Preface

In 2019, the first part of the Compendium Deep Foundation formed the basis of a new series of books that aims to address the increased demands on deep foundation products, and the growing complexity of the process and machine technology in deep foundation engineering. Knowledge of the various deep foundation processes and the relevant machinery and equipment is one of the most important basic requirements to be successful in this field. Now the present "Compendium Deep Foundation, Part 2: Ground Improvement" continues the series of books. It describes current processes, equipment and applications for ground improvement in deep foundation engineering. As a supplement to this, IT solutions for use in ground improvement are presented. Particularly in the field of digital aids, there have been enormous advances in development in recent years. These are far from complete and also offer a huge potential for innovation in the future.

As in part 1 of the Compendium, which deals with drilling processes, the same applies for this part 2: we do not want this book to compete with literature which, although likewise deals with the construction of geotechnical structures, goes deeper into the dimensioning rather than the execution of construction work. It is rather intended to supplement them and answer questions about the construction processes and the equipment required. The Compendium should thus be of use for designers and contractors, as well as for newcomers to deep foundation engineering as a reference work and assist in the daily work on the construction site. The Compendium does not claim to be comprehensive; it reflects the current state of the art in the chosen subject areas. Thus, in some chapters, the naming and description of special processes has been omitted. Additionally, there are further processes that can be assigned to ground improvement, but which are not dealt with in this Compendium. These processes are referred to at the beginning of the Compendium.

Our special thanks go to the management of Liebherr-Werk Nenzing GmbH. During the compilation of the first part, it was already clear how much time and costs such a book would involve. Nevertheless, we received full support and were thus able to successfully complete the second part of the Compendium.

Many thanks are, of course, also due to all those involved in the production of this book. Firstly, the employees of Liebherr-Werk Nenzing GmbH from the departments of technical design, product management, marketing and system development should be mentioned. They assisted the authors above all in the technical details of the machinery. The employees in the marketing department with great motivation and meticulousness produced the high-quality renderings, which give the Compendium its special character. They also gave the book its final touch through valuable advice and professional editing.

The numerous clear illustrations in this Compendium are intended to aid understanding. Our thanks for these are due to the team at kom DESIGN · 1 GmbH, who was responsible for the illustrations, graphical layout and overall preparation of the book.

We also thank Adam Zehentner for numerous illustrations that he compiled with high technical expertise and great attention to detail.

As in part 1, numerous suppliers and customers of Liebherr-Werk Nenzing GmbH were also very helpful in part 2. They supported the two authors by patiently and unselfishly providing many tool models, photos and important information. In particular, help in this regard came from the following companies and persons: BSP, EMDE, Eurodrill, GMB, Karl Rainer Massarsch, MENARD, Obermann, Robl, STRABAG, terra infrastructure, TEC Systems and Vibro Services.

We also thank all those not mentioned here but who have also made their contribution to the success of the book.

With this part 2 of the Compendium, we hope to contribute to the dissemination of knowledge about deep foundation engineering and wish all friends of this field, and those who will hopefully become friends of it, much success and much pleasure in reading this book.

Nenzing, November 2023

Peter Quasthoff
Markus Schönit

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5 Cutter soil mixing

The previously described soil mixing processes have been in development since the 1950s [14]. One considerably younger soil mixing process is cutter soil mixing, which was derived from diaphragm wall cutting technology at the start of the 2000s [43].

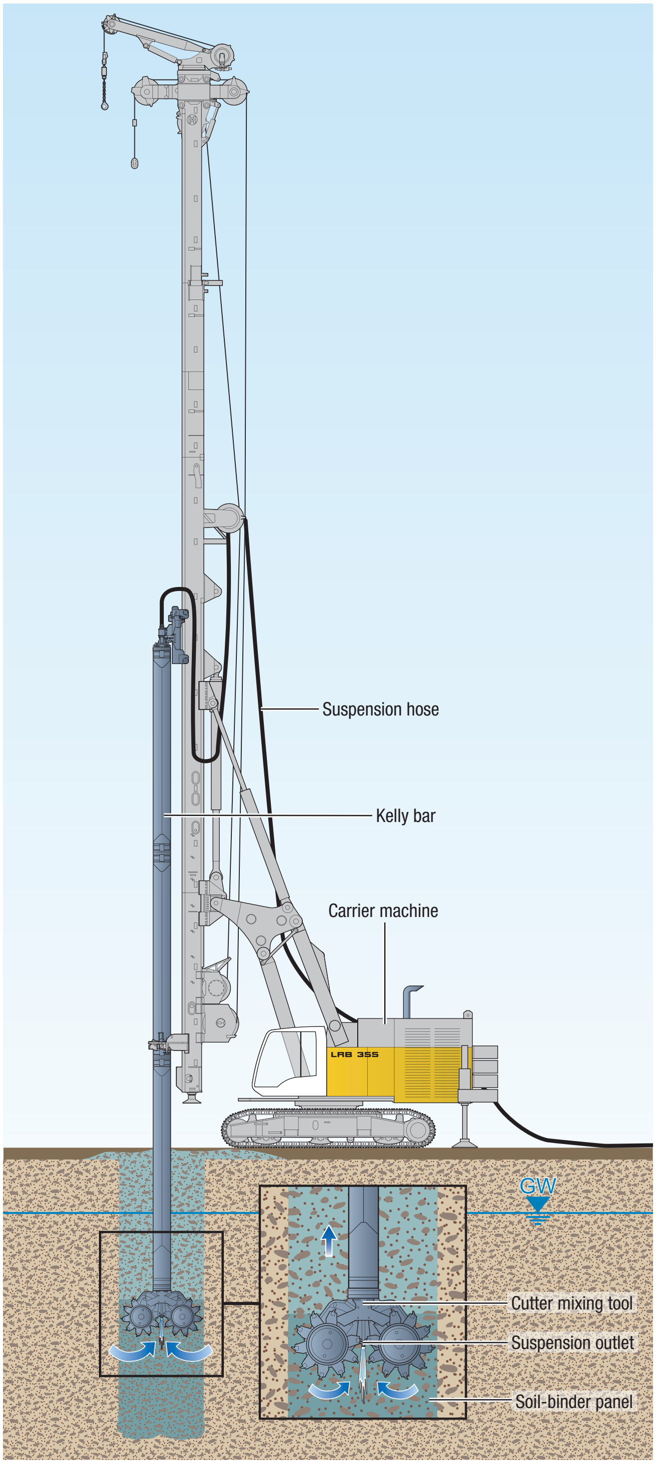


Fig. 5.1: Process principle of cutter soil mixing

This hybrid technique combines the existing experiences of soil mixing with the newest experiences of cutting technology for the excavation of diaphragm walls.

In this process, the soil is loosened by rotating cutter wheels and mixed with self-hardening binder suspension. The binders used are predominantly cement or cement-bentonite mixed to a suspension with water, plus additional materials (fly ash) or admixtures (plasticiser, retarder) when necessary.

The principle of cutter soil mixing is that the soil matrix is mechanically broken by the cutter wheels, which are fitted with cutting teeth, and the soil is mixed with the binder suspension in order to achieve a homogeneous soil mortar. The main difference from the previously described wet and dry mixing processes is that the mixing tools rotate around a horizontal axis. This means that cutter soil mixing produces soil mixing elements with a rectangular cross-section.

5.1 Process principle

The mixing equipment for cutter soil mixing consists of a Kelly bar and a mixing tool. The mixing tool is a cutter with cutter wheels driven by hydraulic motors mounted inside the roller-shaped cutter wheels. The mixing tool, also called a cutter mixing head, is fitted to the rectangular Kelly bar.

