

Steffen Praetorius/Britta Schößer

Bentonite Handbook

Lubrication for Pipe Jacking

WILEY
Ernst & Sohn
A Wiley Brand

Acknowledgement

Intensive specialist discussion about challenges in pipe jacking practice and scientific findings has found its way into this Bentonite Handbook and sprouted new (research) ideas. For their valuable contributions, we wish to thank the After Sales staff of the Utility Tunnelling department at Herrenknecht AG as well as the experienced and motivated specialists on pipe jacking sites. For their detailed discussions, we wish to thank Ms. Dipl.-Ing. Geotechnik/Bergbau *Christel Flittner*, Mr. Dipl.-Ing. Tiefbohrtechnik *Oliver Knopf*, Ms. *Irmhild Lauter*, Mr. *Ulrich Schröder*, Mr. *Hermann Spengler* and Mr. Dipl.-Geol. *Björn Zenner*.

Mr. Dipl.-Geol. *Matthias Botzenhardt* made a particular contribution with his expert assistance regarding the subject of additives. The production of drawings and text was supported by Mr. Dipl.-Ing. *Nick Biermann*, Ms. *Melanie Ruff*, Mr. *Roman Duda* and Mr. *Tobias Bucher*.

We wholeheartedly thank Mr. Prof. Dr.-Ing. *Markus Thewes* and Mr. Dr.-Ing. *Marc Peters* as well as the research and development colleagues of the Utility Tunnelling department at Herrenknecht AG and at the Chair of Tunnelling and Construction Management at the Ruhr University, Bochum for their sympathetic support and the pleasant working atmosphere. The publisher Ernst & Sohn and particularly Mr. Dr. *Helmut Richter*, Ms. *Esther Schleidweiler*, Mr. Dr. *Michael Bär* and Mr. *David Sturge* deserve our gratitude for their support in the implementation and design of the book.

We would be pleased to receive feedback and suggestions.

Steffen Praetorius and Britta Schößer

Foreword

Pipe jacking is an indispensable process for the installation of underground pipes. Constant improvement of the machinery in recent decades has led to pipe jacking projects being successfully completed in almost any geology and hydrogeology, with challenging routes. The success of a pipe jacking project is ensured by smooth interaction of the tunnelling technology and the process operations. The main challenges, which are met daily on pipe jacking projects, are to minimise potential risks and to increase the practical distances.

The development of the jacking force over the length of the drive – and particularly the skin friction along the pipe string – is of central importance for the implementation of pipe jacking projects. Improved working methods can avoid increased jacking forces and the resulting delays to progress or stoppages. One essential element in the reduction of skin friction is well functioning annular gap lubrication, with the lubricant and the lubrication technology being adapted to suit the constraints of the jack and particularly the ground conditions. Both components – lubricant and lubrication technology – depend on important details and demand a good basic understanding on the part of the construction staff.

The lubricant mostly consists of a bentonite suspension, whose rheological parameters yield point and viscosity have to be adapted to suit the prevailing geological conditions on each pipe jacking project. It has to be correctly prepared and the rheological parameters checked according to standards. The lubrication technology supplies the lubricant continuously in sufficient quantity into the annular gap. In advance, the required quantities of lubricant over the course of the jack have to be determined, prepared in good time and kept available in sufficient volume. These figures depend directly on the size of the tunnelling machine and the jacked pipe as well as the soil mechanics parameters grading distribution, compaction and permeability. When an automatic bentonite lubrication system is used, the number of injection fittings in the pipe section at a lubrication point has to be decided as well as the spacing of the lubrication points and their injection intervals in the tunnelling machine and in the pipe string.

Precise matching of the individual aspects makes it possible to hold the pipe string in the correct position, considerably reduce the coefficient of friction between pipe and ground and finally keep the skin friction controllable as jacking proceeds.

The Bentonite Handbook deals with the various aspects of annular gap lubrication comprehensively, and should serve well as a design aid and a guideline for site practice. It is of course not possible to exhaustively deal with all practical problems of pipe jacking. Responsible action by well trained engineers will always remain the basis of good and successful construction even with the use of this book.

Professor *Markus Thewes*

Tabel of content

Acknowledgement	VII
Foreword	IX
List of symbols used	XV
I. Greek symbols	XV
II. Latin symbols	XV
1 Basics	1
1.1 Basics and technical implementation of bentonite lubrication systems	1
1.1.1 Control unit	2
1.1.2 Mixing tank	2
1.1.3 Storage tank	5
1.1.4 Main jacking station	5
1.1.5 Tunnelling machine	5
1.1.6 Lubrication ring	5
1.1.7 Intermediate jacking station	5
1.1.8 Jacked pipe	5
1.1.9 Lubrication station	5
1.1.10 Injection fittings	6
1.1.11 Bentonite pump	6
1.1.12 Compressed air feed	7
1.1.13 Control cable	7
1.1.14 Bentonite or feed line	7
1.2 Annular gap lubrication in pipe jacking	7
1.3 Preliminary remarks about the ground	8
2 Bentonite and bentonite suspensions	11
2.1 Composition and structure	11
2.2 Hydration behaviour	12
2.3 Card house structure and thixotropy	15
2.4 Yield point, viscosity and gel strength	16
2.5 Stability	21
2.6 Usual types of bentonite	23
2.6.1 Natural bentonite (Ca or Na)	23
2.6.2 Activated or active bentonite	23
2.6.3 Bentonite with polymer additives	24
3 Additives	25
3.1 Polymers	25
3.1.1 Functions of polymer additives	25
3.2 Types of polymer additives	28
3.2.1 Starch	28
3.2.2 Xanthan	29
3.2.3 Guaran	30
3.2.4 Modified celluloses (PAC, MEC, HEC, CMC)	30

3.2.5	Polyacrylamide/-acrylate	31
3.3	Overview of polymer additives and their functions	31
4	Correct preparation of bentonite suspensions	29
4.1	Mixing	29
4.1.1	Procedure for the preparation of suspension	30
4.2	Mixing equipment	33
4.3	Mixing instructions	34
4.3.1	Mixing instructions for mixers with mixing pump	34
4.3.2	Mixing instructions for mixers with water jet pump	34
4.4	Hydration tank	35
5	Properties of the suspension and measurement processes	37
5.1	Viscosity: Marsh funnel	37
5.2	Yield point: ball-harp rheometer	40
5.3	Viscosity and gel strength: Rotational viscometer	42
5.4	Filtrate water and thickness of filter cake: filter press	43
5.5	Density	45
5.5.1	Measurement using a mud balance	45
5.5.2	Measurement using a pycnometer	45
5.6	Water hardness: test strips	46
5.7	pH value	46
5.7.1	Determination with pH test strips	46
5.7.2	Measurement with a pH meter	46
5.8	Conductivity	46
5.9	Temperature	47
6	Ground and groundwater	49
6.1	Geology of solid rock	49
6.1.1	Classification of rocks	50
6.1.2	Mineral content and mineral structure	50
6.1.3	Uniaxial rock compression strength	50
6.1.4	Tension strength	53
6.1.5	Rock mass strength	54
6.1.6	Rock abrasiveness	54
6.1.7	Interface structure	55
6.1.8	Degree of weathering	58
6.1.9	Rock mass classification	59
6.2	Geology of soils	65
6.2.1	Types of minerals	65
6.2.2	Grain size and grain size distribution	65
6.2.3	Grain rounding	77
6.2.4	Pores	78
6.2.5	Compactness	80
6.2.6	Shear strength	82
6.2.7	Atterberg limits	83
6.2.8	Swelling capability	85

