, ductility, grain size, texture, porosity, mineral hardness, possible foliation. Material parameters include the hardness of the mining tools (Rockwell hardness) and the set torque of the disc cutter as well as the cutting width of the cutting ring. Design parameters are, among others, the shape of the disc cutter (flat or curved flanks), the rounding radius in the gauge area, the arrangement of the disc cutter on the cutter head (spoke or spiral), the spacing of the cutting tracks, the disc cutter diameter, and the distance of the cutting tracks from the cutting wheel surface. In addition, the mode of operation and tool management (monitoring and replacement cycles) also determine wear.

It is recommended that reference data be used to assess tool wear. In addition to comparable soil and rock properties, operational data and design features of the TBM should be included to estimate tool wear. Furthermore, the mineralogical composition, the cutterhead design and the type of cutting tool, as well as the process technology aspects of the tunnelling operation shall be taken into account.

6.4 Soil conditioning in EPB

In tunnelling with earth-pressure supported tunnel faces, soil conditioning is generally used to modify the geotechnical properties of the excavated soil in such a way that the conditioned soil material has suitable properties as a support medium for tunnelling and ensures the most trouble-free and economical tunnel excavation possible. The objectives of conditioning for tunnelling with earth-pressure supported tunnel faces can be summarised as follows **[54]**:

- Temporary improvement of the properties of the support medium, especially the flow characteristics, to ensure the material flow in the excavation chamber and in the screw conveyor.
- Reduction of the water permeability to avoid or reduce possible destabilising seepage flows from the tunnel face into the excavation chamber.
- Increase of the compressibility of the support medium in order to minimise, process-related volume and support pressure fluctuations in the excavation chamber.
- Support of the entire tunnel face with an almost homogeneous material to transfer the support pressure to the existing ground.
- Reduction of the internal friction of the support medium in order to decrease the drive torques and the energy consumption of the cutting wheel and the screw conveyor as well as to reduce the wear on mining tools and other machine components.

In coarse-grained or mixed soils, tenside foams are usually added with the potential additional use of polymers or fine material suspensions, while in fine-grained soils polymer, bentonite and clay suspensions or even just water can be used.

The original geotechnical properties of the existing soil are modified by the use and addition of conditioning agents. Addition of such agents shall be taken into account when assessing further transport and disposal options.

The required concentration of the respective conditioning agent can be estimated based on previous experience, the characteristic values of the subsoil and results of the relevant tests. The cutting wheel design, the technical parameters of the TBM and the required support pressure shall also be taken into account. Conditioning agents shall be selected in such a way that they enable homogeneous soil mixing and do not flow uncontrollably into the ground.

The additives added to the soil should comply with the following minimum criteria:

- Simple and controllable dosage (guaranteed by the use of liquid additives)

- Avoidance of blockages in the feed lines and outlet nozzles of the additives and when conveying the conditioned material out of the excavation chamber
- Rapid efficacy development
- Avoidance of environmental hazards or the deterioration of the landfill classes for disposal

In tunnelling with earth-pressure supported tunnel faces, particularly in variable clay-containing sedimentary rocks (e.g. clay and siltstones) and in over-consolidated fine-grained soils with a clay content (cohesive soils of stiff, semi-solid or solid texture), the nature of the loose, non-compacted excavated material initially shows no marked tendency to stick together; however, with these soils, the deformation behaviour of the excavated material is generally not suitable for closed mode operation with full-face support. As an example, starting from a semi-solid consistency of the loosened soil, the consistency index I_C of the soil mixture decreases in the course of the addition of conditioning agents (or also through a groundwater inflow). The sticking potential in the area of stiff and soft consistency strongly increases before it decreases again in the area of soft consistency **[40]**. Therefore, there is a sensitive interaction between the workability and the tendency to stick when conditioning cohesive subsoil. Consequently, a minimum quantity of suitable conditioning agents is required for the closed mode operation of a tunnel drive with an earth-pressure supported tunnel face in order to achieve good workability with a sufficiently low stickiness.

During tunnelling, conditioning agents do not or only slightly penetrate into the surrounding ground, but are removed from the tunnel with the excavated material and thus have a significant influence on the disposal of the excavated material.

The excavated soil mixture may not have sufficient geotechnical properties to allow the excavated material to be transported or disposed of economically. Therefore, a relationship exists between the conditioning and the disposal of the soil. Possible measures to alter the geotechnical properties with regard to disposal are described in **Section 6.7**.

In any case, a series of tests should be carried out in advance to determine the change in the existing geogenic soil by adding the conditioning agents described below, in order to ensure safe disposal in advance of the construction work. In extreme cases, this can lead to the exclusion of certain conditioning agents and subsequently to the exclusion of certain tunnelling methods.

The conditioning agents can be divided into different categories. These include water hazard classes (local regulations apply), degradability (at least 60 % primary degradability and at least 80 % biodegradability) and toxicological limit values for mammals (LD50) and aquatic organisms (EC50).

Due to the multitude of conditioning agents, the composition of soils and their properties, a general classification of conditioned soils is not possible. It shall be considered for each individual case where limit values are observed and how the conditioned material can be further treated. Information is noted in the regulations in **Chapter 2**.

6.4.1 Foam

The use of foam is necessary and should be planned for when tunnelling with an earth-pressure supported tunnel face outside the classic areas of application. For example, water-permeable, coarse-grained or mixed-grained soils with increasing water pressure require tenside foams with or without polymer additives.

It has been shown that both the design of the foam nozzles and the choice of conditioning agents or conditioning agent products have a decisive influence on the properties of the foams and the quantities of substances.

When selecting a TBM, the following aspects and requirements for the foam technology have to be considered:

- Planning of the rotational distribution and injection points in the cutting wheel
- Estimation of the tenside and polymer concentrates (if necessary, suitability tests)
- Consideration of the requirements for the disposal of the excavated material

In highly permeable soils, the combination of foam and suspension-like conditioning agents can be beneficial in the case of high groundwater pressure. It shall be taken into account that the foam quality is affected by some clay minerals. The mineralogical interactions between the subsoil and conditioning agents shall be analysed on a project-specific basis.

6.4.2 Liquid Conditioning Agents

Water, clay and polymer suspensions are suitable as liquid conditioning agents. However, in fine-grained soils, the use of water and bentonite suspensions should be thoroughly investigated to determine if an increase in the stickiness of the soil transpires as a result of their use. In coarse-grained soils with increasing permeability, high-viscosity suspensions or suspensions of high density are usually suitable in order to counteract liquefaction of the soil mixture. The volumes of possible conditioning agents added as well as their influence on the excavated soil have to be taken into account during transport and disposal of the material.

6.5 Support media in slurry machines

6.5.1 Bentonite suspension

With slurry support, the stability of the tunnel face is maintained by a bentonite suspension adapted to the geotechnical boundary conditions and a sufficiently high support pressure in the excavation chamber. The relevant rheological parameters are the yield point and the viscosity of the suspension. These properties determine the ability of the support medium to transfer the support pressure to the grain structure of the soil in terms of effective stresses.

At present, there are three recognised mechanisms for the transfer of support pressure depending on the pore volume of the in-situ ground **[51]**, **[52]**: (a) outer filter cake formation in fine-grained soils, (b) pure penetration in coarse-grained soils and (c) inner filter cake formation in medium-grained soils (**Figure 11**).

The determining parameter regarding the transfer of the shear stress during the penetration process into the ground is the yield point. The suspension stagnates when the depth of penetration becomes large enough so that the integral of the shear stresses formed across the particle surfaces corresponds to the difference between the support pressure in the excavation chamber and the existing earth and/or groundwater pressure **[51]**.

As a result of the viscosity of the support fluid and the associated reduced flow capacity, the risk of support fluid loss due to sudden, uncontrolled flow into the ground is reduced. The slightly higher density of the bentonite suspension compared to the density of water means that the excess pressure of the support medium in the crown and thus the risk of blowouts and/or break-ups is lower **[48]**.

Additionally, the bentonite suspension serves as a conveying medium for the transport of the excavated soil material from the working chamber to the separation plant. For hydraulic mucking, a low yield point and low viscosity are favourable to increase the conveyance efficiency.

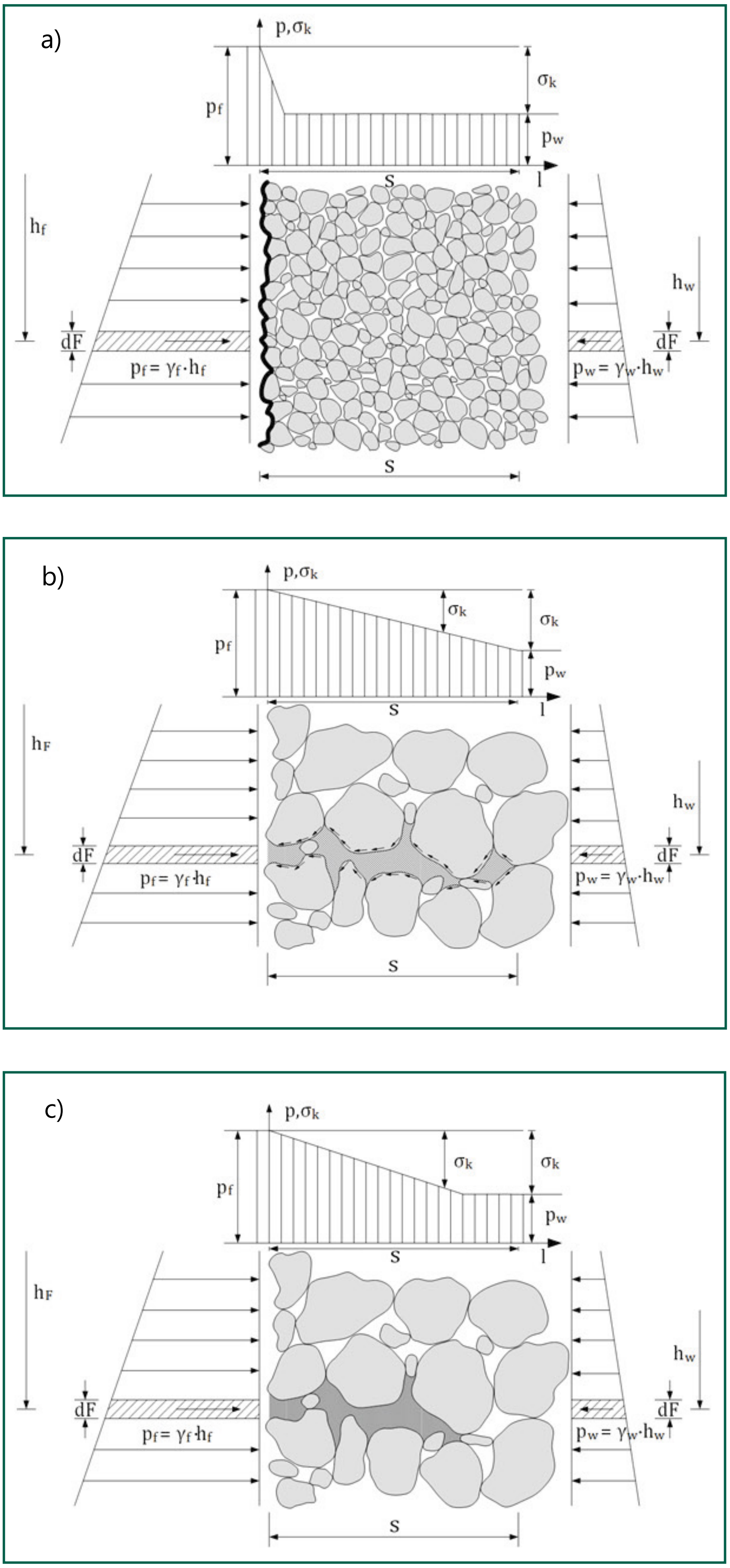

Figure 11 *Mechanisms of support pressure transmission: a) filter cake formation, b) penetration, c) internal filter cake*

Any use of additives in the slurry shield shall be checked individually for each process with regard to their effectiveness and environmental compatibility as well as their technical compatibility.