Soil mixing elements are formed in the following working steps, see Fig. 5.2.

To contain excess suspension, it is advisable to excavate a retaining trench before the start of cutting work.

The mixing equipment is positioned in the wall axis and the cutter mixing head is lowered steadily into the soil. The prevailing soil matrix is broken up mechanically by the cutter wheels. Binder suspension is injected through an injection pipe fitted between the cutter wheels from the start. Due to the counter-rotation of the cutter wheels, an initial partial mixing with the thus liquidised soil is achieved, and the material is conveyed over the cutter mixing head.

The direction of rotation of the cutter wheels can be changed but they should preferably always counterrotate to ensure uniform mixing. The scraper plates mounted between the cutter wheels have the function of scraping soil from the wheels in order to improve the mixing process in particularly cohesive soil. The counterrotating cutting teeth ensure so-called compulsory mixing.

After the final depth has been reached, mixing of the soil continues as the cutter mixing head is withdrawn. During extraction of the tool, the soil-binder mixture above the cutter mixing head is conveyed under the cutter mixing head by the rotating cutter wheels. With continued defined addition of binder, the mixed soil mortar is mixed through for a second time, creating a homogeneous soil-mortar panel.

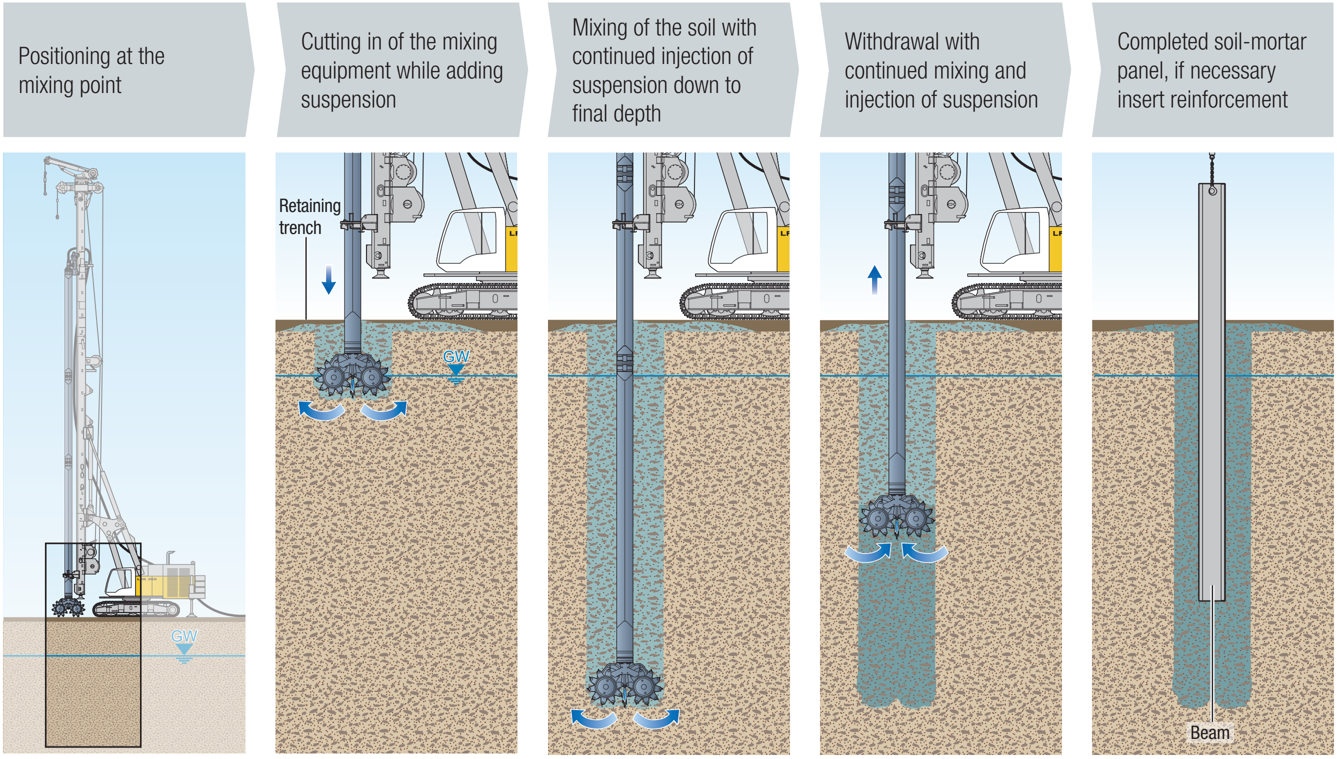


Fig. 5.2: Procedure for cutter soil mixing

The soil-binder mixture remains as a plastic soil mass until the end of the mixing process so that it is possible to lower and extract the cutter mixing head.

Repetition of the cutter soil mixing process and overcutting of adjacent panels produces wall elements of mixed soil. The cross-sectional size of the panels in a soil mixing element corresponds to the dimensions (length, width) of the deployed cutter mixing head with its cutter wheels. The width of the cutter mixing head determines the wall thickness. Typical wall thicknesses produced by cutter soil mixing vary between 450 and 1,200 mm.

It is not necessary to construct a guide wall, as is required for a diaphragm wall. In many cases, it can however be necessary to use a previously prepared guide in the form of a cutting template in order to ensure exact positioning of the cutter mixing head. This can be made of cast-in-place concrete as for bored piles or in the form of heavy steel beams, see Fig. 5.3. Such a cutting template is mostly used where the width of the working space is restricted or next to existing buildings.

Cutter soil mixing is an economic process used in the production of retaining and cut-off walls as a ground improvement measure or as a foundation element, for example, as a single trench panel element (barrette pile), since the soil can be used as a construction material and scarcely any soil has to be removed.

The carrier machines used can reach great depths and rapid progress is possible with this process so that daily rates of up to 300 m² can be achieved.

Fig. 5.3: Cutting guides of steel beams (a) and of cast-in-place concrete (b)

It is possible to check and control the verticality and positional accuracy of the trench during the mixing process. For this purpose, the mixing equipment is fitted with two inclinometers to measure deviations in two axes. Any deviations are displayed on a screen in the operator's cabin and can be immediately detected and corrected. Since it is possible to monitor the inclination and thanks to the counterrotation of the cutter wheels, wall elements can be constructed with great precision.

Due to the slender construction of the cutter mixing head housing, the rotating cutter wheels are always in immediate contact with the surrounding soil, which is beneficial for thorough mixing in the penetration and withdrawal phases. This means that the cutter wheels can cut themselves out, which reduces the danger of jamming during withdrawal and demands less lifting force.

