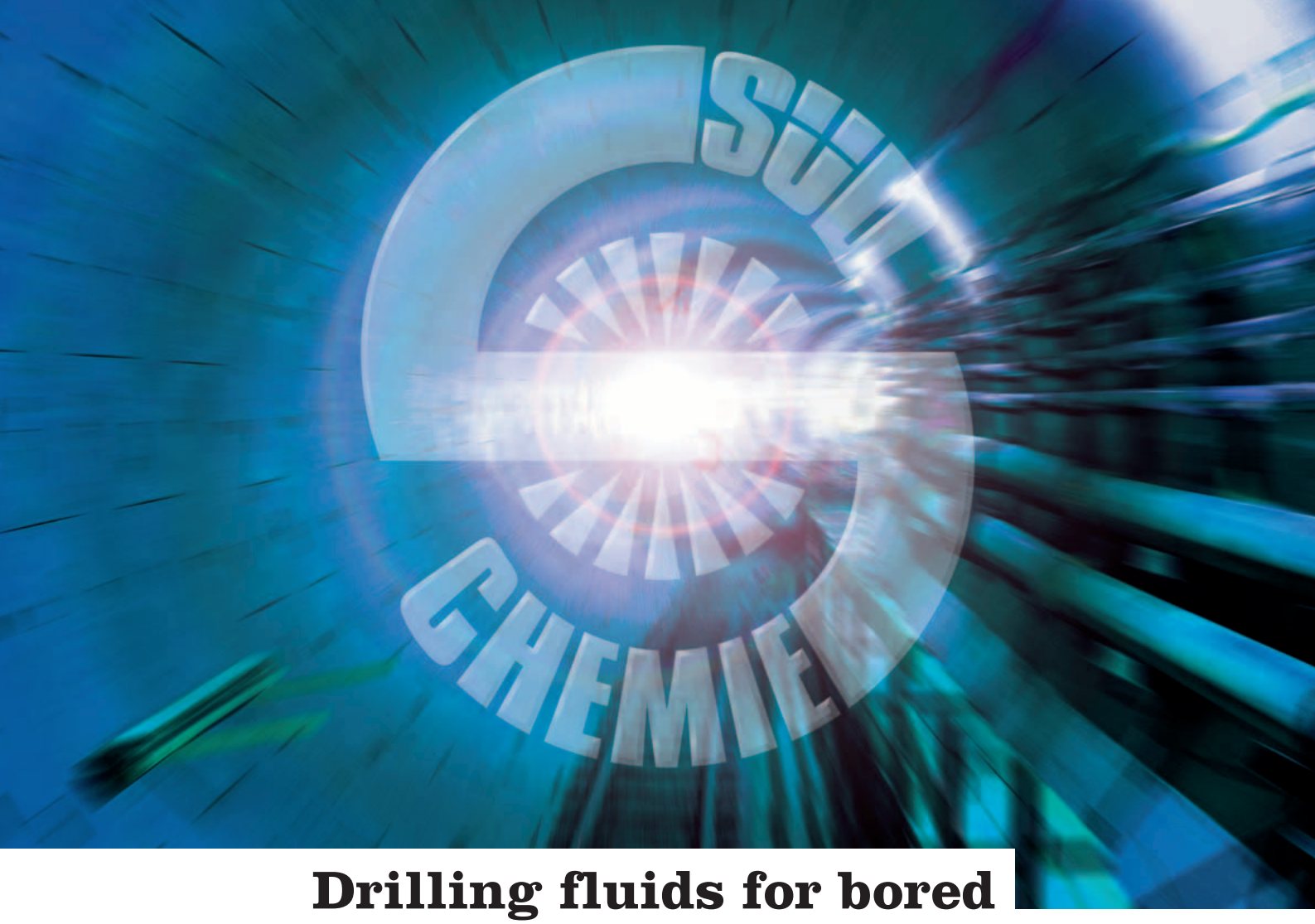


Drilling fluids for bored tunnels construction

SÜD-CHEMIE
Creating Performance Technology

General information/ The Slurry-shield technique

Keys to success

- **To define the characteristics of the drilling fluid according to the project specificity in terms of cost and technical efficiency, in respect of the local regulations.**
- **Availability of pertinent elements concerning the ground conditions, the capacity of the tunnelling machine and the overall environment of the project.**
- **The follow up on site of the »Fluid Solution« and its potential adaptation.**

The sophistication and improvement of the mechanised tunnelling techniques, particularly with the shield tunnelling significantly participated to the development of the tunnels construction worldwide. The apparition of these machines actually allowed the construction of tunnels considered before as very difficult and even not feasible with conventional tunnelling methods.