6.3	Stability and stand-up time.....	85
6.3.1	Assessment of stability according to the working face behaviour.....	85
6.3.2	Evaluation of stand-up time using the RMR and Q systems.....	87
6.4	Hydrogeology.....	88
6.4.1	Basic hydrological terms.....	88
6.4.2	Permeability.....	89
6.4.3	Determination of permeability of soil.....	93
6.4.4	Determination of permeability in rock.....	96
6.5	Influence of various rock properties on the use of bentonite.....	99
6.6	Contamination in the ground, groundwater or mixing water.....	100
6.6.1	pH value.....	100
6.6.2	Salt water.....	101
6.6.3	Water hardness due to calcium or magnesium ions.....	101
6.6.4	Chlorine.....	102
6.6.5	Iron.....	102
6.6.6	Humic acids.....	102
6.6.7	Cement / concrete.....	102
6.6.8	Overview of the thresholds for contamination of the mixing water.....	103
6.6.9	Effects of contaminations on the properties of the suspension.....	103
7	Bentonite suspensions for annular gap lubrication.....	105
7.1	Size of the annular gap.....	105
7.1.1	Skin friction.....	106
7.2	Vertical position of the pipe string in the driven cavity.....	107
7.2.1	Floating.....	108
7.2.2	Ballasting.....	109
7.2.3	Vertical position of the pipe string in stable ground.....	109
7.2.4	Vertical position of the pipe string in unstable ground.....	110
7.3	Functions of the lubricant in the annular gap.....	111
7.3.1	Support function.....	112
7.3.2	Lubricating function.....	115
7.3.3	Carrying capacity.....	116
7.3.4	Consequences of poor adaptation of the lubricant.....	117
7.4	Adaptation of the bentonite suspension to the ground.....	119
7.4.1	Basic geological parameters.....	119
7.4.2	Flow diagrams for rock.....	119
7.4.3	Flow diagrams for soils.....	121
7.4.4	Relationships between ground and lubricant parameters.....	123
7.4.5	Hydrogeological parameters.....	124
7.5	Rheological parameters of the bentonite suspension.....	124
7.5.1	Particle size.....	125
7.5.2	Yield point.....	127
7.5.3	Viscosity.....	129
7.5.4	Gel strength.....	130
7.6	Suspension quantities.....	132
7.6.1	Definition of terms.....	132

7.6.2	Basic principles for the determination of the required suspension quantity.....	141
7.6.3	Calculation of the suspension quantities V_{machine} and $V_{\text{pipe string}}$	145
7.7	Time-dependant loss volumes.....	147
7.8	Lubrication strategies.....	148
7.8.1	Interval-controlled systems.....	148
7.8.2	Volume-controlled systems.....	150
7.8.3	Lubrication strategies for initial and subsequent injection	152
7.8.4	Special lubrication strategies with Direct Pipe© and related processes ...	153
8	Lubrication technology	155
8.1	Arrangement and spacing of the lubrication points in the pipe string	155
8.2	Number and arrangement of the injection fittings per lubricating point in the pipe cross-section	156
8.3	Non-return valves.....	157
8.4	Lubrication circuit	158
8.5	Interaction between the support pressure at the face and the annular gap pressure	159
8.6	Bentonite supply in the starting area.....	160
8.7	Lubricant pressure, lubricant quantity and pressure losses.....	161
9	Reporting	163
9.1	Which parameters should be documented for bentonite lubrication?	163
9.2	Forms.....	163
10	Lists of the required injection quantities	167
10.1	Explanation of the lists.....	167
	Literature	197

2 Bentonite and bentonite suspensions

Bentonite suspensions normally consist of water and bentonite, and polymers can also be added. A suspension is a fine distribution of undissolved solids, in this case the bentonite particles, in a carrier fluid. Bentonite makes up, according to the product used, between 3 and 10% of the mass of the suspension.

According to *Grim et al.* [51], bentonite is “... a clay composed predominantly of clay minerals and influenced by their physical properties”. Clays are uncemented sedimentary soils, which consist of mineral particles with a particle size of $< 20 \mu\text{m}$ ($=0.02 \text{ mm}$). The main component of bentonite with a high swelling capability is the clay mineral montmorillonite (60–80 % by mass). Secondary minerals such as quartz, mica, feldspar, illite or carbonates may also be present. The quantities of the minerals in bentonite can vary widely.

The montmorillonite content is the first indication of the quality of bentonite, since the technical properties of bentonite are characterised by the chemical and mineral characteristics and the properties of this clay mineral. Only clays with a montmorillonite content $>50 \%$ should be described as bentonite. Substances with $<50 \%$ montmorillonite content are described as clays with high clay mineral contents.

For bentonite suspensions intended for use as lubricants in pipe jacking, the most interesting properties are stability (resistance against segregation with time), yield point τ_F , viscosity η and gel strength.

2.1 Composition and structure

Clay minerals are plate-shaped, silicate mineral particles with a size of $\leq 20 \mu\text{m}$ ($\leq 0.02 \text{ mm}$; for comparison, a human hair has a diameter of $70 \mu\text{m} = 0.07 \text{ mm}$). Montmorillonite belongs to the group of three-layer minerals. Its crystalline structure consists of one sheet AlO_6 octahedrons and two sheets of SiO_4 tetrahedrons, which are symmetrically surrounded so that to form crystal sheets (Fig. 2.1) [54].

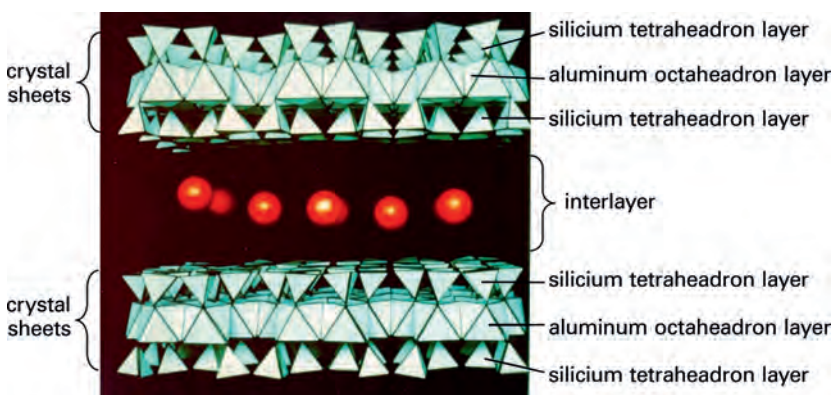


Fig. 2.1 Crystal structure of montmorillonite [8].