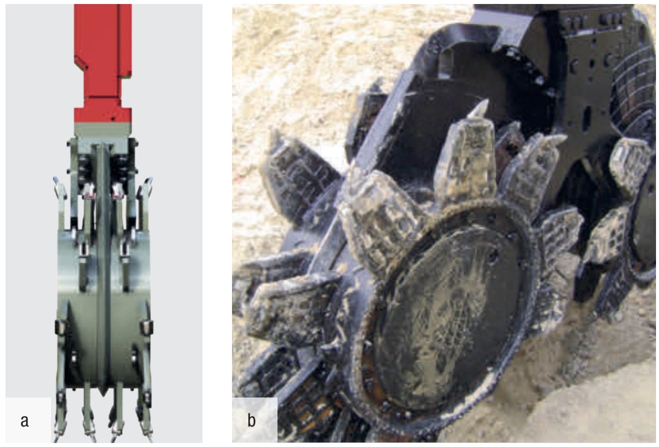


Fig. 5.4: Cutter mixing head, schematic side view (a) and cutting into the soil (b)

5.2 Characteristics and application limits

5.2.1 Characteristics

– High productivity
– No guide wall necessary
– Variable arrangement of the panels
– Rapid and flexible progress
– Vibration-free
– Little effect on the environment
– Can be used in contaminated soil (little soil removal)
– Good verticality of the panels
– No aggregates needed (e.g. sand, gravel)

Fig. 5.5: LRB 355 with cutter soil mixing equipment

The strength of the soil mixing panels that can be achieved depends on the type and quantity of binder injected and the soil properties. Above all, when the soil properties are unknown, trial panels should be constructed in advance to optimise the formula of the suspension. As a rough guide, the following binder suspension formulas and uniaxial compressive strengths can be assumed:

Tab. 5.1: Examples of suspension formulas [99]

	Cut-off wall	**Retaining wall/foundation element**
Cement	200 – 450 kg/m³ suspension	600 – 1200 kg/m³ suspension
Bentonite	15 – 30 kg/m³ suspension	15 – 30 kg/m³ suspension
w/c ratio	2.0 – 4.0	0.5 – 1.0

Tab. 5.2: Examples of characteristic values of soil mixing panels

	Cut-off wall	**Retaining wall/foundation element**
Compressive strength	0.5 – 1.5 MN/m²	2 – 12 MN/m²
Permeability	< 1 x 10^{-8} m/s	–

Fig. 5.6: Two LRB 155 during cutter soil mixing

If required, reinforcement elements such as steel beams or sheet piles can be inserted in the fresh soil mixing panels, see Fig. 5.8. This produces a structurally effective retaining system.

Fig. 5.7: Cutter soil mixing with LRB 255

Fig. 5.8: Steel beam as a reinforcement element: insertion (a) in a structurally effective retaining wall (b)

5.2.2 Application limits

The limits to application are posed both by the machinery used and the prevailing ground conditions.

Suitable soils for cutter soil mixing are, in particular, loosely to medium densely stratified sand-gravel mixtures. Silty sands are also well suited. The cutting technology can however also loosen and mix densely stratified non-cohesive and very stiff cohesive soils, as well as coarse-grained gravels and crushed stones. Application is also possible in contaminated soils as long as the contents of the soil do not affect hydration of the binder, in which case longer mixing times and correspondingly larger quantities of binder have to be expected. In general, appropriate qualification tests are necessary to determine the mixing parameters for the construction of soil mixing panels in contaminated soils.

5.3 Machinery with equipment

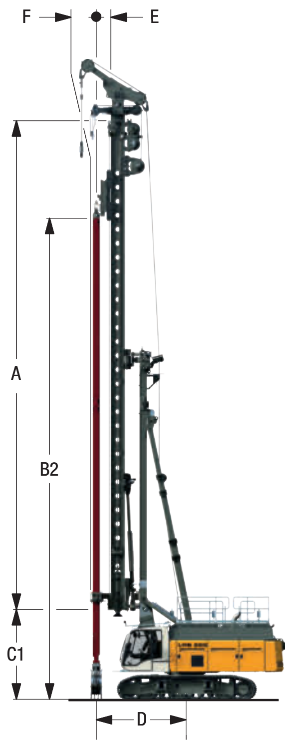
5.3.1 Carrier machines

Carrier machines of the LRB and LB series are used in cutter soil mixing. The entire mixing equipment consisting of a rectangular Kelly bar and the cutter mixing head is mounted to the leader through upper and lower guides. The upper and lower guides form the interfaces between carrier machine and mixing equipment and are also described as upper Kelly guide and lower Kelly guide.

5.3.1.1 With top drive (TD)

In the TD (Top Drive) version, the upper end of the Kelly bar terminates at the Kelly head, which is flanged rigidly to the Kelly bar. The Kelly head is fixed with a pin through a socket connection at the upper Kelly guide. The upper Kelly guide is connected to the carrier machine's leader through the crowd sledge. The maximum effective length and thus also the mixing depth depend on the length of the Kelly bar segments, which can be installed up to the upper Kelly guide, and consequently also on the length of the leader. Since the Kelly bar segments are only available in standardised lengths and can only be installed accordingly, the maximum effective length cannot be fully exploited in every configuration. For this reason, the usable length is given for each largest possible Kelly bar configuration.

With top drive, the lower Kelly guide can be mounted as a fixed or a rotating version. While both fixed and rotating Kelly guides can be used with carrier machines of the LRB series, only the rotating version is used with carrier machines with rigid leader which cannot be rotated (LB series, LRB 23 and LRB 355).



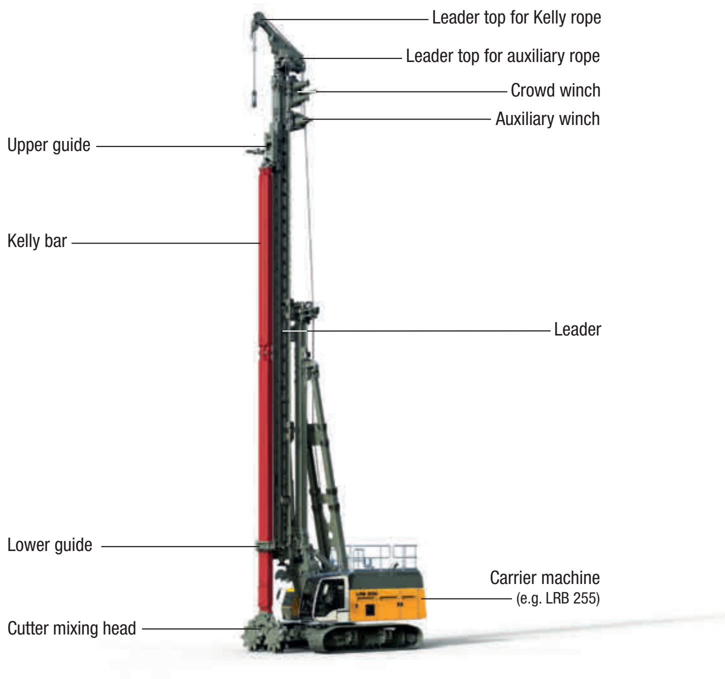
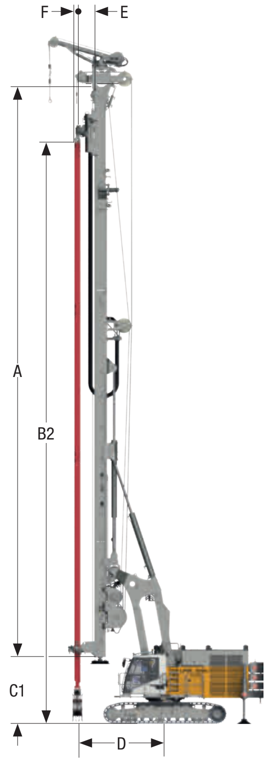


Fig. 5.9: Carrier machine of the LRB series with top drive (TD) and fixed Kelly guide

Tab. 5.3: Technical data of LRB series with top drive (TD) and fixed Kelly guide

Machine	Leader length [m] **A** =	Max. effective length [m] **B1** = above ground	Usable length [m] **B2** = above ground	Vertical leader adjustment [m] **C1** = above ground	Distance from rotational axis to mixing axis [mm] **D** =	Distance from mixing axis [mm] **E** = to front edge of leader	**F** = to front edge of lower Kelly guide
LRB 125	12.8	15.2	12.6	5.0	3125	620	260
LRB 125 XL	14.9	17.2	16.6	5.0	3125	620	260
LRB 16	12.8	15.8	12.6	5.0	3125	620	260
LRB 18	14.9	17.7	16.6	5.0	3125	620	260
LRB 155	18.2/21.2/ 24.2	18.6/21.6/ 24.6	17.6/20.6/ 23.6	3.4	3595	620	260
LRB 255	21.2/24.2 27.2/30.2	21.0/24.0/ 27.0/30.0	20.6/23.6/ 26.6/29.6	3.4	3845	620	260