6.5.2 High-density slurry

When tunnelling in highly permeable ground that lies outside the particle size distribution range of medium and coarse gravel (soil), as well as in strongly fissured or karstic rock, a support medium is required that develops a suitable transmission mechanism in the subsoil. For this application, the concept of high-density suspensions (High Density Support Medium, density range approx. 1.4 to 1.8 t/m^3) was developed **[50]**, **[53]**. The high-density suspension is also suitable for tunnelling scenarios where there is limited cover in certain areas, such as river crossings with minimal overburden **[49]**.

The increased density of the support fluid results in a lower pressure in the crown area for the same total supporting force (see **Figure 12**). This ensures a higher factor of safety against break-up due to the support pressure (blowout and break-up) and reduces the danger of the support suspension escaping to the surface above the tunnel. A high solids content leads to an increased viscosity and yield point of the suspension, so that a lower penetration depth in the subsoil is achieved and uncontrolled suspension losses are avoided **[53]**.

6.6 Soil transport and separation

Within the framework of the economic feasibility study, spoil transport shall be considered when selecting the TBM. This refers to the transport of the excavated material from the excavation chamber, the transport within the TBM and gantries, as well as to the above-ground intermediate muck storage area/separation plant up to and including the transport from the intermediate muck storage area/separation plant to the final location following removal from site.

Here it is important to note that the selection of the TBM is initially based on the support of the tunnel face. However, the requirements for the face support also influence the spoil transport. When tunnelling with an earth pressure-supported tunnel face, the soil transport is usually influenced by the type of soil conditioning selected. In the case of slurry machines, the excavated soil is first transported via the support medium and requires subsequent separation from the support medium through a separation process. The expenditure for soil transport and the necessary separation processes shall be taken into account when considering the overall cost of the project.

For the transport of the excavated material in the excavation chamber, above all, the interaction between the excavation process and the ground has to be taken into account. For example, the cutterhead design and the cutter tools should be adapted to the

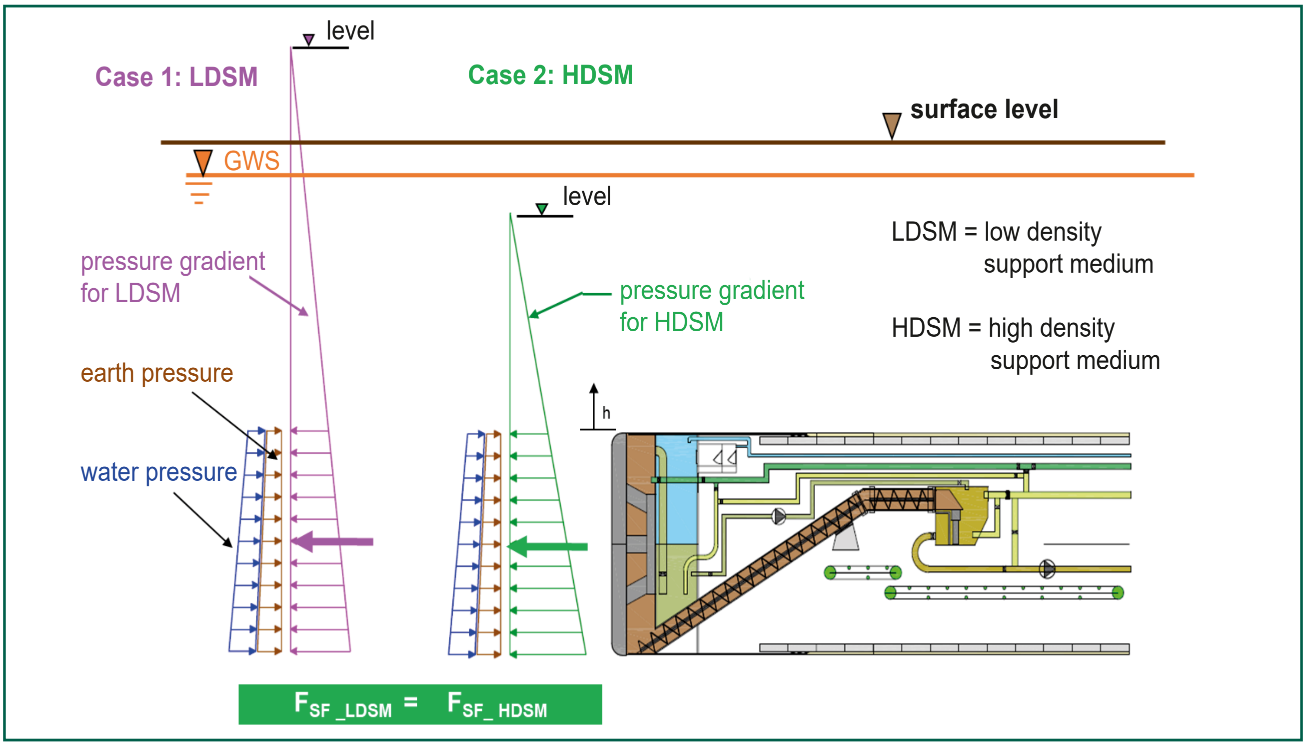

Figure 12 *Pressure gradients of the support pressure in the mining chamber for a standard suspension (LDSM) and a high-density suspension (HDSM)* ***[53]***

subsoil in order to avoid clogging during the removal of the excavated material and to optimise the particle size and shape of the loosened material.

In hard rock tunnelling, the share of both bulky and fine material should be kept as low as possible. The water application to the cutterhead for dust reduction shall be adjusted accordingly to avoid sludge formation on the conveyor belts.

When tunnelling with an earth pressure-supported tunnel face in cohesive soil, a pasty consistency should be aimed for not only to avoid clogging, but also to prevent the soil material from flowing back on inclined conveyor belts if the consistency of the material is too fluid.

When tunnelling with a slurry-supported tunnel face, pumpability through the slurry lines must be ensured.

6.6.1 Transport and temporary on-site storage

The transport of the excavated material from the TBM to the above-ground intermediate storage area is influenced on the one hand by the tunnelling method and on the other hand by logistical considerations depending on the construction operation. The following transport methods are typically used:

- Hydraulic transport via pipework to a separation plant with downstream centrifuges or filter presses
- Continuous belt conveyor to the temporary storage area
- Discontinuous mucking with rail transport
- Discontinuous mucking with tyre-based transport

The choice between the last three types of conveyance mentioned is essentially determined by the follow-on construction work within the tunnel itself as well as by the space requirement on the surface, and is therefore very much project-dependent. In order to determine whether the type of soil transport is critical for the selection of the tunnel boring machine, it is necessary to consider the soil properties that are decisive for the transport, such as particle size distribution, shear strength, liquefaction properties, potential damage to the transport equipment by blocks and stones, and, in the case of fine-grained soils, requirements for the consistency of the spoil. In hydraulic conveying, it is possible to distinguish between circulation conveyance and pure pumping.

In the case of hydraulic conveying, special attention shall be paid to the fact that blocks and stones have the potential to damage the conveying equipment. Furthermore, cavitation effects in foam-conditioned soils, dispersing properties and lump formation in the conveying circuit as well as the influence of polymers and tensides on the pumpability shall be taken into account.

For conventional transport, the geotechnical properties are particularly decisive, such as the consistency of the excavated spoil in fine-grained soils. Added to this are water discharge and stickiness, which can impair the process of mucking in both rail transport and belt conveyance.

On the surface, the effect of the weather in the area (e.g. heavy rain in fine-grained soils) shall be taken into account.

6.6.2 Soil Separation

The hydraulic conveyance of the excavated material through a slurry circuit requires the separation of the solids and the subsequent return of the transport medium into the circuit. Depending on the structure, the rock types can be separated in order to manage the material as sustainably as possible e.g. to extract aggregates for concrete. Conditioned soils from tunnelling operations with earth-pressure balance machines may also require soil separation, depending on the conditioning agents used.

The excavated material shall possess specific geotechnical properties both with regard to potential recycling and also for the transport of the excavated material. These properties can often only be ensured by separating the granular components and subsequent further treatment of the remaining material. When driving in fine-grained soil or if the excavation process of a TBM in solid rock results in finely crushed material, the excavated material may not offer sufficient properties (e.g. with regard to shear strength) for the use of the selected means of transport (truck, belt conveyor, etc.) from the construction site facility to the disposal site. In this case, measures are required to change the geotechnical properties of the extracted material (see **Section 6.7.2**).

The separation and any necessary treatment of the spoil can be decisive in the case that the different types of tunnel boring machines are otherwise equally suitable for excavation of the relevant tunnel. It is therefore necessary to investigate the degree of dispersion to be expected, the requirements for separation of the spoil, and the costs or environmental effects associated with this.

When using bentonite suspension as a transport medium, small amounts of bentonite residue will remain within the separated soil material. However, this bentonite usually does not change the classification of the soil under waste law (see below). Therefore, depending on the classification of the separated soil defined within the local regulations (LAGA in Germany), the different constituents can be recycled accordingly.