In the natural condition, cations like magnesium/calcium (Mg/Ca^{2+}) or sodium (Na^+) are bonded in the interlayer positions, and neutralise the negative surface charge of the crystal sheets. According to the type of attached cations, bentonite is differentiated into sodium and calcium bentonites. Water molecules can also intervene between the layers. The spacing of the layers and thus also the forces, which hold the silicate layers together, depend greatly on the inclusion of water molecules. The spacing can increase due to the absorption of layer water. A single montmorillonite crystal consists of 15 to 20 elementary layers [54].

2.2 Hydration behaviour

One essential property of bentonite is its swelling behaviour on contact with water. Two different types of water absorption on hydration are differentiated [8,75]:

- In *innercrystalline* (or *intracrystalline*) swelling, absorption of excess water at the interlayer cations and clay mineral surfaces causes an enlargement of the elementary layers. This process is reversible.
- In *osmotic swelling*, diffused ion layers form at the clay mineral surface and in the pore solution due to concentration differences of the cations, which causes an electrostatic repulsion of the particles.

In montmorillonite crystals, the hydration process is normally produced by the inclusion of water molecules between the elementary layers (innercrystalline swelling). This widens the spacing of the layers; under suitable conditions, the crystal bonding may even be completely disintegrated.

Sodium and calcium bentonites differ greatly in their hydration behaviour due to the different nature of the interlayer cations [8]. Sodium ions (Na^+) tend more strongly to hydration in the absorbed state than calcium ions (Ca^{2+}) and thus enable greater water absorption and swelling. Sodium bentonite has for this reason a water absorption capacity of 600–700%, calcium bentonite only 200–300 % [50].

Sodium ions are also larger than calcium or magnesium ions (Mg^{2+}) and thus have less bonding force. Water absorption or release alters the layer spacing of the crystals in Ca or Mg saturated montmorillonites in the range between 10–20 Å; the individual silicate sheets remain arranged in layer stacks even after addition of sufficient water. With Na intermediate layer cations, on the other hand, the layer spacing changes through swelling by up to 160 Å. With further water absorption or enlargement, the cohesion of the layer packets is lost and the crystal bond is completely dissolved. The montmorillonite crystal then decomposes into its individual elementary layers [78,55].

2.3 Card house structure and thixotropy

Each elementary layer of a montmorillonite crystal consists of a negatively charged surface and positively charged edges (Fig. 2.2).

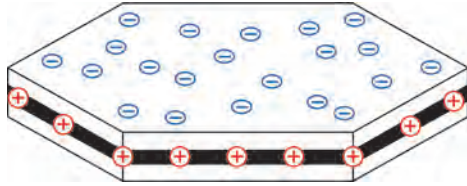


Fig. 2.2 Charge distribution of a montmorillonite elementary layer. The edges are positive (red), the surfaces negative (blue). (Source: Chair of Tunnelling and Construction Management at the Ruhr University, Bochum).

Due to these different charges, dissolution of the crystal bonding into individual sheets after the dissolution of the crystal bonding forms special structures in the water, in which the edge of one crystal settles on the surface of another. This large-volume framework that forms in water is described as a *card house structure* (Fig. 2.3) [69].

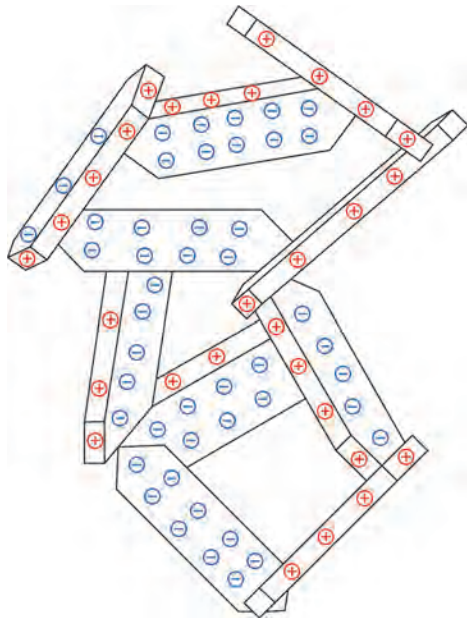


Fig. 2.3 Card house structure. Positive edge charge red; negative surface charge blue. (Source: Chair of Tunnelling and Construction Management at the Ruhr University, Bochum).

This card house structure settles in the bentonite suspension in an undisturbed state, i.e. the suspension sets to a hydrogel (gel). The action of mechanical disturbances (e.g. paddles or pumps) creates intensive movement in the suspension. This loosens the electrostatic bonds between the individual crystals, the card house structures collapses and the suspension changes to a flowing state (sol). This sol/gel conversion in bentonite suspensions is completely reversible and can be repeated any number of times [53,69].

The behaviour described here of the temporary reduction of shear strength through deformation and its reformation is described as *thixotropy* [50].

Jessberger [55] defines thixotropy as the isothermal and reversible alteration of the structure of a material. This is manifested in a reduction of the deformation resistance under mechanical loading and a time-dependant return to a state of greater deformation resistance as soon as the mechanical loading is ended.

2.4 Yield point, viscosity and gel strength

Due to their card house structure, bentonite suspensions possess a *yield point*. The yield point of a material denotes the smallest shear stress, above which it behaves rheologically as a fluid [18].

The card house structure resists the acting shear forces until the critical value of the yield point τ_F is exceeded. Only then is the framework structure torn apart and the system begins to yield [54], [92]. Accordingly the standard DIN 4127 [23] defines the yield point τ_F as the shear stress τ , at which yielding occurs (failure shear stress). In thixotropic fluids like bentonite suspensions, this is dependant on temperature and thixotropic consolidation.

The increase of the yield point τ_F with increasing rest time is described as *thixotropic solidification*. The yield point τ_F reaches its minimum value $\text{dyn } \tau_F$ (dynamic yield point) immediately after the completion of a yield movement ($t = 0$) and asymptotically approaches with continued rest its maximum value $\text{stat } \tau_F$ (static yield point). The development with time of the thixotropic solidification is shown as an example in Fig. 2.4. The curve and the limits of the solidification curve are temperature dependent [23], [92].