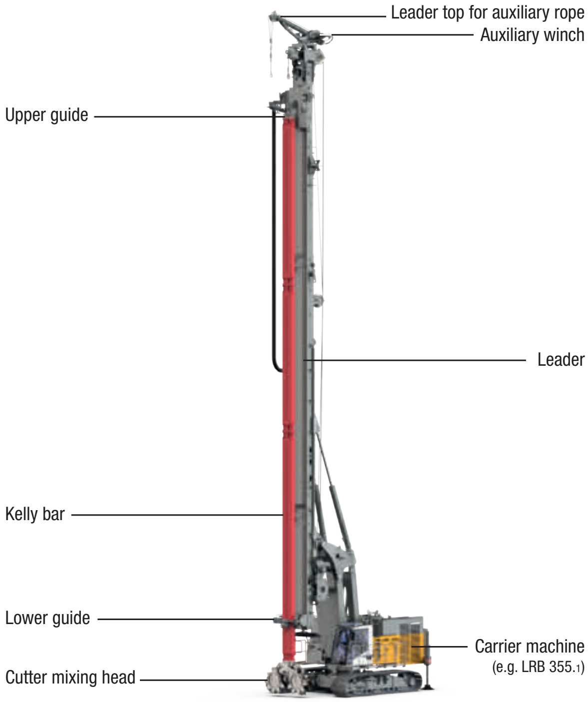


Fig. 5.10: Carrier machine of the LB series, LRB 23 und LRB 355 with top drive (TD) and rotating Kelly guide

Tab. 5.4: Technical data of LB series, LRB 23 und LRB 355 with top drive (TD) and rotating Kelly guide

Machine	**Leader length [m]** **A** =	**Max. effective length [m]** **B1** = above ground	**Usable length [m]** **B2** = above ground	**Vertical leader adjustment [m]** **C1** = above ground	**Distance from rotational axis to mixing axis [mm]** **D** =	**Distance from mixing axis [mm]** **E** = to front edge of leader	**F** = to front edge of lower Kelly guide
LB 35	21.4/23.4	20.5/22.5	19.6/21.6	–	3910	810	460
LB 45	21.4/23.4	20.6/22.6	19.6/21.6	–	3910	810	460
LB 55	26.0/29.0	24.0/27.0	23.6/26.6	–	4210	810	460
LRB 23	21.9	23.6	22.6	3.0	3410	810	460
LRB 355.1	22.2/27.2	22.7/27.7	22.6/27.6	3.2	4110	810	460

Fig. 5.11: LRB 255 with cutter soil mixing equipment

Fig. 5.12: Cutter soil mixing with LRB 155

5.3.1.2 With hollowed top guide drive (HTGD)

In the HTGD (Hollowed Top Guide Drive) version, the upper end of the Kelly bar is not connected with the upper Kelly guide through a Kelly head. The upper Kelly guide is passed through and is provided with an additional holding device. An extended Kelly bar is pushed through the upper Kelly guide and clamped. In the HTGD version, the Kelly bar projects above the leader head of the carrier machine and thus enables greater effective lengths and therefore deeper mixing depths. With this version also, the Kelly bar segments are installed in standardised lengths so that the full effective length cannot always be exploited. For this reason, the usable length is given for each largest possible Kelly bar configuration.

In the HTGD version, a fixed guide with a clamping device is used as the lower Kelly guide. Therefore, application of the HTGD version is restricted to carrier machines of the LRB series with a leader that can be rotated.

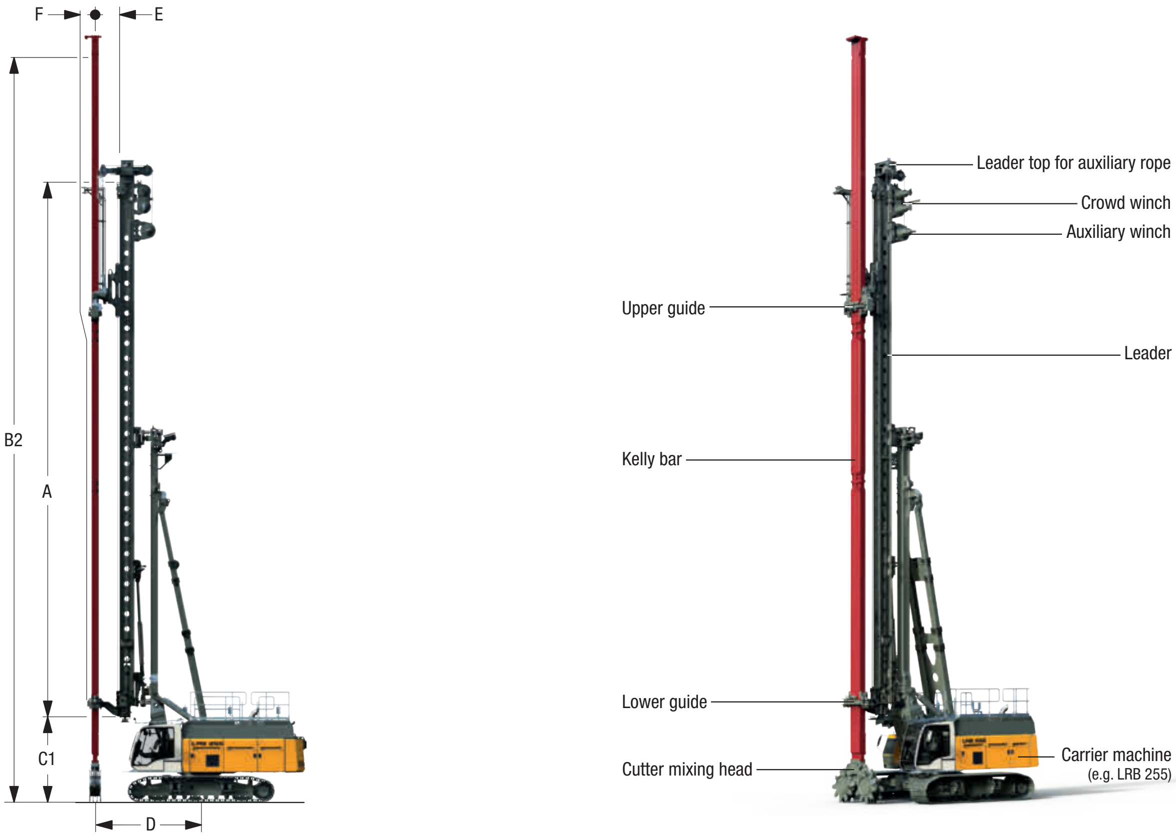


Fig. 5.13: Carrier machine of the LRB series with hollowed top guide drive (HTGD) and clamping device

Tab. 5.5: Technical data of LRB series with hollowed top guide drive (HTGD) and clamping device

Machine	Leader length [m] A =	Max. effective length [m] B1 = above ground	Usable length [m] B2 = above ground	Vertical leader adjustment [m] C1 = above ground	Distance from rotational axis to mixing axis [mm] D =	Distance from mixing axis [mm] E = to front edge of leader	F = to front edge of lower Kelly guide
LRB 155	18.2/21.2/24.2	28.8/31.8/–	28.7/31.7/–	3.0	3945	970	330
LRB 255	21.2/24.2/27.2/ 30.2	31.2/34.2/ 37.2/40.2	29.7/33.7/ 36.7/39.7	3.0	4195	970	330

5.3.2 Kelly bars and Kelly guides

5.3.2.1 Kelly bars

The Kelly bars used in cutter soil mixing differ completely from those used in Kelly drilling. The Kelly bar is generally made as a mono Kelly bar, i.e. not telescopic.