The number and length of bored tunnels is still increasing over 20 years: the shield tunnelling technique is more and more selected by the contractors and the clients with a trend for larger diameters (over 14 meters) and more challenging projects (ground conditions, location, etc).

The development of the shield tunnelling techniques rapidly display the importance of the drilling fluids used during the construction. Fluids and techniques are inextrictably: slurry shield machines with bentonite mud and earth pressure balanced shield machines with foam.

Thanks to its experience in the field of drilling fluids used in special foundations and other geotechnical works, the Sud-Chemie group naturally became an active actor in this industry offering a comprehensive range of additives and services adapted to the specificity of each project.

The Slurry-shield technique

This tunnelling technique is based on the use of a drilling mud as indicated by its designation. The main function of this drilling fluid is to stabilize the excavation by insuring a liquid support during the tunnelling phase. It also fulfils other essential functions like the transport of the cuttings or secondary for lubrication, and the cooling of the cutting tools. This drilling fluid is generally a bentonite suspension: its composition and characteristics change while tunnelling.

The definition of the most appropriate drilling fluid and in particular its properties is obviously of main concern for challenging project: heterogeneity of the front face, low overburden, high permeable ground, water sensitive ground, etc. As a result, the choice of the drilling mud additives will have to comply with all the specificity of each drilling mud functions in accordance with environmental aspects.

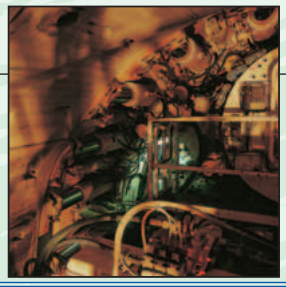
Stabilisation of the excavation

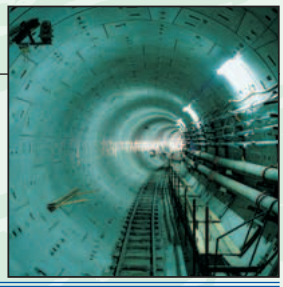
Depending on the permeability of the ground, and more precisely its porosity, as well as the support pressure, the drilling mud will invade differently all excavated surface according to the 2 following interdependent and simultaneous processes: the filtration under pressure and the gelling or shear strengthening of the mud.

As a result of these 2 processes, a deposit of solids will build up on the surfaces of the excavation: the so called mud cake. This cake is generally of 2 types:

- **The membrane cake or external cake (to the formation)**: it consists of a thin and impervious membrane obtained in a low permeability ground: the invasion of the mud is actually limited.
- **The impregnation cake or internal cake (to the formation)**: this cake is obtained in more open ground in opposition of the previous mud cake: in this case, the drilling mud penetrates deeper the ground formation, from few centimetres to several meters in highly permeable ground. This impregnation zone corresponds to the internal mud cake.

The type of mud cake and the efficiency to stop the drilling mud invasion depend directly on the nature of the ground, the support pressure as well as the rheological and filtration characteristics of the drilling mud. The rheological characteristics are generally restricted to yield point, plastic viscosity and gel strength (See Sud-Chemie glossary).





Case of drilling muds for hyperbaric works

Entering the working chamber is sometimes necessary for repair or maintenance works e.g. inspection, change of cutting tools, cleaning of the cutting head and working chamber clogged by sticky material. In case of unstable ground, these works occur under compressed air. However, to ensure the air support pressure, it is imperative to have previously air sealed the front face.

This is achieved by means of a bentonite drilling mud presenting the adapted rheological and filtration properties to build the required mud cake. However, the ground conditions can be problematic and the mud cake then difficult to obtain:

- **Highly permeable ground:** difficulty to control the loss of drilling mud in the ground and as a consequence to build the mud cake.
- **Sandy formation of low permeability:** fragility of the mud cake or the membrane cake due the drying effect of the compressed air and the mud relief.

The permeability of the mud cake under compressed air is of main concern for the security of the workers entering the working chamber. In certain situations, it will be necessary to add some drilling additives like FIX-SOLS P or EXPANFORT to limit the mud loss into the ground and TUNVIS L to limit the drying of the mud cake.