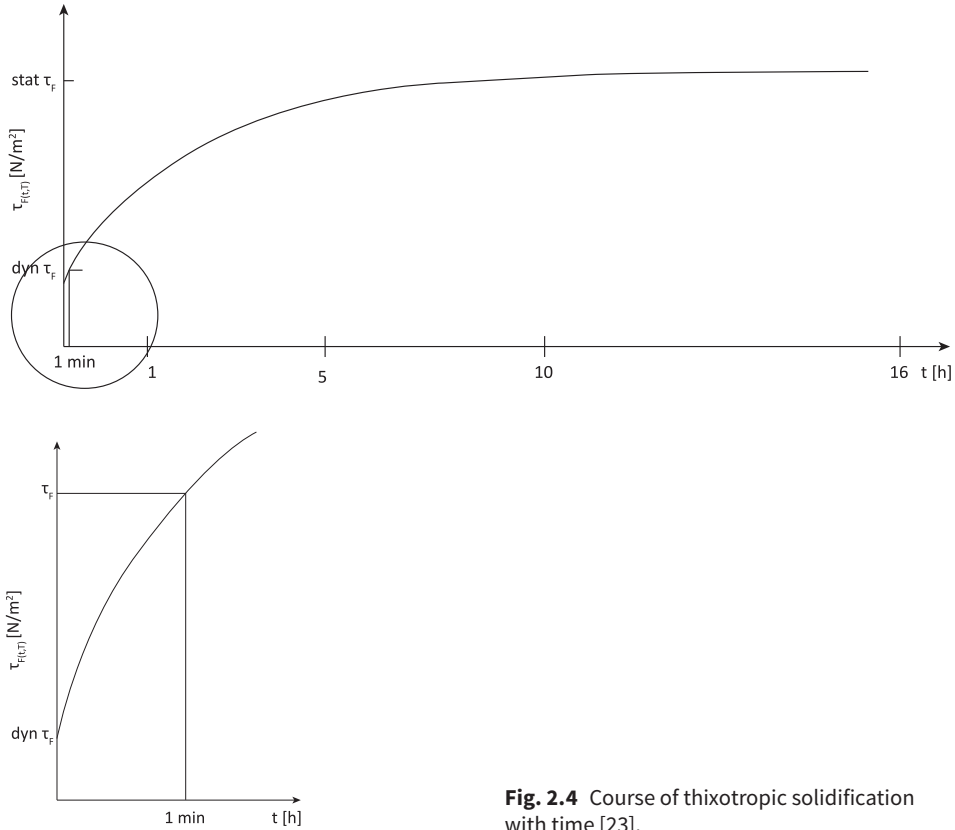


Fig. 2.4 Course of thixotropic solidification with time [23].

The yield point describes the capability of a suspension to set in undisturbed soil. The suspension penetrates into the soil, but its flow speed reduces until the shear stresses are no longer sufficient to further maintain the flow of the suspension; the penetration process stagnates. The yield point in this case depends on the initial conditions and increases with the rest time (thixotropic solidification).

The yield point is directly related to the physical and chemical reactions of the active components (bentonite particles) of the suspension. Increasing density and viscosity through the addition of inert solids does not inevitably lead to higher yield point; it can even be reduced. Pipe jacking practice shows that a combination of active and inert particles in the suspension may lead to increased viscosity.

The static yield point $\text{stat } \tau_F$ – the yield point in the rest state – determines the properties of a bentonite suspension with regard to its function as a support agent; for large open structures below the ground, the highest possible values of the yield point are desirable. The dynamic yield point $\text{dyn } \tau_F$ – the yield point in an agitated state – determines the properties of a bentonite suspension with regard to its function as a lubricant in the annular gap. For this purpose, the lowest possible values of the yield point are desirable (see Sections 7.5.1 to 7.5.3).

The yield point τ_F of a bentonite suspension depends on many factors including bentonite type and concentration, type of preparation, dispersion and hydration time and temperature.

The *viscosity* η is a measure of the viscosity of fluids. This viscosity is caused by the internal friction, which adjacent fluid layers exert on each other because their molecules reciprocally attract each other. The higher the viscosity of a fluid, the stronger is the bonding between its molecules and the less it moves – its flow capability is reduced.

According to DIN 1342-1 [17], the viscosity η is defined as the relationship between the shear stress τ and shear rate D :

$$\eta = \frac{\tau}{D} \quad (2.1)$$

with

η = viscosity [N s/m²]

τ = shear stress [N/m²]

D = shear rate [s⁻¹]

Thixotropy can according to DIN 1342-1 [17] be defined in terms of viscosity. The viscosity reduces from its initial value in the rest state due to continued mechanical agitation and increases again after the end of the agitation.

The flow behaviour of fluids can be described with various types of flow curves with various mathematical approaches. Characteristic flow curves for Newtonian, Bingham and structural viscous flow types are shown in Fig. 2.5.

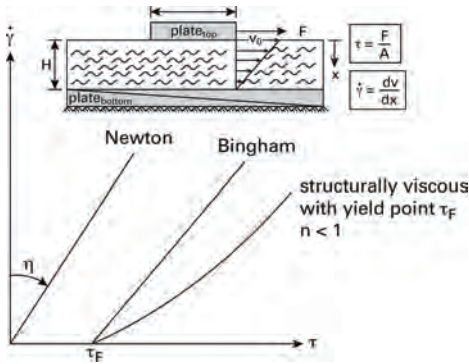


Fig. 2.5 Flow curves for Newtonian flow, Bingham flow with yield point and structural viscous flow [100].

Newtonian flow only occurs in clay mineral dispersions at very small concentrations. There is a proportional relationship between the shear stress τ and the shear rate D . The flow curve is therefore linear through the origin of the coordinates with a constant viscosity η as the gradient (see Fig. 2.5) [54].

Bingham flow is characterised by the occurrence of a yield point τ_F . Such a system behaves like a solid at small shear stresses, and flowing only occurs after the yield point τ_F is exceeded. Also in this case, the flow behaviour is linear and the viscosity is constant (see Fig. 2.5) [18,100]. Such a flow curve can be expressed as a simplification with the Bingham flow equation:

$$\tau = \tau_F + \eta D \quad (2.2)$$

In fluids that are not purely viscous, viscosity depends on the shear rate and/or the duration of the shear loading and is thus not constant. Examples of this are *structurally viscous fluids*, which show a reduction of viscosity with increasing shear rate (also described as *shear thinning* or *pseudoplastic behaviour*). In this case, the ratio between shear stress τ and shear rate D is not constant, so that the viscosity η can only be given as a function of the shear rate D . It is then, for example, determined at points through the gradient of the flow curve. This viscosity is described as the *differential viscosity* η' . If the viscosity η reduces with increasing shear rate D , i.e. structural connections are reduced with increasing shear loading, this is termed *structural viscose* behaviour (see Fig. 2.5) [54].