The rectangular Kelly bar specially developed for cutter soil mixing comprises the base element, the lower Kelly bar and depending on the chosen configuration, several elements installed one above another to form the intermediate Kelly bar. In the TD version, the Kelly bar has a Kelly head at the top. In the HTGD version, an upper Kelly bar is used instead of the Kelly head. The individual Kelly bar segments are connected firmly and rigidly to each other at their flat end surfaces. This is absolutely necessary since high bending moments can occur in the mounted Kelly bar, especially during assembly and withdrawal.

Before starting work, the Kelly bar is assembled for the appropriate depth depending on the machine configuration being used. The lower Kelly bar is designed with a fixed length of 11 m, while the intermediate Kelly bar can be installed in various lengths between 3 and 10 m. With the HTGD version, the upper Kelly bar also has a fixed length of about 12 m.

All supply hoses and cables (hydraulic, electrical and suspension hoses) run protected inside the Kelly bar to the cutter mixing head, see Fig. 5.16. Accordingly, when a Kelly is extended the supply hoses and cables also have to be extended.

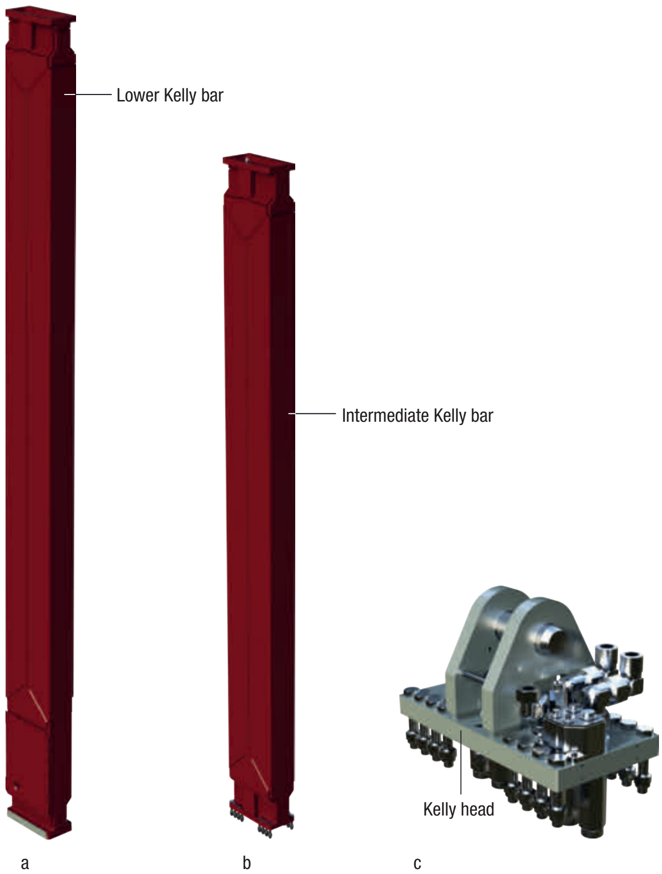


Fig. 5.14: Kelly bar consisting of lower Kelly bar (a), intermediate Kelly bar (b) and Kelly head (c)

Fig. 5.15: Kelly bar und cutter mixing head before lifting

Fig. 5.16: Kelly bar with internal supply hoses

Fig. 5.17: LRB 255 with clamping device

Fig. 5.18: LRB 355 with cutter soil mixing equipment

5.3.2.2 Kelly guides

The upper and the lower Kelly guides form the interface between leader and Kelly bar.

Depending on the version used, the upper Kelly guide is connected to the Kelly bar and positively locked (with pins) in the top drive version, or clamped firmly in the case of the hollowed top guide drive.

This makes it possible to transfer crowd and pull forces from the carrier machine to the Kelly bar and thus also to the cutter mixing head. The upper and lower Kelly guides also prevent the cutter mixing head deviating and thus ensure accurate working.

In the TD version, two different types of Kelly guide are distinguished. The fixed version is preferred with rotating leaders, or when the mixing equipment is not required to rotate during construction.

Rotation of the mixing equipment, for example in order to carry out corner connections, can usually be carried out by means of the leader rotation capability of the carrier machine. With LRB series carrier machines, the leader can be rotated +/- 90°. In this case, the fixed version of the lower Kelly guide can be used, see Fig. 5.19.

Two exceptions to this are the carrier machines LRB 23 and LRB 355, which have no leader rotation capability.

In case rotation of the leader is not possible or the rotating range of the leader cannot by exhausted, the lower Kelly guide is equipped with a special hydraulic rotating device to rotate the mixing equipment. With this rotation capability, the Kelly bar, which is fixed with clamping bars, can be rotated by +/- 110°. In this case, the Kelly head is supported permitting rotation at the pin of the upper Kelly guide and the lower Kelly guide is directly fixed to the leader through an adapter, see Fig. 5.20.

In the HTGD version, the lower Kelly guide is designed as fixed version. The upper and lower Kelly guides are provided with clamps, which means the Kelly bar can be reclamped without problems. With this version, rotation of the entire mixing equipment is only possible when a carrier machine with a rotating leader is used, see Fig. 5.21.

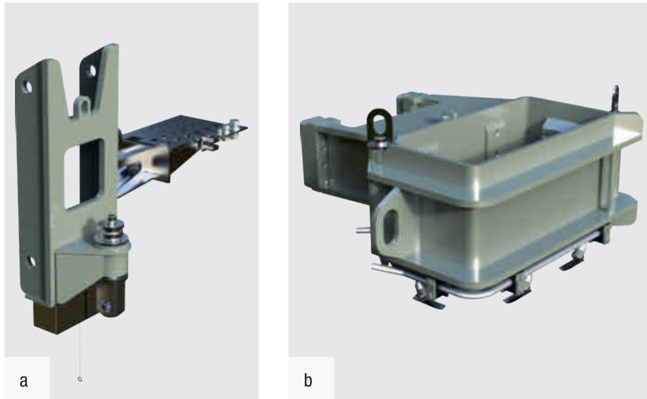


Fig. 5.19: Fixed Kelly guide (TD): upper guide (a) and lower guide (b)

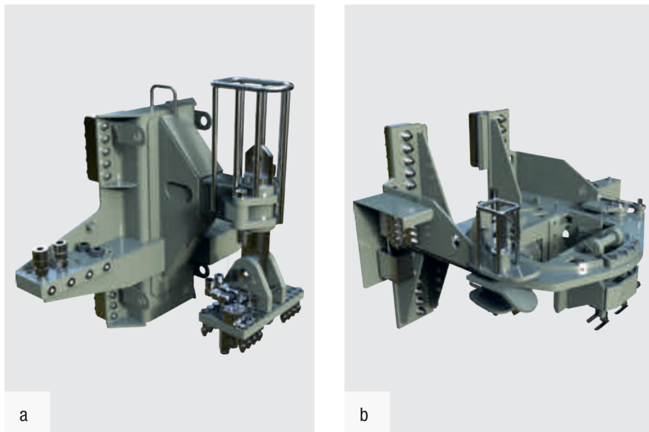


Fig. 5.20: Rotating Kelly guide (TD): upper guide (a) and lower guide (b)