The separation of the fine particles by passing the material through centrifuges is facilitated by the prior addition of flocculants. Due to the extensive number of flocculants available on the market, it is not possible to make a general statement regarding the environmental compatibility of these products. The safety data sheet that is required to be prepared by the respective product manufacturer provides information regarding this.

Material obtained from centrifuges, filter presses and high-performance cyclones usually constitutes a very fine-grained material that is mostly of a sludge-like consistency. Recycling is usually not possible, and therefore the material is normally disposed of. The same applies to the used bentonite suspensions, which are normally disposed of as liquid waste.

6.6.3 Transport from site

Transportation from the construction site is done either by rail or road, in rare cases also via waterways. When transporting the excavated material, care shall be taken to ensure that the prevailing environmental regulations are observed.

In general, excavated material shall be transported in such a way that it is not affected by environmental influences (rain, heat, etc.) and its properties are not changed. This also applies in principle to temporary storage in the construction site storage area. In doubt, conveyor systems and storage areas shall be enclosed.

If necessary, transport vehicles shall be covered to prevent both the penetration of rain and the formation of dust through dehydration. Tyre washing systems shall always be provided in the event the spoil is transported from site via the road network.

Material from separation plants and chamber filter presses usually possesses a higher residual moisture content than material from tunnelling without support of the tunnel face or with support of the tunnel face with earth pressure. For this reason, watertight truck bodies or wagons shall be provided for the transport to prevent the residual water from escaping.

Material from tunnelling operations with an earth pressure-supported tunnel face may have to be treated prior to transport, e.g. by adding lime. For this purpose, a dust-free dosing equipment should be selected if possible.

6.7 Management of the excavated material

Depending on the type of machine used, the excavation process and process technology can produce an excavated material that possesses different properties from the original ground. In the case of tunnel drives with a slurry-supported tunnel face, soil of different particle sizes is made available by the separation in a separation plant, while in tunnels driven with an earth pressure-supported tunnel face the different types of soil are mixed, and may also have had conditioning agents added to soils. Therefore, depending on the machine type and in addition to separation, soil remediation may be required (see Section 6.6.2). Within the framework of the economic feasibility study, the recycling and disposal (e.g. landfilling) of the excavated material shall also be taken into account when selecting the TBM.

The properties of the ground or the excavated material are significantly altered by the excavation process, possible soil conditioning or separation of the material, and also by the differing operation techniques of the TBM by their operator. In addition, an uncontrolled groundwater inflow can lead to a sudden change in the consistency of fine-grained excavated material during tunnelling without active face support.

If the excavated material does not exhibit sufficient properties (e.g. with regard to shear strength) for disposal, additional measures are required. For an assessment of the geotechnical properties, shear strengths of the excavated material can be determined for individual consistency indices during tunnelling in fine-grained soils, within the scope of the investigations required for the geotechnical report.

The following economic and ecological aspects, which should be taken into account within the framework of a concept for the disposal of the excavated material, are decisive when examining the recyclability of the resulting excavated material:

- Transport of excavated material or processed products from the construction site to the disposal site
- Creation of interim storage facilities
- Establishment of disposal possibilities
- Treatment of material (preparation of material)
- Planning of the tunnel works (excavation, lining installation)
- Effects to be considered in the context of the planning approval decision

6.7.1 Responsibilities and legal regulations

In principle, the client, i.e. the future operators, shall already include sufficient disposal space during the planning approval procedure. Generally, the selection of the tunnelling method is already made at the tender stage and therefore both the initial state of the ground and possible negative effects of the conditioning agents are known. The client should therefore ensure the appropriate safety of disposal.

In the case of possible recycling of the excavated material, the client should already estimate the percentage of suitable material. The contractor cannot be expected to accurately estimate the disposal costs within the typically short tendering period.

6.7.2 Soil recycling concept

With a view to the most economical and sustainable use of the spoil, a corresponding spoil management concept (known in Switzerland as the „materials management concept") is required from the client during the project planning phase. This concept should be based on the principle of recycling the excavated material as much as possible.

With regard to environmental aspects, assessment of the shortest and most efficient transport routes possible, and a cost-efficient recycling of the excavated material, may lead to a clear preference for certain types of TBMs. If, for example, a separation of the particle sizes for recycling makes sense, the use of a separation plant is justified in spite of the higher costs that would be incurred when compared to the disposal of the untreated spoil.

Excavated material that cannot be reused should be viewed with particular caution regarding disposal costs. Here, the choice of the excavation method should also be made with regard to the possible increase in volume by means of conditioning agents or the hydraulic conveying circuit as well as mixing with reusable components.

6.7.3 Alteration of the geotechnical properties of the excavated material

If extracted material is to be used, for example, as aggregate for concrete or as a building material for earthworks, it shall be suitable for this purpose and meet the corresponding geotechnical requirements. In the event that such recycling is not possible, but only disposal is considered, minimum requirements also apply to the suitability and practicability of the deposited material. The same applies to transport from the construction site to the place of disposal.

Should the spoil material (possibly conditioned or contaminated as a result of the separation process) not achieve the required properties, suitable measures shall still be taken on the construction site or in appropriate temporary storage facilities to improve the properties of the material to be disposed of.

The properties of the excavated material are essentially determined by the geotechnical boundary conditions of the ground. Furthermore, the ground is also influenced by the interaction between the tunnel boring machine and the ground. According to **[45]**, the choice of the excavation method is a determining factor in the evaluation of the recycling possibility and is influenced by the following parameters:

- Shape (e.g. chips for hard rock tunnelling)
- Particle size distribution
- Relaxation
- Geogenic contamination (asbestos, metals, pyrite etc.)
- Anthropogenic contamination (conditioning agents, lost grease lubrication etc.)
- Chemical substances (e.g. excavated material processing and hydrocarbons in the TBM excavated material)
- Mechanical properties

Special measures for the disposal of the excavated material are, in addition to the subsequent intended use, generally dependent to a large extent on the geogenic contamination as well as on the actual water content or possible conditioning agents that have been added. The water content influences the workability and the compactability of the decomposed material. To improve the properties of the material with regard to disposal, it is usually advisable to reduce the current water content.

The simplest measure, however also the most time and space intensive, is drying of the soil by wind, sun, and „bleeding" (the so-called gravity drainage) in open storage. The drying process can be accelerated by loosening (e.g. by milling) or rearrangement and/or by a special design of the storage areas (e.g. arrangement of a permeable filter material under the soil to be drained). However, this relatively simple measure is highly dependent on the weather (dust formation/saturation).

Furthermore, there are various methods of mechanical soil improvement available, in which the workability of the extracted material is improved by the addition of suitable building materials. Here, either the particle size distribution is modified by mixing in a usually dry, coarse soil material, or the water content is reduced by the added material. The processes are also suitable in connection with the use of the excavated material as a secondary building material, such as recycled building materials from construction waste, or industrially produced aggregates, such as pulverised fly ash, and thus enable conservation of resources.

Alternatively, the water content can be reduced by adding a binder. Depending on the particle size distribution of the excavated material, the use of mixed binders, for instance, can be possible. Mixed binders are combinations of standardised hydraulic binding agents or their main hydraulic constituents and lime powder. The soil-specific selection of the mixed binder enables control of the reduction of the water content (through the lime component) and the strength development (through the proportion of hydraulic binders). The quantities to be added depend on the recycling requirements; possible quantities to be added can be estimated according to **[29]**.

Another possible variant can be the production of temporarily flowable, self-compacting backfill materials from the conditioned soils **[30]**. In order to guarantee the constant quality of a self-compacting backfill material, sufficient homogeneity shall be achieved in addition to the basic compatibility of the soils. Flowability is the decisive property for self-compacting and thus void-free backfilling. The water requirement is determined by the extracted soil, the hydraulic binding agents to be added (e.g. cement according to DIN 197-1), and physically binding additives (e.g. bentonite). Normally, the excavated soil material already has a sufficiently high water content so that the flowability is comparatively easy to realise. Various procedures for selecting measures to change the geotechnical properties of the excavated material and the material to be disposed of are shown in **Figure 13**.

6.7.4 Disposal

The foremost option for the excavated material obtained from tunnelling should be recycling. If this is not possible or sensible despite various measures, for example due to the material properties or lack of demand, the excavated material shall be disposed of. Particularly when using conditioning agents, care shall be taken to ensure that the excavated material meets the requirements for disposal from both a chemical, and physical point of view. The relevant laws and regulations form the basis for this **[26]**, **[27]**, **[28]**.

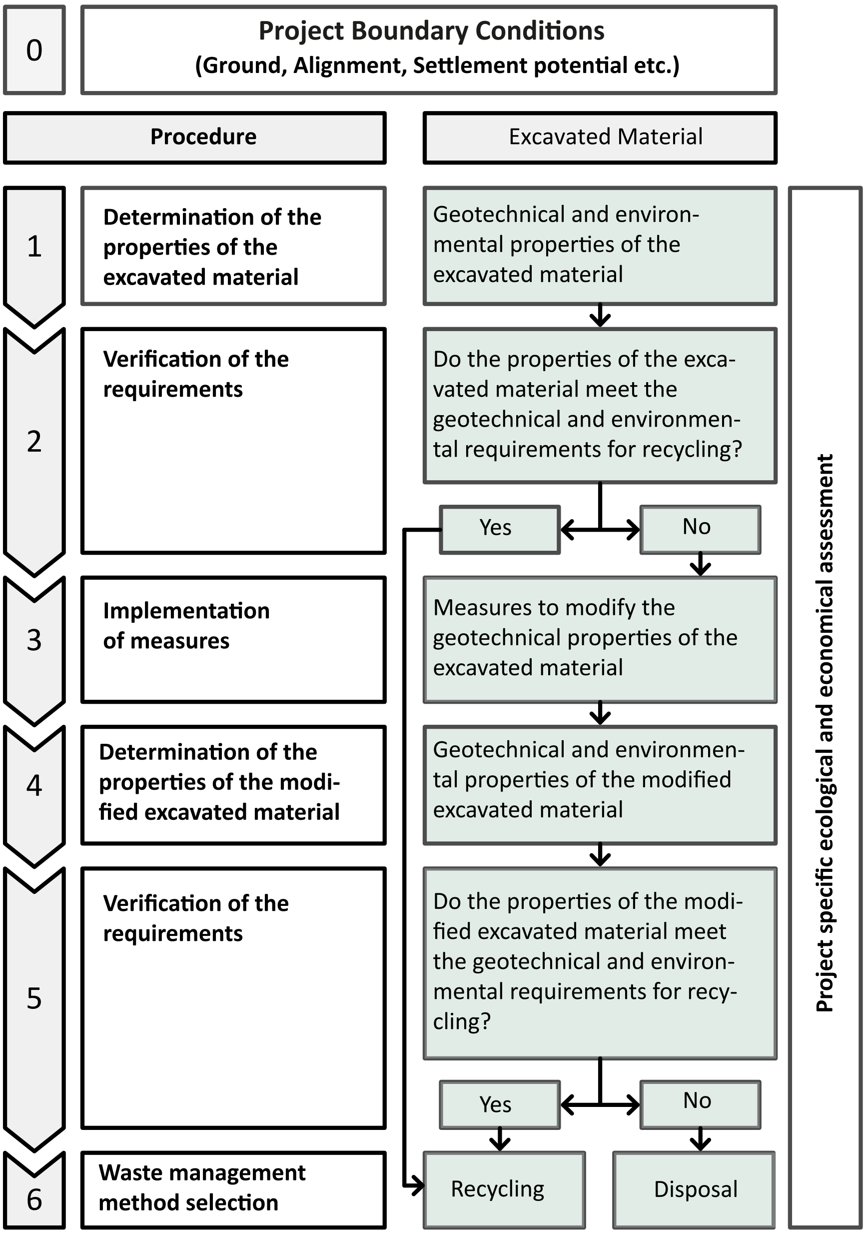

Figure 13 *Illustration of the various steps for the selection of measures to modify the geotechnical properties of excavated material and material to be disposed of*