Cuttings removal and mud treatment

While tunnelling, elements from the ground and the ground water are dispersed into the drilling mud. These elements consist in solids but also chemicals like chloride, sulphates, calcium, gypsum, peat, etc. To maintain the rheological and filtration properties required for the front face support as well as for the transport of the drilled cuttings, it is necessary to »clean« the mud: The biggest elements are eliminated by means of vibrating screens, hydrocyclones and other conventional equipment. The finest elements can not be eliminated mechanically: other liquid/solids separation techniques used in the water treatment industry are then necessary: floccculation/coagulation, centrifugation,

Indicative drilling mud formulations are given below for simplified ground conditions :

Ground conditions	Anticipated difficulties	Drilling fluids functions	Indicative characteristics of the drilling fluid					Sud-Chemie drilling mud*
			AP (cp)	PC (cp)	YP (Pa)	Gel 0/10 (lb/100ft²)	API Filtrate loss (ml	
Water sensitive clay formation: plastic clay, marl ($K < 10^{-8}$ m/s)	Density, Viscosity as a result of fines dispersion, Risk of Sticking and Clogging	Maintain the viscosity, the filtrate loss and density	10 – 20	5 – 15	1 – 5	1/5	< 20	BENTONIL mud** + TUNLUB or TUNVIS + salts (KCl, …) + Mud Detergent TUNDET
Clay, limestone, sandstone ($K < 10^{-7}$ m/s)	Density, Viscosity as a result of fines dispersion	Maintain the viscosity, the filtrate loss and density	10 – 20	5 – 15	1 – 5	1/5	< 25	BENTONIL mud + BENTOCRYL 86
Formation of Medium permeability: fine sand, sandy and clay ($K = 10^{-6}$ m/s)	Membrane mud cak	Filtrate loss and Viscosity	15 – 20	5 – 15	5 – 10	1/5	< 25	BENTONIL mud + TUNVIS
Sandy formation ($K = 10^{-4} – 10^{-5}$ m/s)	Loss of drilling mud, Mixed mud Cake	Filtrate loss and Viscosity	20 – 30	5 – 15	10 – 20	3/5	< 25	BENTONIL mud + TUNVIS
Formation of high permeability: alluvium, gravel ($K > 10^{-3}$ m/s)	Loss of drilling mud, Mixed mud Cake	Insufficient viscosity to limit losses	> 40	5 – 20	> 25	10/20	< 25	BENTONIL mud + TUNVIS + Clogging agents: FIX-SOLS P , bentonite granules…

*** The definition of the drilling mud is the result of documentary analysis and laboratory investigation.**
**** BENTONIL is the Sud Chemie trade mark for the different qualities of bentonites produced in France : from standard products like C Forages to customized quality.**

Earth-pressure balanced shield machine

etc. Pumping high density drilling fluids on long distances requires an adapted rheology. However, it may happen that these properties required to ease the mucking and the mud treatment are not adapted for the front face support e.g. high yield point to bore in coarse material limiting the efficiency of the desanding equipment. This aspect should be considered when defining the drilling mud characteristics and selecting the additives.

References

- AFTES (French association for underground construction): Recommendations related to drilling fluids used with a slurry shield machine 14.11.2001
- TUNNELS & OUVRAGES SOUTERRAINS magazine.

The earth-pressure balanced shield machine

This shield tunnelling technique requires the use of a drilling mud commonly called conditioning fluid. However, this fluid does not directly participate to the face support like for the previous technique i.e. slurry shield.

The face support is actually not achieved by means of a liquid support but thanks to the excavated material compressed in the working chamber developing the required »earth pressure« given to this tunnelling technique. These conditioning fluids are generally injected directly to the front face through the cutting wheel, in the working chamber and in the screw conveyor. The main function of these fluids is to modify the overall properties of the excavated muck mass: lubrication, plasticity, compressibility, permeability, etc. These properties are actually necessary for the face support, to ease the removal of the excavated material from the working chamber (screw conveyor and other discharge devices, belt conveyor, mucking cars, etc) and more generally to improve the working conditions of the tunnelling machines: limitation of the cutting and mixing torques, reduction of the cutting tools wear, increase of the advance speed, etc. This »ground treatment« or »ground conditioning« is particularly important when tunnelling in heterogeneous ground (large diameter), in non cohesive and plastic soil.