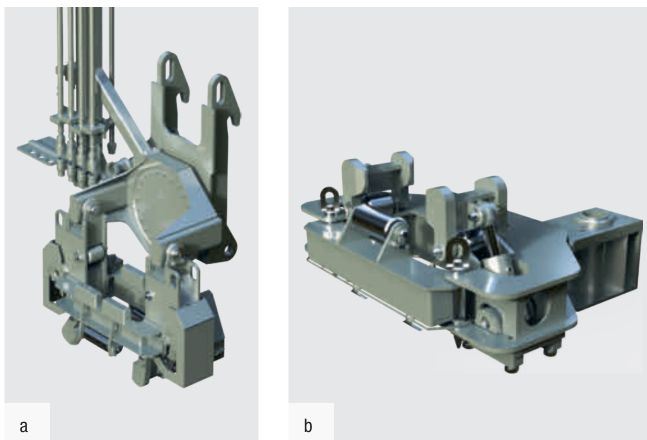


Fig. 5.21: Fixed Kelly guide with clamping device (HTGD): upper guide (a) and lower guide (b)

5.3.2.3 Configurations

The individual Kelly bars are equipped for cutter soil mixing with the appropriate Kelly guides depending on requirements and the carrier machine used. The following systems can be used, also shown in Fig. 5.23:

- Kelly bar with top drive (TD) and fixed Kelly guide
- Kelly bar with top drive (TD) and rotating Kelly guide
- Kelly bar with hollowed top guide drive (HTGD) and fixed Kelly guide with clamping devices

The following Tab. 5.6 shows the scope of application of the various Kelly guides for carrier machines of the LRB and LB series used with top drive (TD) or hollowed top guide drive (HTGD).

Fig. 5.22: LRB 255 with TD version, fixed (a), with HTGD version (b)

a b c

Fig. 5.23: Configurations: TD version, fixed (a), TD version, rotating (b) and HTGD version with clamping device (c)

Tab. 5.6: Attachment possibilities for various Kelly guides

Type	Fixed Kelly guide	Rotating Kelly guide	Kelly guide with clamping device
TD	LRB 125, LRB 125 XL, LRB 16, LRB 18, LRB 155, LRB 255	LRB 125, LRB 125 XL, LRB 16, LRB 18, LRB 155, LRB 23, LRB 255, LRB 355.1, LB 35, LB 45, LB 55	
HTGD			LRB 155, LRB 255

8 Deep compaction with top vibrator

Deep compaction with top vibrator is another form of ground improvement to increase the load-bearing capacity of the prevailing ground for construction purposes.

The properties of the soil are improved by compaction from a top vibrator acting on the piling element, either directly or with addition of extraneous material.

Compaction of non-cohesive (coarse-grained) soils is carried out by **deep compaction**, with **compaction probes** or **beams** being driven into the ground using a **top vibrator**. The compaction results from vertical oscillations generated by the vibrating top vibrator. Waves are propagated into the surrounding soil through the skin and tip of the compaction probe or beam and act on the surrounding soil in the form of shear stresses. The void ratio of the grain structure is reduced under the effect of vibration so that the soil that is suitable for compaction can be redistributed into a soil with higher density. The process of deep compaction with top vibrator, in which compaction probes are vibrated into the soil in order to compact it, was developed in the 1970s as an alternative to vibro-compaction [98] and is regulated in the European standard EN 14731 [35].

On the other hand, cohesive soils and sands with high silt or clay content can be compacted only very poorly by vibration with a compaction probe or a beam, or not at all. The greater the cohesion of the cohesive soil, the less the soil grains can be redistributed and thus compacted.

However, in fine-grained soils, a load-bearing column of gravel, sand or crushed stone can be installed by adding extraneous material. The column increases the stiffness of the soil and thus improves the load-bearing capacity. Improvement of cohesive soils is carried out with deep compaction processes, in which a temporary casing is vibrated into the soil using a top vibrator for the purpose of producing continuous load-bearing gravel columns in order to compact the surrounding soil. This process is called **vibro-replacement.**

Further deep compaction processes have been developed from vibro-replacement with top vibrator over the years; these are processes for the installation of vibro columns, hydraulically bound vibro-replacement columns, geotextile columns and vibro concrete columns, with the intention of making the columns stronger.

The difference between conventional vibro-replacement with coarse-grained extraneous material and hydraulically bound vibro-replacement columns is mainly the type of material added and sometimes also the method of installation. With conventional vibro-replacement, the load-bearing gravel columns are mainly supported by the surrounding soil. In very soft soils with low shear strength, in which no support can be activated to the sides by the surrounding soil, the inner bond of the gravel column can be strengthened by the addition of hydraulic binders or also the use of concrete. The installation of mortared vibro-replacement columns or vibro concrete columns produces foundation elements similar to piles, which can bear comparatively high loads.

Another method of strengthening vibro columns or vibro-replacement columns is to produce geosynthetic-encased columns. In this case the sand or gravel columns are additionally reinforced with the installation of geotextiles around the column. In this way the shear forces of the columns are increased and higher loads can be transferred by the columns without additional deformation.

The processes of producing sand or gravel columns, vibro-replacement columns, hydraulically bound vibro-replacement columns, vibro concrete columns and geosynthetic-encased columns can be carried out both in cohesive and non-cohesive soils. In non-cohesive soils, the displacement effect of casing installation has an additional compaction effect on the surrounding soil.

8.1 Process principle

8.1.1 Mechanical principles of vibration

8.1.1.1 Basic principle

The basic principle of vibration as a construction method is the application of vibration to the soil to be compacted. The vibration is produced by periodic oscillations. These are produced by a top vibrator (also called vibratory hammer or vibratory pile driver), which depending on the construction type can be free-hanging, leader-guided or attached to a hydraulic excavator. The top vibrator generates axial oscillation, which is transferred to the piling element. This is in contrast to the action of vibroflots as described in Chapter 7, which generate horizontal oscillations, see Fig. 8.1.

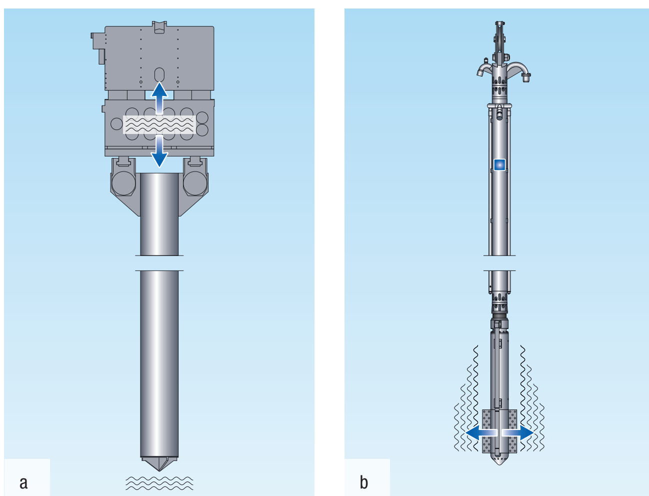


Fig. 8.1: Orientation of oscillations of a top vibrator (a) and of a vibroflot (b)

The piling element is mechanically connected to the top vibrator with a clamp (see Fig. 8.2). This is firmly bolted to the vibrator and can be opened hydraulically in order to introduce the piling element. When the clamp is closed, the exciter block of the vibrator, the clamp and the piling element form a rigid body.