Potential disposal routes shall be identified by the client at the earliest possible stage of planning. Depending on the nature and composition of the material, disposal and landfill areas are to be determined and secured for the project in accordance with the expected allocation or landfill class. When the tunnelling method is determined, any resulting effects on the material properties shall be estimated and taken into account when determining the disposal routes.

If the Client leaves the choice of tunnelling method open, they may have to plan and develop several different disposal concepts for each alternative. Due to their knowledge in the early stages of the project, the Client should be involved in the planning of the disposal of the material.

During the tunnelling operation, the Contractor shall pay particular attention to the use of conditioning agents in the most environmentally friendly manner possible, without compromising the efficiency of the material excavation. Based on the assumption that the technical solution from the Contractor is compliant with contractual requirements as laid out by the Client, the Client shall bear the risk for the disposal of the excavated material in addition to the geological risk as set out in the Geotechnical Baseline Report.

With regard to the recycling of soils, Germany first takes into account the LAGA instruction sheets, in particular bulletin No. 20 „Requirements for the recycling of mineral residues/waste - Technical Rules" **[23]**. This information sheet regulates the use of excavated soil and thus also the disposal of excavated material produced during tunnel construction. Only when, on the basis of the analytically determined contents of chemical composition and physical properties of the soil, recycling in accordance with the LAGA recommendations is no longer permitted, the material needs to be disposed of in landfills. In other jurisdictions, the local regulations shall be considered.

Material from the coarse and intermediate stages of the hydrocyclone cascade in separation plants can usually be recycled. Therein, the fines content is usually less than 5 %. However, these soils typically have special mechanical properties: Residual bentonite or clay coagulates can swell again on contact with water and provide the material with properties comparable to cohesive soils. In this case, the material should only be reused in areas that are protected from water ingress. For example, the material can be used to backfill below the carriageway within the tunnel. Alternatively, a further processing stage for washing the material can be provided in a separation plant. In the simplest case, the soil material is sprayed with water on an oscillating dewatering screen. The remaining bentonite content in the soil can thus be significantly reduced, and therefore the quality of the soil and the possibility of reuse is correspondingly increased.

Material conveyed in the slurry stream (high-density material conveyance) and treated by filter presses and/or centrifuges can generally not be easily disposed of. Possible measures to improve the geotechnical properties of the tunnel spoil are described in **Section 6.7.3**.

With regard to the disposal of soils treated with additives, the manufacturers' remarks concerning the biodegradability of the additives alone are not sufficient. In particular, with regard to the residual components of hydrocarbons, the relevant regulations concerning the pollutant contents for the respective placement or landfill classes shall be observed at all times, and checked with regard to recycling or disposal. Not least for economic reasons, the use of additives should be kept at a minimum in both slurry and earth pressure balanced tunnelling.

Soils that are to be disposed of should already be divided into different categories in the planning phase. In Germany, this classification is undertaken according to LAGA **[23]**, and the landfill classes **[28]** are suitable when assigning soils to different categories. An appropriate concept for the disposal of the excavated material should be developed in advance of the project. This concept should, following the recommendation of the Swiss Expert Group for Underground Mining, take the following points into account:

- Predicted quantities of the excavated material, taking into account the geotechnical and environmental properties and tunnelling method, e.g. within the scope of defining homogeneous areas.
- Available and/or required areas for intermediate storage or for treatment
- Predicted volume or predicted flow of excavated material
- Availability of disposal sites
- Capacity of a treatment plant to be installed
- Management of waste or overproduction

Local regulations relative to the jurisdiction where the project is situated shall be considered.

In addition, negative effects on the environment should be limited through appropriate measures. On the basis of previous experience, the following points should be clarified within the tunnel construction project:

- Recycling of material whose specific characteristics are not legally covered
- Handling of geogenically contaminated excavated material
- Consideration of concrete aggregates extracted from excavated material with regard to EN 206

6.8 Annular gap filling

At the tailskin, the gap between the tunnel intrados and the extrados of the segmental tunnel lining shall be continuously backfilled as the tunnel boring machine advances. The primary purpose of this filling is to create a load transfer, thus inducing a mechanical reaction between the segmental lining and the ground. Support of the ground is performed by the tunnel lining; as a result of this load acting upon the lining, the lining is in turn supported by the ground in the form of an elastic bedding. The annular gap filling prevents deformation of the ground and thus limits tunnelling-induced settlements. Simultaneously, it ensures the positional stability of the segmental lining.

Load-bearing backfill of the annular gap when tunnelling in rock can be provided by granular material that is blown into the gap through openings in the segments behind the machine. Pea gravel is generally used. In tunnel boring machines with an active face support, the annular gap filling also has the task of preventing the backflow of the support medium. For this purpose, the annular gap filling shall seal the gap, and therefore the material itself shall be impermeable. An injection material, such as grout, is better suited for this purpose than a porous filling.

Current state-of-the-art technology consists of the injection of specifically designed grout or bi-component material via several pipes distributed around the circumference of the tailskin directly into the gap that is continuously created during tunnelling at the back of the tailskin. On the one hand, the material in question shall be adequately fluid for pumping, but on the other hand, it should not leak out after it has been introduced and should stiffen and harden as soon as possible. Early stiffening is important to prevent the segmental lining from floating upwards and also to counteract the forces exerted on the tunnel invert by the TBM gantries. The timely stiffening and hardening of the annular gap grouting material as well as the complete filling of the annular gap shall be ensured by suitable checks, e.g. by means of control openings in the segments.

There are various methods of producing, transporting and injecting the annular grout material:

- Transport of the components onto the TBM and production of the grouting material „just in time" in the gantry area
- Transport of the ready-mixed grouting material via containers (e.g. skip) to the TBM and grouting with the addition of an accelerator if necessary
- Use of a two-component system, whereby both the basic component and accelerator are pumped from the portal area directly onto the TBM and to the injection openings. The components are not mixed unless directly at the tailskin and thus lead to an immediate gelation of the grouting material in the annular gap.

The latter method has become increasingly popular in recent years.

In the case of single lining, in which the lining of the tunnel consists exclusively of the segmental lining, the annular gap grouting material is responsible for the complete sealing of the tunnel, in addition to the sealing system installed within the segments themselves. One method, among others, of achieving this, is by additional injection of the pea gravel with mortar in hard rock tunnels. In the case that annular gap grout is used, secondary grouting may be necessary.

7 Selection criteria and other project constraints

7.1 Guidelines on the use of the selection tables

The recommendations concerning the fields of application and selection criteria are summarised in the tables in **Appendix 3** for each type of machine. System suitability is first assessed on the basis of key geotechnical parameters and processes. Economic evaluation criteria are largely disregarded. The tables are suitable for a preselection of a tunnel boring machine using process of elimination. If several machine types are possible, the final overall suitability assessment is then carried out following the analysis of all project-specific parameters and processes (see procedure in **Figure 1**), taking into account economic and environmental aspects.

In the selection tables, main areas of application, extended areas of application and restricted areas of application are given, the significance of which is explained below in addition to the input parameters.

7.1.1 Input parameters for the selection tables

The characteristic values from the geotechnical report and, if necessary, bandwidths and values from the reports of the tunnel engineering experts serve as input parameters for the selection tables from **Appendix 3**.

For the support pressure ranges given in the selection tables, it should be noted that the support pressure does not necessarily correspond with the active water pressure. In any case, a support pressure calculation in accordance with the applicable standards and guidelines is required, in which the required support pressure is determined from both the earth pressure and water pressure. If the tunnel face is stable, the support pressure can also be lower than the water pressure if suitable and feasible drainage measures are taken. Given appropriate hydrogeological conditions and permissible boundary conditions, it is even possible to operate without tunnel face support. However, stability and water inflow calculations shall be carried out.

7.1.2 Main areas of application

The fields marked in black (symbol „+") describe ranges of key parameters in which the machine type has already been used successfully largely without the deployment of additional measures. Technical performance of the TBM may differ depending on the manufacturer. Experience of the contractor also plays a decisive role. Through consideration of additional parameters, both broadening and narrowing of the main areas of application for one parameter are possible.

7.1.3 Extended areas of application

The application of a particular tunnel boring machine in the dark grey areas (symbol „o") may require specific additional technical measures. However, the technical feasibility has, in principle, been proven. The achievable tunnelling performance and efficiency may be reduced compared to the main area of application.

7.1.4 Limited areas of application

Deployment of a tunnel boring machine in the areas marked in the light grey (symbol „–") will most probably lead to considerable additional measures for ground improvement or complications during tunnelling. The achievable driving performance and economic efficiency of the TBM are significantly reduced compared to the main area of application. A well-founded technical, economical and contractual risk analysis and a comparison of variants with other driving methods are strongly recommended.

7.1.5 Classification in soft ground

The particle size distribution of the soil directly and indirectly represents the primary evaluation criterion for the stability and permeability of the ground. Based on the shear strength parameters and the water pressure, and taking into account the particle size distribution, the stability of the rock shall first be evaluated and the required support pressure shall be determined. With increasing earth and groundwater pressure, the technical demands on the TBM increase.