Bentonite suspensions are neither Newtonian nor Bingham fluids, but show thixotropic behaviour [55,82,94] and possess a dynamic and a static yield point. Mechanical shear deformation such as the action of a paddle or a pump on the suspension in the rest state liquefies it, with a simultaneous reduction of the yield point from its maximum value (static yield point $\text{stat } \tau_F$) to its minimal value (dynamic yield point $\text{dyn } \tau_F$). If the suspension is then left without agitation, it solidifies again and regains its original yield point within a certain time (Fig. 2.6).

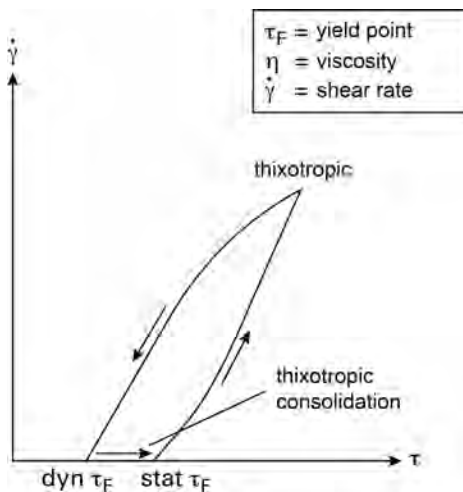


Fig. 2.6 Flow curve of a thixotropic fluid (bentonite suspension) [100].

Fig. 2.6 shows the essential elements of the flow behaviour of a bentonite suspension through a typical flow curve. In comparison to Fig. 2.5, it can be seen that bentonite suspension cannot be clearly assigned to one flow curve type. After reaching the yield

point, the viscosity first reduces with increasing shear rate and in this region can only be given at points though the gradient. As soon as the framework structure has been totally destroyed at higher velocities, the curve becomes linear and the viscosity in this region is almost constant. For this reason, bentonite suspension is measured with a rheometer from high to low shear rates to determine the dynamic yield point (Fig. 2.7).

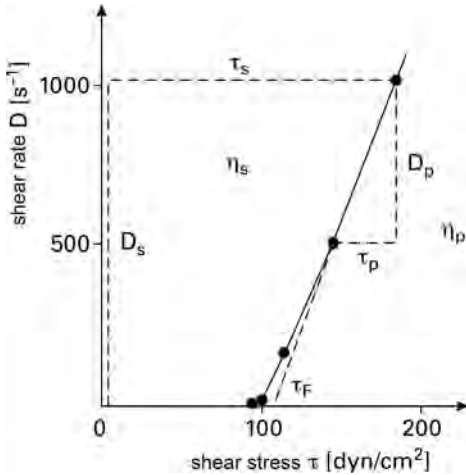


Fig. 2.7 Flow curve of a bentonite suspension [69].

For the description of the flow behaviour of a bentonite suspension, the following assumptions are made [69].

The *apparent viscosity* η_s is calculated from the shear stress τ at a shear rate of $D = 1000 \text{ s}^{-1}$. In this case it is neglected that the suspension has a yield point τ_F .

$$\eta_s = \frac{\tau_s}{D_s} \quad (2.3)$$

The apparent viscosity is the “real” viscosity of a suspension. The observed viscosity depends on the flow velocity during the filtration process in the ground. At low velocities, the viscosity is high, and at high velocities, the viscosity is low. For the pumping system, the apparent viscosity should be as low as possible. In a Bingham fluid, the viscosity reduces with increasing agitation above the yield point. Intensive agitation leads to turbulent flow in the pumped line.

For the determination of the *plastic viscosity* η_p , only the part of the flow curve regarded as linear between $D = 500 \text{ s}^{-1}$ and $D = 1000 \text{ s}^{-1}$ is evaluated (see Fig. 2.7).

$$\eta_p = \frac{\tau_p}{D_p} \quad (2.4)$$

The plastic viscosity corresponds to the linear part of the curve of a thixotropic suspension. The plastic viscosity seems to be constant. Its value is of significance for the determination of the pressure losses in the pumped lines during the pumping process. It is essentially determined by the solids content and the nature of the solids.

The viscosity of a suspension is also linked with the gel strength. A high viscosity always demands a high pump power in the lubrication system.

The *gel strength* describes the capability of a suspension to form a gel structure. It is a measurement of thixotropy under static conditions. The gel strength is defined as the shear stress, which is necessary in order to destroy the gel structure under static conditions (i.e. at rest). This change from the gel at rest to the sol in movement is measured, for example, with a rotating viscometer at low shear rates after 10 s and 10 min in the rest state.

This so-called “0–10 min gel strength” is of great significance for application as face support. In practice, the filter cake at the face is destroyed by the excavation tools on the cutting wheel. After the excavation tools have passed through, the suspension starts to build a filter cake at the face again. For this process, it needs the time for thixotropic consolidation again in order to regain its original condition. This time should naturally be as short as possible in order that the state of impermeability is restored at the face as quickly as possible. For this reason, the lowest possible value of the 0–10 min gel strength is helpful.

In general, various curves of gel strength are differentiated. As shown in Fig. 2.8, the variation of the specific gel strength of a fluid with time should be as low and flat as possible for use in lubrication systems.

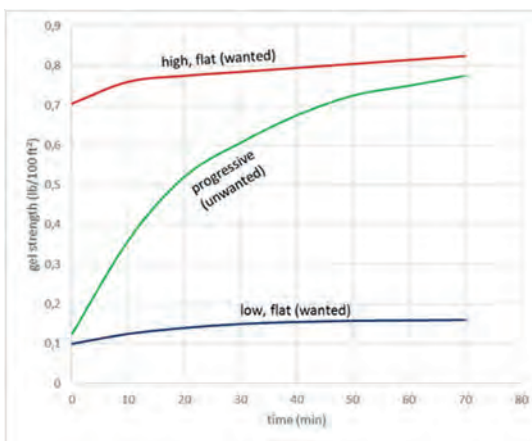


Fig. 2.8 Different types of gel strength [80].

2.5 Stability

The stability of a suspension describes, according to DIN 1342-3 [18], “the property of not segregating or only slightly in the course of time”. If the components of a suspension segregate, then the suspension is unstable. Stable suspensions on the other hand do not segregate (Fig. 2.9). The suspension components can however be separated from each other by mechanical and/or chemical means.

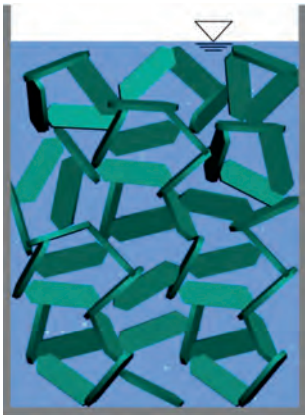


Fig. 2.9 Stable bentonite suspension with evenly distributed solid particles in water [97].