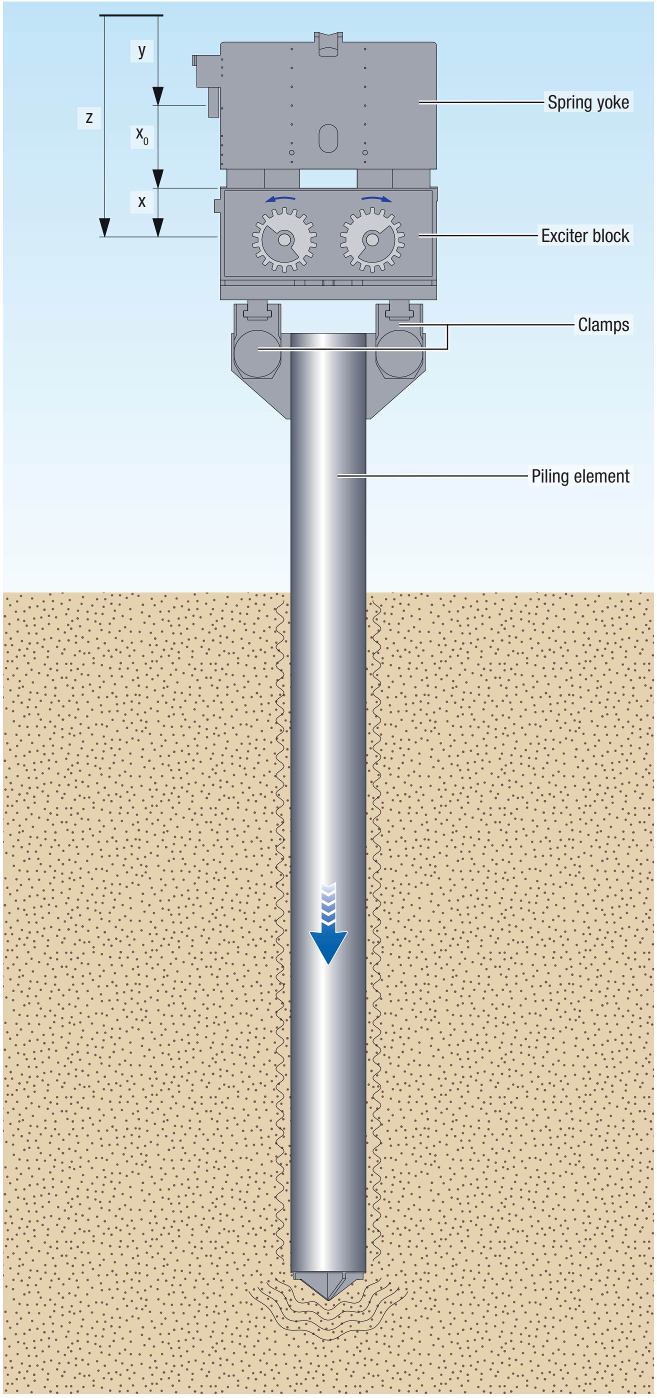


Fig. 8.2: Vibrator-piling element-soil system

This is vibrated by the forces exerted by the vibrator. In a few rare cases, the piling element is directly bolted to the vibrator without a clamp. As soon as the piling element comes into contact with the soil, oscillations from the piling element are transferred into the soil. The grain structure of the soil, which is in immediate contact with the piling element, is changed into a "pseudo-liquid" state, i.e. the friction between the soil grains is considerably reduced [63]. This results in considerably reduced resistance to friction and displacement, which eases the penetration of the piling element, which then penetrates into the soil under its self-weight, the weight of the vibrator and any additional surcharge.

Surcharge for free-hanging vibrators is applied with ballast slabs, which are bolted to the vibrator. When the vibrator is leader-guided, surcharge can be applied by using the crowd system. Vibrators mounted on hydraulic excavators can be loaded using the action of the excavator boom.

8.1.1.2 Generation of oscillation

The oscillation is generated using rotating eccentric masses, which are housed inside the so-called exciter block of the vibrator. The exciter block is mounted to the carrier machine through the so-called spring yoke (also described as a pulling yoke or oscillation isolator). Between the spring yoke and the exciter block are elastomers, which serve to isolate the oscillation. The elastomers behave relatively softly in the range of working frequencies of the vibrator, so that scarcely any oscillation is transferred from the exciter block to the spring yoke. The name "spring yoke" dates back to the first years of vibrator development, when steel springs were used to prevent the propagation of oscillation between the exciter block and the carrier machine.

The eccentric masses are massive steel discs, which have teeth around the perimeter on one side to connect them with the drive. They have considerably less material on one side, so the centre of gravity lies outside their rotational axis. With steel discs, this is achieved by cutting or sometimes also drilling holes, see Fig. 8.3a. Another method of increasing the distance between the centre of gravity and the rotational axis is the use of inserts made of metals with a higher density than steel (for example tungsten), see Fig. 8.3b.

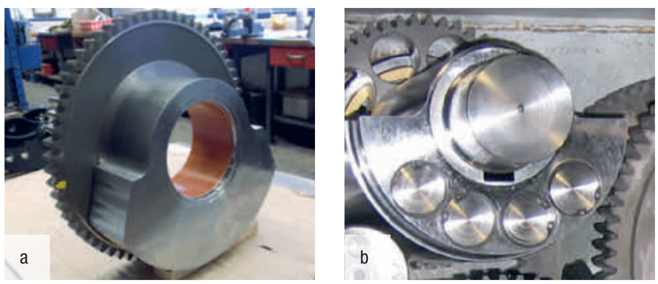


Fig. 8.3: Eccentric mass made of steel (a), with heavy metal inserts (b)

One exception to this type of oscillation generation are so-called resonators. Resonators are top vibrators, which use a mass with linear movement to generate oscillation instead of rotating eccentric masses. This mass is moved up and down hydraulically at a high frequency. Details of oscillation generation with resonators follow in Section 8.3.2.4.

8.1.1.3 Motion of the piling element

For a better understanding of the vibration process, it is helpful to consider the motion of the piling element. First, it is necessary to introduce several path coordinates, as are shown in Fig. 8.2. All the path coordinates are positive in the penetration direction of the piling element, they increase with depth.

The path coordinate x represents the local position of the exciter block. When the vibrator generates oscillations, the piling element moves alternately upward and downward about its rest position due to the harmonic oscillation. The rest point is denoted by x_0. Fig. 8.4 shows an example curve of the local piling element motion for the freely oscillating system. Freely oscillating means that the spring yoke remains in its position, i.e. the vibrator hangs from the carrier machine without any crowd or pulling motion. The periodic up and down motion of the rigid body of exciter block, clamp and piling element can be represented by a sine function. Fig. 8.4 shows this motion for one oscillation period with a continuous line. The magnitudes of the values of x lie in the range of millimetres up to a few centimetres.

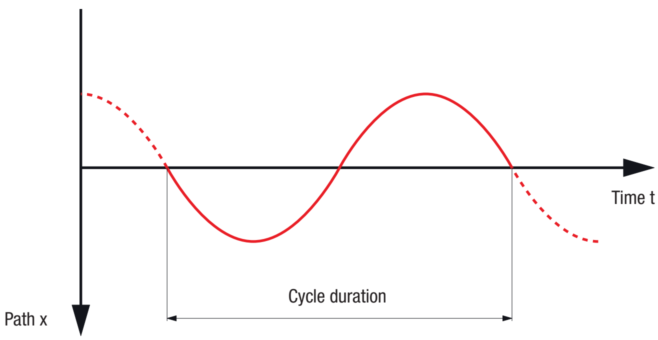


Fig. 8.4: Local motion of the piling element for free-hanging system

Another path coordinate is the path coordinate y. This gives the global position of the exciter block and shows the penetration depth of the piling element. The zero level is normally the working level of the carrier machine. If values are specified for the vibration depth in the planning and execution of vibration works, then these are equivalent to values of the global position y. Fig. 8.5 shows an example of a path-time curve of the global piling element motion while the piling element is vibrated into the soil.