7.1.6 Classification in hard rock

The recommendations of the tables are primarily intended for the selection of TBMs and not for the assessment of the boreabilty of the rock. Rock classification and evaluation of the stability are based on the RMR system. It is recommended to analyse all six parameters of the RMR system for each tunnel boring machine and project. The analytical or numerical verification of the stability and the determination of the support pressure are also recommended.

7.2 Other project boundary conditions

In addition to the requirements of the ground and the location of the construction project in the surrounding area, reasons relating to approval processes or occupational safety can also influence the choice of a TBM. Below is a list of some boundary conditions. They do not represent an exhaustive list, but should rather give examples that may be of importance for the selection of a TBM in practice.

7.2.1 Planning approval decision, water legislation requirements

Legal approval requirements, such as those set out in the planning approval decision, often restrict the choice of tunnel boring machines. For example, temporary groundwater extraction and the associated lowering of the groundwater level can be severely restricted or even prohibited, so that closed, pressure-balanced tunnelling methods shall be used instead of open-face tunnelling. A further aspect regarding this are water quality requirements for the discharge of wastewater into receiving water bodies.

7.2.2 Settlements and structure underpinning

In inner-city areas, and especially when crossing below structures or infrastructure, the permissible ground deformations at the surface are generally limited. In addition to the absolute maximum values of the deformation, the extent and gradient of the settlement trough shall be taken into account as a criterion. In consideration of these requirements, which shall already be determined in the planning phase, the appropriate tunnel boring machine shall be selected to adhere to the admissible limits.

7.2.3 Occupational Safety

Relevant regulations on occupational safety **[5]**, **[31]**, **[33]**, in conjunction with the Occupational Health and Safety Act, serve to implement EC Directive 92/57/EEC for the minimum health and safety requirements applicable to temporary or mobile construction sites. They apply, in principle, to all construction sites and thus also to underground construction. Their application is intended to ensure that occupational health and safety is taken into account as early as the planning phase, thus influencing the selection process for the tunnelling method. Guideline **[33]** developed by the German Tunnelling Committee (DAUB) and the national tunnelling associations of Austria and Switzerland is based on the aforementioned regulations and contains essential requirements for the use of tunnel boring machines. In Austria, the more recent guideline RVS issued by the FSV 09.01.51 **[46]** applies. Guideline **[33]** from the German Tunnelling Committee (DAUB) is currently being revised.

For the evaluation of occupational safety, a risk analysis shall be prepared, taking into account the construction method and local boundary conditions. The result of the risk analysis highly influences the selection process of the tunnel boring machine.

If, for example, gases such as methane or argon are anticipated to be present within the rock, the construction ventilation system shall be designed accordingly or intrinsically safe equipment shall be incorporated on the tunnel boring machine. The presence of asbestos in rock also requires special attention. Appropriate permanent measuring equipment combined with an optical and acoustic warning system that is automatically triggered when critical measured values are reached, shall be permanently installed in the machine area and at critical locations within the tunnel. Closed machine types with active tunnel face support (SLS, EPB, VDS, HYS) offer further advantages if the mucking system is closed as well. The requirements for the segment gaskets shall also be defined. For the final condition, double-lining systems are to be investigated, if necessary. ■

Appendices

Appendix 1 Application Example

Water-body crossing with two different layers of soft ground

An example of the application of this recommendation is provided below. The process, consisting of seven steps, follows the flow chart provided in **Chapter 4**. Some of the steps may have to be run through iteratively in order to consider all boundary conditions. **Figures A1 and A2** illustrate the selection process for the application example, in which the individual steps for a TBM drive that passes beneath a water-body are