Among the different possible conditioning fluids used during an EPB drive, foam is at the moment the most frequent additive compared to polymers, bentonite and water. Compressed air is obviously a particular case. The definition of these soil conditioning fluids is quite complex: it supposes to anticipate the behaviour of the ground while tunnelling. The absence of standardised laboratory tests recognised by the industry does not facilitate this analysis. The main difficulty is actually to define the best soil conditioning operation in respect to the optimum working conditions of the TBM. The choice of the additives will also have to take into consideration the potential effects of these

Ground Conditions	Anticipated difficulties	Functions of the drilling fluid	Sud-Chemie Fluid solution*
Water sensitive clay formation: plastic clay, marl (K < 10-8 m/s)	Risk of sticking, clogging of cutting tools, high cutting torque	Lubrication	TUNFOAM and TUNLUB L aerated mud TUNLUB L or TUNVIS L polymer mud
Clay, limestone, sandstone (K < 10-7 m/s)	High cutting torque	Plastificizing, Homogeneization, Lubrification	TUNFOAM aerated mud TUNLUB L or TUNVIS L polymer mud
Formation of low to medium permeability: fine sable, silty and sandy clay (K = 10-6 m/s)	Face support Wear of cutting tools, screw conveyor	Plastificizing, Homogeneization, Lubrification	TUNFOAM aerated mud TUNLUB L or TUNVIS L polymer mud
Sandy Formation (K =10-4 – 10-5 m/s)	Idem	Idem	TUNFOAM and TUNLUB L aerated mud, Bentonite mud**
High permeability Formation: alluvium, gravel (K > 10-3 m/s)	Limit of the technique	N.A.	N.A.

* The quality of the foam is based on several parameters such as concentration of surfactant, foam expansion ratio (FER) and foam injection ratio (FIR). These parameters are generally anticipated by the laboratory tests conducted on representative soil samples and definitively confirmed on site.

** Re. to the filtration rappelées dans le § 2 – 1.

Other Shield Tunneling Methods/ Back-fill grout

chemicals in terms of environmental once incorporated into the excavated ground.

Face support

The stability of the front face is achieved by the pressurization of the excavated material filling the working chamber while the TBM advances. In theory, the excavated material must stay at constant volume. The transmission of the support pressure requires that the excavated material in the working chamber exhibits certain properties: plasticity, compressibility, impermeability etc. The injection of soil conditioning fluids, mostly foam, through the cutting wheel and in the working chamber helps obtain such a material.

Muck removal

The excavated ground is extracted from the working chamber by means of a discharge device, generally a screw conveyor. The rotating speed of this equipment is proportional to the advance speed to balance the volume of excavated ground entering and exiting the working chamber. The properties of plasticity, homogeneity as well as the lubricated aspect of the muck are also necessary to ease this operation. In certain cases, complementary injections of soil conditioning agents in the screw conveyor can be necessary to reduce the torque and limit the clogging process. Indicative formulations of soil conditioning drilling fluids are given by simplified types of ground conditions (see table 2):

Other Shield Tunneling Methods

The use of drilling fluids is not as crucial in these techniques as for the previous ones; they are restricted to specific situations as presented in the following chapters:

Arm digger shield

In unstable water bearing ground conditions, spraying onto the front face TUNFOAM aerated mud associated to specific additives (polymers and /or other chemicals) helps minimizing compressed air losses and as a result allows tunnelling.

Hard rock tunnelling machine

In case of hard rock tunnelling, the front face stability is generally not a major issue. The use of drilling fluids is then restricted to unexpected situations like the crossing of zones exhibiting bad mechanical characteristics: fault, cave, etc. or high pressure water ingress while tunnelling. Specific products can then be used:

- Bentonite cement grouting (cf. fiche d'application)
- Water absorbent: FIX-SOLS for conditioning liquefied muck and minimize water ingress in case of limited water flow.

The generation of dust during hard rock tunnelling can be effectively controlled by a water mist or the application of a wetting spray based on a special foam formulation: TUNDUST

Back-fill grout

During the tunnelling operation, a void is created between the tunnel lining and the surrounding ground. Filling this annulus with an adapted grout is imperative: it actually minimizes the possible settlements on the surface. The injection of this back fill grout happens at the extremity of the shield through the tail seal brushes and continuously during tunnelling so as to fill in immediately the annulus. The formulation of such grout is specific to each tunnelling project: batching and mixing equipment and ground conditions.

The location of the project will also orientate the choice for local aggregates: fillers, crushed limestone, sand, saw dust, etc. The use of bentonite and in particular our BENTONIL CV15 is of main interest for improving the stability of the grout as well as its pumpability. Others additives like plasticizers, thinners can be associated to the grout. Our laboratory can help contractors defining the best.

Süd-Chemie services

- **A laboratory equipped for soil characterization and simulation of field conditions to define the appropriate drilling fluids solution.**
- **Technical assistance on site thanks to the presence of several SUD CHEMIE Subsidiaries on the five continents.**
- **Production units capable to adapt existing products and formulation of products in case of specific demand.**

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