Walz and Pulsfort [97] differentiate three types of segregation (Fig. 2.10):

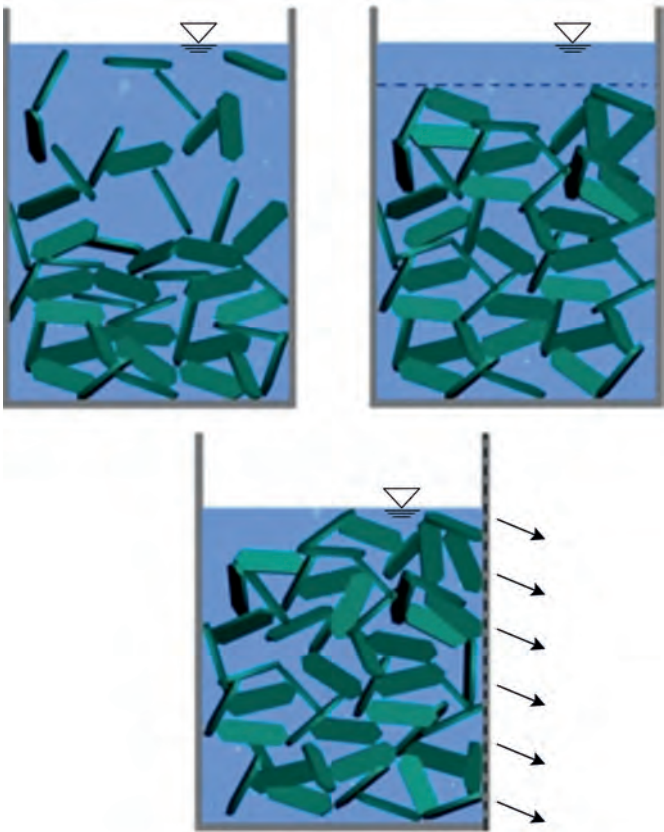


Fig. 2.10 types of segregation of bentonite suspensions: sedimentation (left), consolidation (middle), filtration (right) [97].

1. *Sedimentation* describes the deposition or sinking of solids in a fluid under the action of gravity. The result of sedimentation is that the density of the fluid decreases in the upper part and increases in the lower part.
2. *Consolidation* describes the squeezing together of a tipped or heaped material (card house) under its own weight or other internal forces, with water being pressed out.
3. *Filtration* describes the separation of solid and liquid components of a suspension. In bentonite suspensions, this is the loss of water to a porous surface or a porous body (e.g. the surrounding ground acting as a filter) as a result of pressure acting on the suspension. Filtration occurs when the suspended solid material either cannot penetrate into the pores or the suspension stagnates in the pores of the filter (see Section 7.3.1)

Filtration is directly connected with filter cake formation (see Section 7.3.1). Above all in permeable soil such as sand, the thinnest and most impermeable filter cake provides stabilisation. A filter cake can only be formed with a certain, acceptable degree of filtration and thus water loss. Vice versa, a small degree of filtration can only be achieved with a good quality, i.e. thin and impermeable, filter cake.

2.6 Usual types of bentonite

The bentonite products available on the market can be divided into three basic types:

- natural calcium or sodium bentonite
- activated sodium bentonite
- polymer-modified bentonite

2.6.1 Natural bentonite (Ca or Na)

The water absorption and hydration capacity of natural bentonites differ greatly and depend on which cations are attached between the elementary layers (see Section 2.2). Calcium bentonite with bivalent Ca^{2+} and/or Mg^{2+} ions has a water absorption capacity of one and a half to two times its own weight; for sodium bentonite with univalent Na^+ ions between the layers, this is five to ten times. The exact values depend on the deposit genesis of the bentonite, its montmorillonite content, the sodium content and the type of ion exchange [7].

2.6.2 Activated or active bentonite

Since natural sodium bentonite is less common than calcium bentonite, it is considerably more expensive. Calcium bentonite can however be converted into sodium bentonite by exchanging the ions. This can be undertaken naturally by adding sodium carbonate (Na_2CO_3) or through a technical process. The process (Fig. 2.11) is called *activation* and bentonite produced in this way is called active bentonite [7].

Where $C_{excavation}$ is a supplement factor to the excavation surface area for the injection into the surrounding ground, $F_{borehole}$ the surface area of the excavated cross-section and $L_{comparative}$ is the length of the comparative distance (e.g. 500 m), for which the supplement to the excavation surface area was determined.

Correspondingly, the pumping rate $Q_{pipe\ string}$ (in m^3/min) according to advance rate $v_{advance}$ is

$$Q_{pipe\ string} = V_{pipe\ string} v_{advance} \quad (7.28)$$

In these equations,

- $V_{machine}$ is the initial suspension quantity injected from the tunnelling machine (in m^3/m)
- $V_{pipe\ string}$ is the subsequent suspension quantity injected from the pipe string (in m^3/m)
- $V_{annular\ gap}$ is the annular gap volume (in m^3/m)
- $V_{extra\ suspension}$ is the extra suspension volume from the machine (in m^3/m)
- $OD_{borehole} = OD_{machine} + l_{annular\ gap}$ the outside diameter of the bored hole (in m)
- OD_{pipe} is the outside diameter of the jacked pipes (in m)
- s is the penetration depth (in m)
- $C_{porosity}$ is the factor for the porosity in soil according to Table 7.12
- $C_{joint\ volume}$ is the factor for the joint volume in rock according to Table 7.13.
- $V_{advance}$ is the advance rate (in m/min)
- d_w is the effective grain diameter (generally assumed equal to d_{10} , i.e. the grain size where 10 % by weight passes the sieve; in mm)
- $2a$ is the joint opening width (in mm)
- Δp is the pressure difference between the start and the end of the penetration depth (in N/m^2 ; typical values $\approx 0.1\text{--}0.3\text{ bar} = (1\text{--}3) \times 10^4\text{ N/m}^2$)
- τ_F is the (static) yield point (in N/m^2)
- $C_{excavation}$ the supplement factor for the suspension injected into the surrounding ground (in m^3)
- $F_{borehole}$ the developed area of the excavated section (in m^2)
- $L_{comparative}$ the length of the comparative distance (here 500 m) for the supplement to the casing surface area (in m)

7.7 Time-dependant loss volumes

The loss of lubrication bentonite into the surrounding ground and the reduction to the extent of destruction of the lubricating film occur dependant on time. Any exact calculation of these effects is however difficult. For example, there is no reliable information about the breakdown of a lubrication bentonite with time as a function, of the chemical composition of the water, which could be used in such a calculation. The calculation of the extra suspension quantity given above covers the normal loss with time, also taking into account that a certain time is required for the further advance. The sizing of the extra suspension quantity is thus indirectly dependant on time; longer stoppages are not taken into account.