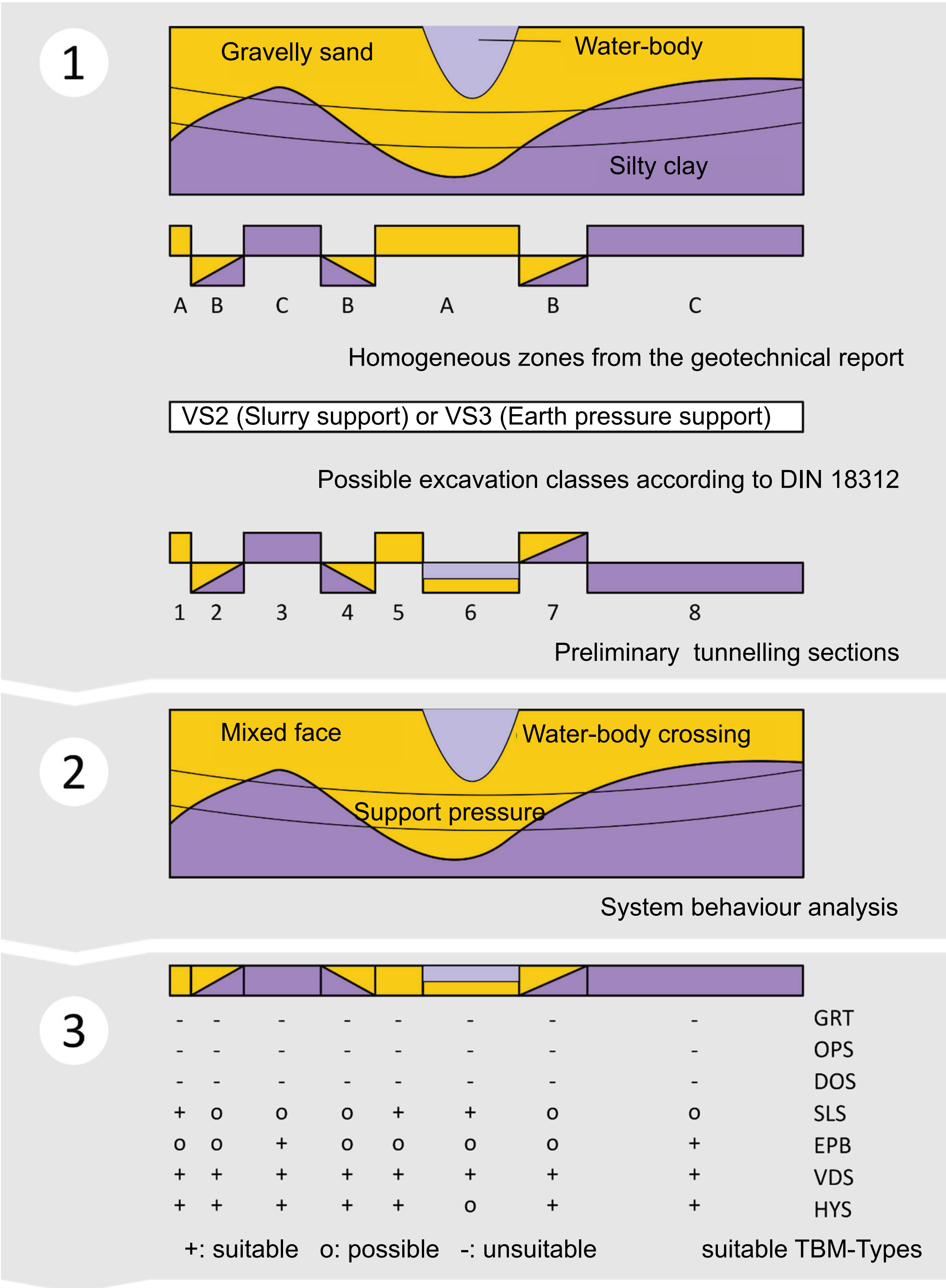

Figure A1
Flow chart, steps 1-3

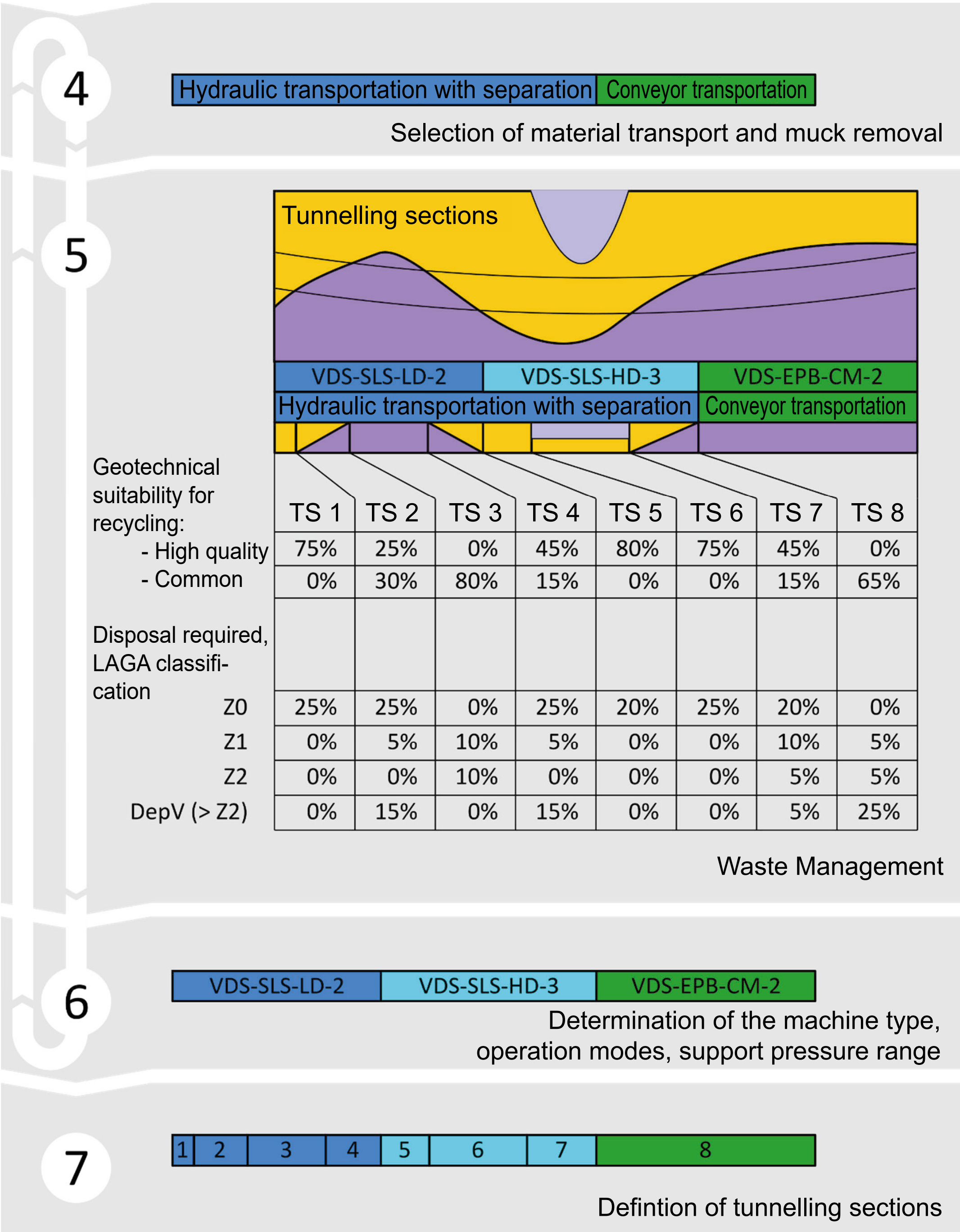

Figure A2
Flow chart, steps 4–7

shown. **The first step** shows the analysis of the geotechnical report. Firstly, the geological longitudinal section is depicted, a tunnel with a trough-shaped vertical gradient underneath a body of water with minimal overburden. In the example there are two geological layers: a layer of gravelly sand which lies atop a layer of silty clay. The tunnel horizon intersects the boundary between the layers of soil three times. From the geotechnical report homogeneous zones of soil are derived. In this example, there are four areas that are completely located in one of the two soil layers (homogeneous zones A and C). In between there are a total of three areas with mixed-face conditions (homogeneous zone B), in which the boundary between the layers is crossed. According to DIN 18312, all homogeneous zones can be assigned to the potential excavation classes VS 2 (slurry support) and VS 3 (earth pressure support). Under consideration of the homogeneous zones and potential excavation classes, preliminary tunnelling sections (TS1 – TS8) are produced, which are determined by the geotechnical and project-specific boundary conditions with regard to the TBM selection and the operating modes. In the example, the homogeneous zone A below the watercourse is further subdivided in order to take into account the specific requirements of the watercourse underpass. This results in eight tunnelling sections for the above example.

In the **second step** the system behaviour is investigated. Further to the geotechnical conditions, additional tunnel construction aspects are also considered. In the example, the specific challenges of high support pressures, crossing underneath a body of water with limited overburden and mixed face conditions arise. The system behaviour can have a decisive influence on the suitability of certain machine types.

The **third step** consists of considering the previously determined homogeneous zones and the analysis of the system behaviour, a selection matrix for each of the eight tunnelling sections is drawn up to determine which TBM types are suitable or possible in principle, according to the DAUB recommendations and which TBM types shall be excluded. In the example, it is assumed that the area below the water-body must be excavated within a strictly controlled permissible support pressure range as a result of the low overburden, which favours a more precise support pressure control using SLS and VDS over earth pressure supported variants (EPB).

In the **fourth step**, in coordination with the considerations for the spoil management, the material transport both within the machine, as well as material transport out of the tunnel and within the construction site is analysed. The **fifth step**, spoil management analysis, is a further criterion for machine selection in addition to the technical boundary conditions. In the abstract and simulated example presented here with freely chosen assumptions, the environmental properties of the excavated material and its geotechnical suitability for recycling are considered. Material that is classified not to be reusable (here > Z2) shall be disposed of according to the local regulations. Excavated material in recycling classes Z0, Z1 and Z2 can be reused if it is geotechnically suitable. The highest possible quality of recycling should be aimed for.

In the example it is assumed that after separation of the particle sizes, the gravelly sand is largely suitable for road construction, i.e. it can be used for high-quality recycling, while the silty clay can be used in earthworks if it is environmentally suitable. The lower part of the table in **Figure A2** shows the excavated material that has to be disposed of. Since here 25 % of the excavated material falls into the landfill classes, but at the same time 65 % of the excavated material is suitable as non-contaminated material for recycling in earthworks, complex separation can be dispensed with and only continuous sampling is required. This, in turn, makes it possible to switch to belt conveyance in this section. On the other hand, the high proportions of material that can be recycled for road construction in the tunnelling sections TS 1, TS 4, TS 5 and TS 6 provide a great incentive to carry out a separation of the spoil in line with recycling requirements.

In the **sixth step**, the machine type is then determined taking into account all the previously established boundary conditions. In addition, the most suitable combinations of machine type, the corresponding muck removal method, operating modes and tunnelling parameters are also determined in this step. If necessary, steps 4 to 6 are carried out iteratively, should the considerations within step 6 result in a change of boundary conditions for the muck removal and/or the disposal.

Finally, in the **seventh step**, the planning area is divided into the final tunnelling sections according to these specifications. The tunnelling sections now contain clear definitions of the operating modes, the muck removal methods and the value ranges of the tunnelling parameters.

The example shown here results in a variable density shield machine that is operated as a slurry shield (VDS-SLS) in the sections TS 1 to TS 7 and is converted to outright EPB operation (Closed Mode = CM) with belt conveyor (VDS-EPB) for the TS 8. In addition to this, the high-density mode (indicated by the designation HD) is selected for the sections TS 5 to TS 7, while the low-density mode (LD) is selected for the tunnelling sections TS 1 to TS 4. The support pressure ranges (up to 2 bar in TS 1 to TS 4 as well as in TS 8; up to 3 bar in TS 5 to TS 7) are also noted in the abbreviated designations of the tunnelling modes. These specifications also result in the muck removal variants, which ultimately also interact with the waste management concept.

Appendix 2

Process-related parameters

The following tables list the standard geotechnical and process technology parameters for both soil and rock. For each parameter, it is marked whether it is relevant for the certain excavation classes according to DIN 18312. The assignment of the types of tunnel boring machines dealt with in this recommendation is made according to chapter 4 as follows:

Tunnelling class VS1:
Excavation without support of the tunnel face

GRT: Gripper TBM

OPS: Single shield/ open shield

DOS: Double Shield

EXS/RHS: Roadheader

EPB in Open Mode

Tunnelling class VS2/VS3:
Excavation with support of the tunnel face

SLS: Slurry shield

EPB: Earth pressure balance machine

VDS: Variable-density machine

HYS: Hybrid/multi-mode machine

Appendix 2.1 Process-related parameters for tunnelling in soil

Prozessbezogene Kenngrößen für Lockergestein Process-related parameters for tunnelling in soil	Symbol	Einheit Unit	VS1	VS2/VS3
Ortsbruststützung + Setzungsanalyse Face support + settlement analysis				
Korngrößenverteilung Grain size distribution		%	X	X
Wichte/Wichte unter Auftrieb Unit weight/submerged unit weight	γ / γ'	kN/m³		X
Lagerungsdichte Relative density	D	–	X	X
Reibungswinkel Friction angle	φ'	°	X	X
Kohäsion Cohesion	c'	kN/m²	X	X
E-Modul Young's modulus	E	MN/m²	X	X
Dilatanzwinkel Dilatancy angle	ψ	°	X	X
Porenanteil Porosity	n	–	X	X
Porenzahl Void ratio	e	–	X	X
Durchlässigkeitsbeiwert Permeability	k	m/s	X	X
Erddruckbeiwert (horizontal) Coefficient of lateral earth pressure	K_h	–	X	X
Grundwasserdruck Water pressure	p_{GW}	kN/m²	X	X
Undrainierte Kohäsion Undrained cohesion	c_u	kN/m²		X
Bodenabbau Soil excavation				
Verklebung Stickiness				
Plastizitätszahl ($I_P=w_L-w_P$) Plasticity index	I_P	%	X	X
Konsistenzzahl ($I_C = (w_l - w) / I_P$) Consistency index	I_c	–	X	X
Fließgrenze Liquid limit	w_L	%	X	X
Ausrollgrenze Plastic limit	w_P	%	X	X

Prozessbezogene Kenngrößen für Lockergestein **Process-related parameters for tunnelling in soil**	**Symbol**	**Einheit** **Unit**	**VS1**	**VS2/VS3**
Wassergehalt Water content	w	%	X	X
Mineralogische Zusammensetzung inkl. Anteil quellfähiger Tonminerale Mineralogical composition			X	X
Gebirgswasserzufluss Water inflow	Q_W	l/s	X	X
Feinstkornanteil (Massenanteil < 0,002 mm) Clay and silt content		%	X	X
Verschleiß **Wear**				
Abriebwert A_{BR} ("LCPC-Wert") Abrasivity Coefficient LCPC-Index	A_{BR}	g/t	X	X
Brechbarkeitskoeffizient Breakability Coefficient	B_R	%	X	X
Äquivalenter Quarzanteil Equivalent quartz content	äQu	%	X	X
Steinanteil (Massenanteil mittl. Korngröße > 63 – 200 mm) Cobble content		%	X	X
Blockanteil (Massenanteil mittlere Korngröße > 200 mm) Boulder content		%	X	X
Abrasivität der Blöcke (CAI) Boulder abrasivity (CAI)	A_{In}	–	X	X
Einaxiale Druckfestigkeit Unconfined compressive strength	q_u	kN/m²	X	X
Scherfestigkeit Shear strength	τ	kN/m²	X	X
Lagerungsdichte Relative density	D	–	X	X
Bodenkonditionierung **Soil conditioning**				
Korngrößenverteilung Grain size distribution		%		X
Feinstkornanteil (Massenanteil < 0,002 mm) Clay content		%		X
Feinkornanteil (Massenanteil < 0,06 mm) Silt content		%		X
Plastizitätszahl Plasticity index	I_P	%		X
Konsistenzzahl ($I_C = (W_l – W) / I_P$) Consistency index	I_c	–	X	X

Prozessbezogene Kenngrößen für Lockergestein **Process-related parameters for tunnelling in soil**	**Symbol**	**Einheit** **Unit**	**VS1**	**VS2/VS3**
Fließgrenze Liquid limit	w_L	%	X	X
Ausrollgrenze Plastic limit	w_P	%	X	X
Wassergehalt Water content	w	%	X	X
Stützdruck Confinement pressure	p_s	bar		X
Porenanteil Porosity	n	–		X
Durchlässigkeitsbeiwert Permeability	k	m/s		X
Chemische Grundwasseranalyse Chemical groundwater analysis				X
Organischer Anteil (Kationen) Organic substances content (cations)		%		X
Restbentonitgehalt Residual bentonite content		%		X
Restgehalt an chemischen Additiven Residual chemical additives content		%		X
Undrainierte Kohäsion Undrained cohesion	c_u	kN/m^2		X
Setzmaß Slump measure	h	cm		X (EPB)
Bodenseparierung **Soil separation**				
Restbentonitgehalt Residual bentonite content		%		X
Restgehalt an chemischen Additiven Residual chemical additives content		%		X
Feinstkornanteil (Massenanteil < 0,002 mm) Clay content		%		X
Feinkornanteil (Massenanteil < 0,06 mm) Silt content		%		X
Plastizitätszahl Plasticity index	I_P	%		X
Konsistenzzahl ($I_C = (W_l - W) / I_P$) Consistency index	I_c	–	X	X
Fließgrenze Liquid limit	w_L	%	X	X

Prozessbezogene Kenngrößen für Lockergestein **Process-related parameters for tunnelling in soil**	**Symbol**	**Einheit** **Unit**	**VS1**	**VS2/VS3**
Ausrollgrenze Plastic limit	w_P	%	X	X
Wassergehalt Water content	w	%	X	X
Undrainierte Kohäsion Undrained cohesion	c_u	kN/m²		X
Bodentransport und -deponierung **Soil transport and disposal**				
Korngrößenverteilung Grain size distribution		%		X
Feinstkornanteil (Massenanteil < 0,002 mm) Clay content		%		X
Feinkornanteil (Massenanteil < 0,06 mm) Silt content		%		X
Plastizitätszahl Plasticity index	I_P	%		X
Konsistenzzahl ($I_C = (W_l – W) / I_P$) Consistency index	I_c	–	X	X
Fließgrenze Liquid limit	w_L	%	X	X
Ausrollgrenze Plastic limit	w_P	%	X	X
Wassergehalt Water content	w	%	X	X
Feinstkornanteil (Massenanteil < 0,002 mm) Clay content		%		X
Reibungswinkel Friction angle	ϕ'	°	X	X
Kohäsion Cohesion	c'	kN/m²	X	X
E-Modul Young’s modulus	E	kN/m²	X	X
Restbentonitgehalt Residual bentonite content		%		X
Restgehalt an chemischen Additiven Residual chemical additives content		%		X
Gebirgswasserzufluss Water inflow	Q_W	l/s	X	X

Appendix 2.2 Process-related parameters for rock

Prozessbezogene Kenngrößen für Festgestein Process-related parameters for rock	Symbol	Einheit Unit	Alle Vortriebsklassen* All excavation classes
Ortsbruststützung + Setzungsanalyse Face support + settlement analysis			
Gefüge Structure		–	X
Verwitterungsgrad Weathering grade	VU/VA/ VE/VZ	%	X
Zerlegung Ratio matrix/fragmentation		–	X
Anisotropie Anisotropy		–	X
Porenanteil Porosity	n	–	X
Quellpotenzial Swelling potential		–	X
Zerfallsbeständigkeit Slake durability index	I_{d2}	%	X
Trennflächen Discontinuities			
Kluftfüllung Joint filling			X
Raumstellung der Trennflächen Discontinuity orientation			X
Abstand der Trennflächen Normal spacing of discontinuity sets		cm	X
Zerlegungsgrad Fracturing degree/discontinuity frequency			X
Seitendruckbeiwert Coefficient of lateral rock pressure	K_h	–	X
Gebirgswasserzufluss Water inflow	Q_W	l/s	X
Wasserdruck Water pressure	p_{GW}	kN/m²	X
Materialabbau Excavation			
Einaxiale Druckfestigkeit Unconfined compressive strength	σ_c	kN/m²	X
Spaltzugfestigkeit Tensile strength	σ_z	MN/m²	X

Prozessbezogene Kenngrößen für Festgestein **Process-related parameters for rock**	**Symbol**	**Einheit** **Unit**	**Alle Vortriebsklassen*** **All excavation classes**
RQD Rock Quality Designation	RQD	–	X
Verwitterungsstufe Weathering grade		–	X
RSR Rock Structure Rating	RSR	–	X
RMR Rock Mass Rating	RMR	–	X
GSI Geological Strength Index (Hoek Brown)	GSI	–	X
RMI Rock Mass Index	RMI	–	X
Q-Index Q-value	Q-value	–	X
Mineralogie Mineral composition			X
Karbonat-Anteil Carbonate content			X
Verfestigung (Zementation) Cementation			X
Trennflächen **Discontinuities**			
Kluftfüllung Joint filling			X
Blockgröße Block size		cm	X
Raumstellung der Trennflächen Discontinuity orientation			X
Abstand der Trennflächen Normal spacing of discontinuity sets		cm	X
Zerlegungsgrad Fracturing degree/discontinuity frequency			X
Verklebung **Stickiness**			
Zerfallsbeständigkeit Slake durability index	I_{d2}	%	X
Wassergehalt Water content	w	%	X
Gebirgswasserzufluss Water inflow	Q_W	l/s	X

Prozessbezogene Kenngrößen für Festgestein **Process-related parameters for rock**	**Symbol**	**Einheit** **Unit**	**Alle Vortriebsklassen*** **All excavation classes**
Mineralogie Mineral composition			X
Verschleiß **Wear**			
Abriebindex A_{IN} Abrasivity	A_{IN}	–	X
Quarzanteil Equivalent quartz content	äQu	%	X
Abrasivität RAI (RAI=äQu · UCS) Rock Abrasivity Index	RAI	–	X
Einaxiale Druckfestigkeit Unconfined compressive strength (UCS)	σ_c	MN/m^2	X
Spaltzugfestigkeit Tensile strength	σ_z	MN/m^2	X
Scherfestigkeit Shear strength	τ	kN/m^2	X
Tonmineralische Zusammensetzung Clay mineral composition			X
Verwitterungsgrad Weathering grade	VU/VA/ VE/VZ	–	X
Verfestigung (Zementation) Cementation			X
Bodentransport und -deponierung **Soil transport and disposal**			
Max. Kantenlänge Max. block size		mm	X
Wassergehalt Water content	w	%	X

* Note: Due to the complex and similar technologies of the different tunnel boring machines, especially of the shield machines, the excavation classes of the tunnel boring machines according to DIN 18312:2019 are not differentiated here. A specification of excavation classes of the tunnel boring machines according to DIN 18312:2019 has to be performed on a project-specific basis.

Appendix 3 Areas of application and selection criteria

Appendix 3.1 Areas of application and selection criteria GRT

Geotechnische Kennwerte Geotechnical parameters	Gripper-TBM (GRT) Grippper TBM (GRT)		
		+	Haupteinsatzbereich/main field of application
		o	erweiterter Einsatzbereich/extended application
		–	Einsatz eingeschränkt/application limited

Lockergestein (Soil)					
Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
Konsistenz (Ic) nach DIN EN ISO 17892-12 Consistency (Ic)	breiig very soft 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
Lagerungsdichte nach DIN 18126 Relative density	dicht dense	mitteldicht medium dense	locker loose		
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100
Festgestein (Rock)					
Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5 / 5 – 25	25 – 50	50 – 100	100 – 250	> 250
	– / 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) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5	sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+	+	+	o	o
Quellpotential Swelling potential	kein none	gering poor	mittel fair	hoch high	
	+	+	o	o	
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	+	–		–	–

Einsatz nicht empfohlen
Application not recommended

Appendix 3.2 Areas of application and selection criteria DOS

Geotechnische Kennwerte Geotechnical parameters	Doppelschildmaschine (DOS) Double Shield Machine DOS)	
		+ Haupteinsatzbereich/main field of application
		o erweiterter Einsatzbereich/extended application
		– Einsatz eingeschränkt/application limited

Lockergestein (Soil)

Einsatz nicht empfohlen
Application not recommended

Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
Konsistenz (Ic) nach DIN EN ISO 17892-12 Consistency (Ic)	breiig very soft 0 – 0,5	weich soft [illegible] – 0,75	steif stiff [illegible] – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
Lagerungsdichte nach DIN 18126 Relative density	dicht [illegible]	mitteldicht medium dense	locker loose		
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100

Festgestein (Rock)

Gesteinsfestigkeit [MPa] Unconfined 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) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5	sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+	+	+	o	o
Quellpotential Swelling potential	kein none	gering poor	mittel fair	hoch high	
	+	+	o	o	
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	+	–	–	–	–

Appendix 3.3 Areas of application and selection criteria OPS

Geotechnische Kennwerte Geotechnical parameters	Einfachschild (OPS) Single Open Shield (OPS)		
		+	Haupteinsatzbereich/main field of application
		o	erweiterter Einsatzbereich/extended application
		–	Einsatz eingeschränkt/application limited

Lockergestein (Soil)					
Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
	–	–	–	o	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
	–	–	–	o	
Konsistenz (Ic) nach DIN EN ISO 17892-12 Consistency (Ic)	breiig very soft 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
	–	–	–	–	o
Lagerungsdichte nach DIN 18126 Relative density	dicht dense	mitteldicht medium dense	locker loose		
	+	–	–		
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	o	–		–	–
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
	+	+	o	–	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100
	+	+	+	o	o
Festgestein (Rock)					
Gesteinsfestigkeit [MPa] Unconfined 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) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5	sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+	+	+	o	o
Quellpotential Swelling potential	kein none	gering poor	mittel fair	hoch high	
	+	+	o	o	
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	+	–		–	–

Appendix 3.4 Areas of application and selection criteria SLS

Geotechnische Kennwerte Geotechnical parameters	Slurryschild (Flüssigkeitsschild) (SLS) Slurry Shield (SLS)		
		+	Haupteinsatzbereich/main field of application
		o	erweiterter Einsatzbereich/extended application
		–	Einsatz eingeschränkt/application limited

Parameter					
Lockergestein (Soil)					
Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
	+	+	+	o	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
	–	o	+	o	
Konsistenz (Ic) nach DIN EN ISO 17892-12 Consistency (Ic)	breiig very soft 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
	– / o	o	o	o	o
Lagerungsdichte nach DIN 18126 Relative density	dicht dense	mitteldicht medium dense	locker loose		
	+	+	o		
Stützdruck [bar] Confinement pressure[bar]	0	1 – 4		4 – 7	7 – 15
	o	+		+	+
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
	+	+	o	–	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100
	+	+	+	o	o
Festgestein (Rock)					
Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5 / 5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o / o	o	o	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	o	o	o	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	o	o	o	o
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0	0 – 10	10 – 25	25 – 125	> 125
	o	o	o	o	o
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5	sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+	+	o	o	o
Quellpotential Swelling potential	kein none	gering poor	mittel fair	hoch high	
	+	+	o	–	
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	o	+		+	+

Appendix 3.5 Areas of application and selection criteria EPB

Geotechnische Kennwerte Geotechnical parameters	Erddruckschildmaschine (EPB) Earth Pressure Balanced Shield (EPB)		
		+	Haupteinsatzbereich/main field of application
		o	erweiterter Einsatzbereich/extended application
		–	Einsatz eingeschränkt/application limited