During longer stoppages (some days), it is recommended to maintain the bentonite lubricating film from time to time with regular injections. After regular stoppages, such as overnight or at weekends, it is recommended to run the lubrication system again before restarting the advance in order to reactivate the lubricating film.

7.8 Lubrication strategies

The objective of lubrication is to reduce the skin friction or control the required jacking force by maintaining an optimal support and lubrication effect in the annular gap. If the jacking force is as low as possible, the pipe can be jacked in the most favourable case from the main jacking station in the launching shaft alone without any need for intermediate jacking stations (interjacks). This can achieve high (net) advance rates.

The term lubrication strategy covers all measures, constraints and considerations, which determine the selection of a lubrication cycle, i.e. all settings for the injection of lubricant through the individual valves or injection nozzles of the lubrication station in the pipe string and the tunnelling machine.

7.8.1 Interval-controlled systems

The lubrication cycle describes the official opening times of the injection valves or connections of the lubrication station in the machine and pipe string taking into account the sequence of the lubrication station in the control system.

In an interval-controlled system, it is generally possible to configure a normal and an extra cycle. The normal cycle provides a control of the lubrication station in the sequence of their installation in the course of the advance, i.e. the lubrication cycle starts at lubrication station 1, and then opens valves 1, 2, and 3 in sequence. Then it changes to lubrication station 2, and again opens all valves one after the other. The larger the driven length is, the longer a complete lubrication cycle lasts. This however also means that with high advance rate in certain ground areas, particularly the tunnelling machine can be supplied with little lubricant. Areas near the shaft are mostly oversupplied since the largest number of lubrication station have been driven through here (Fig. 7.29).

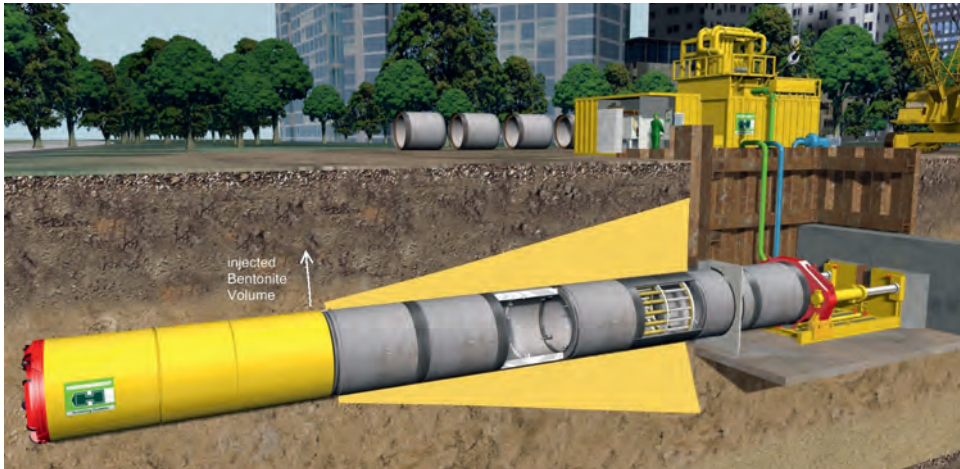


Fig. 7.29 Uneven distribution of injected bentonite over the length of the drive when only normal cycle is used. (Source: Herrenknecht AG).

This effect can be prevented by using the extra cycle, which after switching to each lubrication station switches to the lubrication station in the tunnelling machine again, i.e. after supplying lubrication station 2 in the pipe string, lubrication station in the machine is supplied, then lubrication station 3 in the pipe string etc. This scheme can be continued for example in the form 1–2–1–3–1–4–1–5–1–6. Use of the extra cycle ensures that particularly the important areas in the machine are supplied with sufficient bentonite. Several bentonite stations can also be used in the extra cycle, e.g. 1–2–2–1–2–3–1–2–4–1–2–5–1–2–6–1–2, in order to prefer supply to larger areas around the tunnelling machine. In this way, the area near the shaft is not overlubricated (Fig. 7.30).

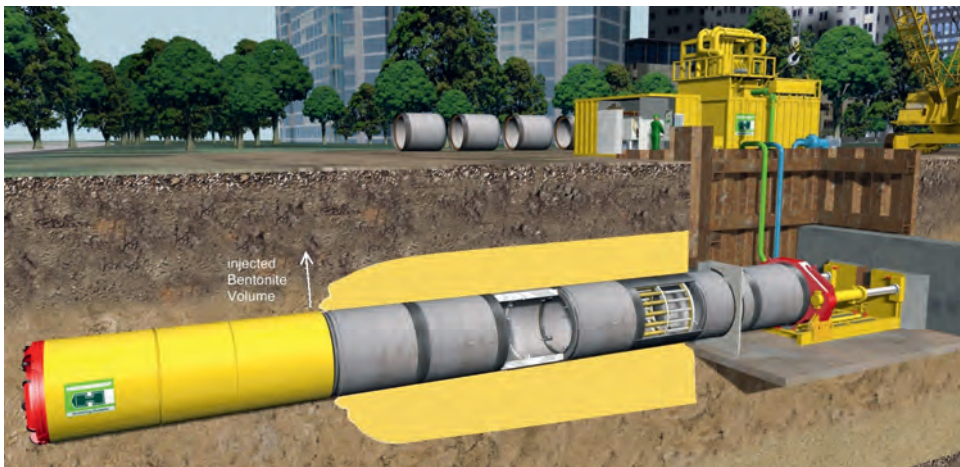


Fig. 7.30 Uniform distribution of injected bentonite over the length of the drive when normal and extra cycles are used. (Source: Herrenknecht AG).

7.8.2 Volume-controlled systems

A further development of bentonite systems is the so-called volume-controlled systems. These enable more targeted and thus simpler and more efficient injection of bentonite along the tunnel drive. This permits a reaction to differences on a specific route such as individual zones in gravel (Fig. 7.31). Each bentonite station, which passes through this zone, then injects the selected subsequent suspension quantity of extra bentonite suspension.