Lockergestein (Soil)					
Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
	–	o	o / +	+	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
	–	–	o	+	
Konsistenz (Ic) nach DIN EN ISO 17892-12 Consistency (Ic)	breiig very soft 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
	o	+	+	o	o
Lagerungsdichte nach DIN 18126 Relative density	dicht dense	mitteldicht medium dense	locker loose		
	+	+	+		
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	+	+		o	–
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
	+	+	o	–	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100
	+	+	o	o	–
Festgestein (Rock)					
Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5 / 5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o / 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	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	o	–	–
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0	0 – 10	10 – 25	25 – 125	> 125
	o	o	o	o	o
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5	sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+	+	o	o	–
Quellpotential Swelling potential	kein none	gering poor	mittel fair	hoch high	
	+	+	o	–	
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	o	+		o	–

Appendix 3.6 Areas of application and selection criteria VDS

Geotechnische Kennwerte Geotechnical parameters	Variable-Density-Schild (VDS) Variable Density Shield (VDS)		
		+	Haupteinsatzbereich/main field of application
		o	erweiterter Einsatzbereich/extended application
		–	Einsatz eingeschränkt/application limited

<table>
<tr><th colspan="7">Lockergestein (Soil)</th></tr>
<tr><td rowspan="2">Feinkornanteil (< 0,06 mm) DIN 18196
Fines content (< 0,06 mm)</td><td colspan="2">< 5 %</td><td>5 – 15 %</td><td>15 – 40 %</td><td>> 40 %</td><td></td></tr>
<tr><td colspan="2">+</td><td>+</td><td>+</td><td>o</td><td></td></tr>
<tr><td rowspan="2">Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s]
Permeability k [m/s]</td><td colspan="2">sehr stark
very high
> 10^{-2}</td><td>stark
high
10^{-2} – 10^{-4}</td><td>durchlässig
permeable
10^{-4} – 10^{-6}</td><td>schwach
low
< 10^{-6}</td><td></td></tr>
<tr><td colspan="2">–</td><td>o</td><td>+</td><td>o</td><td></td></tr>
<tr><td rowspan="2">Konsistenz (Ic) nach DIN EN ISO 17892-12
Consistency (Ic)</td><td colspan="2">breiig
very soft
0 – 0,5</td><td>weich
soft
0,5 – 0,75</td><td>steif
stiff
0,75 – 1,0</td><td>halbfest
very stiff
1,0 – 1,25</td><td>fest
hard
1,25 – 1,5</td></tr>
<tr><td>–</td><td>o</td><td>o</td><td>o</td><td>o</td><td>o</td></tr>
<tr><td rowspan="2">Lagerungsdichte nach DIN 18126
Relative density</td><td colspan="2">dicht
dense</td><td>mitteldicht
medium dense</td><td>locker
loose</td><td></td><td></td></tr>
<tr><td colspan="2">+</td><td>+</td><td>o</td><td></td><td></td></tr>
<tr><td rowspan="2">Stützdruck [bar]
Confinement pressure [bar]</td><td colspan="2">0</td><td colspan="2">1 – 4</td><td>4 – 7</td><td>7 – 15</td></tr>
<tr><td colspan="2">o</td><td colspan="2">+</td><td>+</td><td>o</td></tr>
<tr><td rowspan="2">Quellpotential
Swelling potential</td><td colspan="2">kein
none</td><td>gering
little</td><td>mittel
fair</td><td>hoch
high</td><td></td></tr>
<tr><td colspan="2">+</td><td>+</td><td>o</td><td>–</td><td></td></tr>
<tr><td rowspan="2">Abrasivität (äquivalenter Quarzanteil) äQu [%]
Abrasivity (equivalent quartz content) [%]</td><td colspan="2">0 – 5</td><td>5 – 15</td><td>15 – 35</td><td>35 – 75</td><td>75 – 100</td></tr>
<tr><td colspan="2">+</td><td>+</td><td>+</td><td>o</td><td>o</td></tr>
<tr><th colspan="7">Festgestein (Rock)</th></tr>
<tr><td rowspan="2">Gesteinsfestigkeit [MPa]
Unconfined compressive strength [MPa]</td><td>0 – 5</td><td>5 – 25</td><td>25 – 50</td><td>50 – 100</td><td>100 – 250</td><td>> 250</td></tr>
<tr><td>o</td><td>o</td><td>o</td><td>o</td><td>o</td><td>o</td></tr>
<tr><td rowspan="2">Bohrkern – Gebirgsqualität [RQD]
Core sample – rock quality designation [RQD]</td><td colspan="2">sehr gering
very poor
0 – 25</td><td>gering
poor
25 – 50</td><td>mittel
fair
50 – 75</td><td>gut
good
75 – 90</td><td>ausgezeichnet
excellent
90 – 100</td></tr>
<tr><td colspan="2">o</td><td>o</td><td>o</td><td>o</td><td>o</td></tr>
<tr><td rowspan="2">Rock Mass Ratio [RMR]
Rock Mass Ratio [RMR]</td><td colspan="2">sehr schlecht
very poor
< 20</td><td>schlecht
poor
21 – 40</td><td>mäßig
fair
41 – 60</td><td>gut
good
61 – 80</td><td>sehr gut
very good
81 – 100</td></tr>
<tr><td colspan="2">o</td><td>o</td><td>o</td><td>o</td><td>o</td></tr>
<tr><td rowspan="2">Wasserzufluss je 10 m Tunnel [l/min]
Waterinflow per 10 m tunnel [l/min]</td><td colspan="2">0</td><td>0 – 10</td><td>10 – 25</td><td>25 – 125</td><td>> 125</td></tr>
<tr><td colspan="2">o</td><td>o</td><td>o</td><td>o</td><td>o</td></tr>
<tr><td rowspan="2">Abrasivität (CAI)
Abrasivity (CAI)</td><td colspan="2">extrem niedrig
extremely low
0,1 – 0,5</td><td>sehr niedrig
very low
0,5 – 1</td><td>niedrig
low
1 – 2</td><td>mittel – hoch
medium – high
2 – 4</td><td>sehr hoch – extrem hoch
very high – extremely high
4 – 6</td></tr>
<tr><td colspan="2">+</td><td>+</td><td>o</td><td>o</td><td>o</td></tr>
<tr><td rowspan="2">Quellpotential
Swelling potential</td><td colspan="2">kein
none</td><td>gering
poor</td><td>mittel
fair</td><td>hoch
high</td><td></td></tr>
<tr><td colspan="2">+</td><td>+</td><td>o</td><td>–</td><td></td></tr>
<tr><td rowspan="2">Stützdruck [bar]
Confinement pressure [bar]</td><td colspan="2">0</td><td colspan="2">1 – 4</td><td>4 – 7</td><td>7 – 15</td></tr>
<tr><td colspan="2">o</td><td colspan="2">+</td><td>+</td><td>o</td></tr>
</table>

Appendix 3.7 Areas of application and selection criteria HYS

Geotechnische Kennwerte Geotechnical parameters	Hybrid-/Multimodeschild (HYS) Hybrid Shield (HYS)		
		+	Haupteinsatzbereich/main field of application
		o	erweiterter Einsatzbereich/extended application
		–	Einsatz eingeschränkt/application limited

Lockergestein (Soil)					
Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
	–	o	o / +	+	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
	–	-	o	+	
Konsistenz (Ic) nach DIN EN ISO 17892-12 Consistency (Ic)	breiig very soft 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
	o	+	+	o	o
Lagerungsdichte nach DIN 18126 Relative density	dicht dense	mitteldicht medium dense	locker loose		
	+	+	+		
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	+	+		o	-
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
	+	+	o	–	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100
	+	+	o	o	–
Festgestein (Rock)					
Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5 / 5 – 25	25 – 50	50 – 100	100 – 250	> 250
	o / 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	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	o	–	–
Wasserzufluss je 10 m Tunnel [l/min] Waterinflow per 10 m tunnel [l/min]	0	0 – 10	10 – 25	25 – 125	> 125
	o	o	o	o	o
Abrasivität (CAI) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5	sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+	+	o	o	o (VS1/2) / – (VS3)
Quellpotential Swelling potential	kein none	gering poor	mittel fair	hoch high	
	+	+	o	–	
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	o	+		–	–

Appendix 3.8 Areas of application and selection criteria EXX/RHS

Geotechnische Kennwerte **Geotechnical parameters**	**Teilschnittmaschine mit Bagger (EXS) oder Schräme (RHS)** **Excavator (EXS) or Roadheader (RHS) Shield**				
	+ Haupteinsatzbereich/main field of application o erweiterter Einsatzbereich/extended application – Einsatz eingeschränkt/application limited				
Lockergestein (Soil)					
Feinkornanteil (< 0,06 mm) DIN 18196 Fines content (< 0,06 mm)	< 5 %	5 – 15 %	15 – 40 %	> 40 %	
	–	– / o	o / +	+	
Durchlässigkeit k nach DIN EN ISO 17892-11 [m/s] Permeability k [m/s]	sehr stark very high > 10^{-2}	stark high 10^{-2} – 10^{-4}	durchlässig permeable 10^{-4} – 10^{-6}	schwach low < 10^{-6}	
	–	o	o	+	
Konsistenz (Ic) nach DIN EN ISO 17892-12 Consistency (Ic)	breiig very soft 0 – 0,5	weich soft 0,5 – 0,75	steif stiff 0,75 – 1,0	halbfest very stiff 1,0 – 1,25	fest hard 1,25 – 1,5
	–	–	o	+	+
Lagerungsdichte nach DIN 18126 Relative density	dicht dense	mitteldicht medium dense	locker loose		
	+	o	–		
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	+	–		–	–
Quellpotential Swelling potential	kein none	gering little	mittel fair	hoch high	
	+	+	o	–	
Abrasivität (äquivalenter Quarzanteil) äQu [%] Abrasivity (equivalent quartz content) [%]	0 – 5	5 – 15	15 – 35	35 – 75	75 – 100
	+	+	+	+	o
Festgestein (Rock)					
Gesteinsfestigkeit [MPa] Unconfined compressive strength [MPa]	0 – 5 / 5 – 25	25 – 50	50 – 100	100 – 250	> 250
	+ / +	+	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	+	+	o	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	+	+	o	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) Abrasivity (CAI)	extrem niedrig extremely low 0,1 – 0,5	sehr niedrig very low 0,5 – 1	niedrig low 1 – 2	mittel – hoch medium – high 2 – 4	sehr hoch – extrem hoch very high – extremely high 4 – 6
	+	+	+	o	o
Quellpotential Swelling potential	kein none	gering poor	mittel fair	hoch high	
	+	+	o	–	
Stützdruck [bar] Confinement pressure [bar]	0	1 – 4		4 – 7	7 – 15
	o	–		–	–