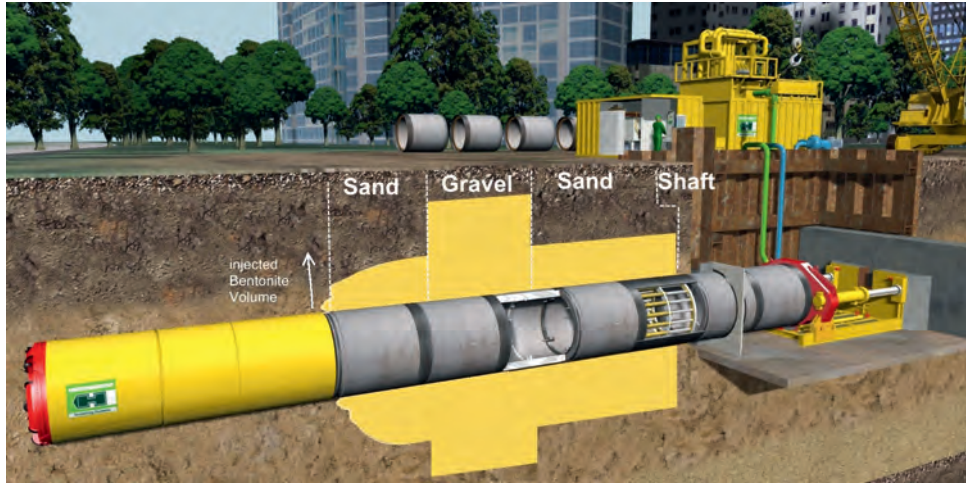


Fig. 7.31 Route-related bentonite distribution with the use of a volume-controlled bentonite lubrication system. (Source: Herrenknecht AG).

A volume-controlled bentonite lubrication system works on the following basic principles:

- The control logic is steered by volume.
- The route is divided into sections each 1 m long. Each section is classified according to the geological conditions and initial and subsequent injection quantities are assigned to the sections (litres per driven metre and metre of advance).
- The system automatically supplies each section of the route with the specified quantities as the drive advances.
- The initial injection quantities are injected at the first bentonite station.
- At the remaining route sections, the subsequent injection volumes within a route section add up (the specified subsequent injection volume for each driven metre is additional) until a bentonite station reaches this route section and then injects the accumulated bentonite quantity.



Fig. 7.32 Display of the system monitor of a volume-controlled lubrication system. (Source: Herrenknecht AG).

For this volume-controlled way of working, the computer maintains the following data (Fig. 7.32):

- The current drive length or position of the tunnelling machine
- The position of the outlet valves (bentonite stations) relative to the pipe sequence and the route
- The stroke lengths of the intermediate jacking stations
- The saved information about the geological conditions, configured suspension quantities and injected quantities for all route sections

The system controls up to four bentonite pumps and displays the associated pressure and flow data graphically.

7.8.3 Lubrication strategies for initial and subsequent injection

The most important area for building up effective bentonite lubrication is where the annular gap is created, directly at the shield or at the latest just behind it at the transition to the jacked pipe. The bentonite injection in this area is described as initial injection (Fig. 7.33). The tasks and objectives of the initial injection are:

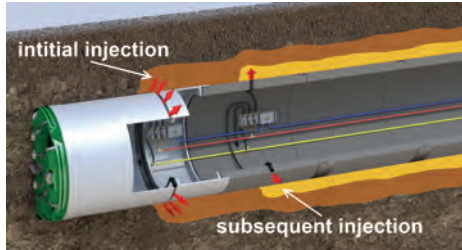


Fig. 7.33 Principle of initial and subsequent injection. (Source: Herrenknecht AG).

- Filling of the annular gap with bentonite suspension, in order to avoid flushing back from the face and cuttings
- To hold excavated particles in suspension through the gel strength of the bentonite suspension
- To support the surrounding ground by applying a support pressure
- To build up a support pressure through the formation of a filter cake or through the penetration of bentonite suspension into the ground until stagnation
- Reduction of skin friction between the undisturbed ground and the jacked pipe

When all these points are fulfilled, the foundations of effective lubrication have been laid.

Since effective lubrication directly at the shield can lead to a great danger of the machine rolling on some projects, the location of the initial injection in these cases is transferred to the first jacked pipe (Fig. 7.34).



Fig. 7.34 Transfer of the initial injection: left normal initial injection, right initial injection in case of great danger of the shield rolling. (Source: Herrenknecht AG).

Other countermeasures against the danger of rolling are tension connections rolling security of the shield with as many concrete pipes as possible or the use of extending anti-roll fins on the shield.

The bentonite quantities injected in the course of the so-called subsequent injection (Fig. 7.33) from the rest of the pipe string serve to compensate any losses of lubricant, which occur in the course of the drive due to washing out or loss into the ground or changing of the suspension properties over the course of the drive due to decomposition, reduction or loss of the yield point or the viscosity etc.

Both the area of the machine (initial injection) and the rest of the pipe string (subsequent injection) have to be supplied with bentonite suspension. The priority is the initial injection.

The supply for initial injection must always be ensured, under all circumstances and in sufficient quantity. For this purpose a separate lubricant supply (separate from the supply to the lubrication points in the following pipe string) is to be provided.

The use of a lubricating ring is very suitable to achieve uniform and homogeneous distribution of the lubricant around the perimeter of the machine or the pipe string. The advantage of this injection system is that the lubricant can be injected into the annular gap and the surrounding ground in sufficient quantity and around the entire perimeter under a moderate injection pressure.

7.8.4 Special lubrication strategies with Direct Pipe® and related processes

With the Direct-Pipe® process, on smaller pipe jacks and for special applications, it can occur that no injection connections can be placed along the pipe string. The reason for this is either that the casing of the product pipe cannot be damaged (Direct Pipe®), or that the pipe diameter is so small that either no installation of lubrication points is generally possible or removal of the lubrication points after the completion of jacking would not be possible.

In this case, the entire bentonite lubrication has to be covered by the initial injection and cannot be topped up. This poses increased requirements for the quality of the products used as well as the jacking technology. Since in such cases larger overcuts are used and the entire bentonite quantity is more or less injected at one location, the use of a bentonite lubricating ring or special large-area bentonite injection boxes is to be recommended.

Order Form

Quantity	Order-No.:	Title	Price* €
	978-3-433-03137-7	Bentonite Handbook	69,-
	909538	Publishing Index Ernst & Sohn 2016/2017	for free
	2534	Free sample issue of the journal <i>geotechnik</i>	for free
	please tick	Monthly email-Newsletter	for free

Delivery- and Invoice address: ☐private ☐business

Company			
Contact Person			Telephone
VAT-ID No.			Fax
Street//No.			Email
Country		ZIP-Code	Location

We guarantee you the right to revoke this order within two weeks. Please mail to Verlag Ernst & Sohn, Wiley-VCH, Boschstr. 12, D-69469 Weinheim.

Wilhelm Ernst & Sohn
Verlag für Architektur und
technische Wissenschaften
GmbH & Co. KG
Rotherstraße 21, 10245 Berlin
Germany
www.ernst-und-sohn.de



Date

Signature

*In EU countries the local VAT is effective for books and journals. Postage will be charged. Whilst every effort is made to ensure that the contents of this leaflet are accurate, all information is subject to change without notice. Our standard terms and delivery conditions apply. Prices are subject to change without notice.

Date of information: Sep 2016 (homepage sample chapter)