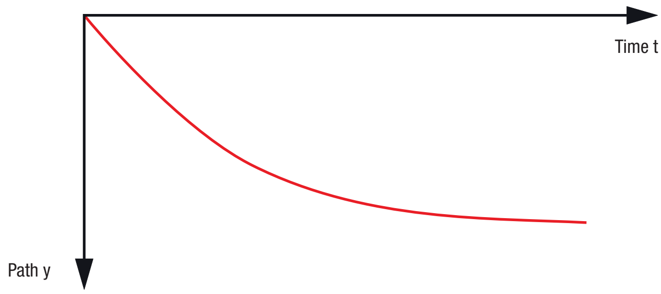


Fig. 8.5: Global motion of the piling element during vibrating in

The path coordinate z gives the absolute position of the exciter block. This is the sum of the local and the global positions:

$$z = x + x_0 + y \quad [\mathrm{m}] \tag{8.1}$$

While a piling element is driven into the soil, the local and global piling element motions are superimposed, resulting in the absolute piling element motion. This means that the vibrator generates oscillations and the exciter block, the clamp and the piling element move up and down periodically. At the same time, a crowd motion is generated by the spring yoke. When

Fig. 8.6: LRB 23 with LV 36

the oscillations transferred into the soil by the piling element sufficiently reduce the friction between the soil grains, this results in a crowd motion due only to the self-weights of the vibrator and the piling element. For this purpose, the hanging of the spring yokes at the carrier machine has to be correspondingly "unlocked", i.e. in the case of a leader-guided vibrator, the crowd sledge is lowered, or in the case of a free-hanging vibrator, the tension rope of the lifting device is loosened and in the case of an excavator-mounted vibrator, the excavator boom is lowered. Moreover, the crowd motion (= global piling element motion) can be supported by applying a surcharge.

Fig. 8.7 shows an excerpt of a typical absolute piling element motion as the object is driven in. This modelling of the piling element motion corresponds to the motion type called slow vibratory pile driving according to [41]. Further details of vibratory pile driving motion types can be found in [80], [84] and [41].

The continuous line in Fig. 8.7 shows the motion curve for one oscillation period, consisting of a downward motion (= penetration) and an upward motion (= extraction) of the piling element. The downward motion of the piling element starts at the upper turning point 0 at time t_0 at position z_0. It ends at the lower turning point 2 at time t_2 and at position z_2. The tip of the piling element is not yet in contact with the soil at the start of the downward motion. It only enters the soil at point 1 (time t_1, position z_1) and deforms and displaces it. When the tip of the piling element reaches the lower turning point 2 (time t_2, position z_2), contact with the soil is lost and the piling element is extracted from the soil again. The upward motion ends at the upper turning point 3 at time t_3 and at the position z_3 and the oscillation period has ended. Then a new downward motion starts, the starting point of which is displaced downward by an irreversible penetration downward. This irreversible penetration corresponds to the difference z_3 - z_0.

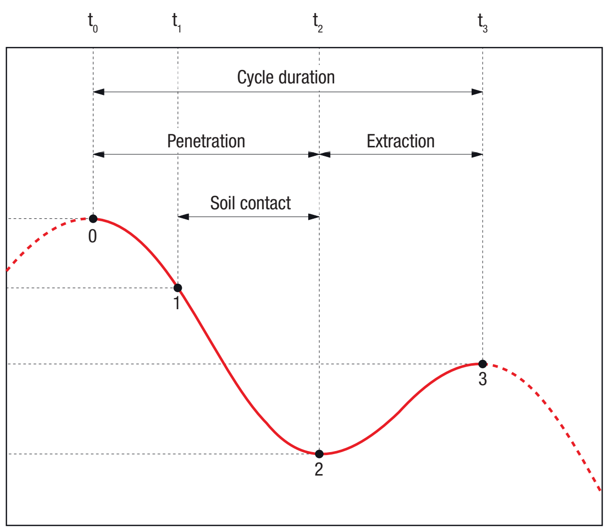


Fig. 8.7: Absolute motion of the piling element during vibrating in

The described simplified model assumption is applicable particularly in non-cohesive soils. In cohesive soils, the tip of the piling element does not always directly lose contact with the soil at the lower turning point but rather later during the upward motion.

In summary, it can be stated that the motion curve of the piling element under vibration is very different to the motion curve for impact driving and pressing due to the periodically repeated extraction. This is very important, particularly regarding the comparability of the processes concerning various properties such as the load-bearing capacity of the piling element or pile driving energy. Further information about this can be found in [84].

8.1.1.4 Parameters

8.1.1.4.1 Static moment

The static moment of an eccentric mass can be calculated from the product of its mass and the distance of its centre of gravity from the rotational axis, see Equation 8.2 and Fig. 8.8.

$$M_{stat,u} = m_u \cdot r_u \quad \text{[kgm]} \tag{8.2}$$

with
$M_{stat,u}$: static moment of eccentric mass [kgm]
m_u: mass of the eccentric mass [kg]
r_u: distance from centre of gravity to rotational axis [m]

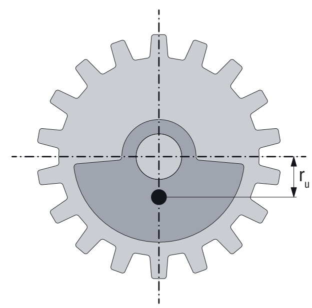


Fig. 8.8: Eccentric mass with distance from the centre of gravity to the rotational axis

The term "static moment" is actually imprecise, but it has become accepted as such among manufacturers of vibrators in the deep foundation business. In engineering mechanics, the neutral term is "static unbalance". The static moment is normally given in the unit kilogram metre and is an important characteristic of vibrators, which has to be considered when choosing the optimal size of vibrator. The statement of a static moment always refers to the total static moment for the vibrator, that is the sum of the static moments of individual eccentric masses, see Equation 8.3:

$$M_{stat} = \sum M_{stat,u,i} \quad \text{[kgm]} \tag{8.3}$$

8.1.1.4.2 Exciter force

The force produced by the rotation of an individual eccentric mass is its centrifugal force. This is directed radially outward from the rotational axis and thus continuously changes its direction with the rotation of the eccentric mass. In order to obtain a vertically directed oscillation for vibration, several equally sized eccentric masses, which rotate in opposite directions, are mounted in the vibrator. Due to the counterrotation, the horizontal components of the centrifugal forces balance each other out, whereas the vertical components add together. This creates the vertically directed exciter force, see Fig. 8.9.

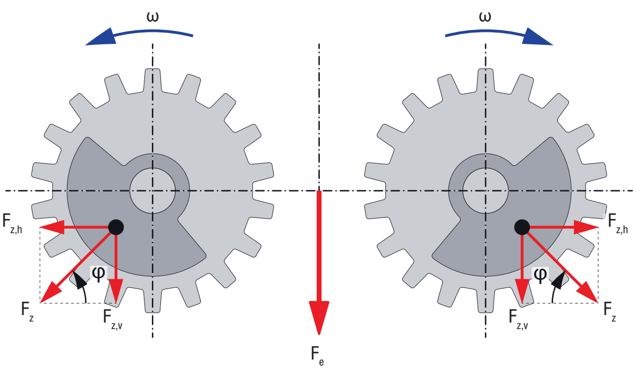


Fig. 8.9: Counterrotating eccentric masses with the resulting forces

$$F_e = \sum F_{z,v,i} = F_{e,max} \cdot sin(\omega \cdot t) \quad \text{[N]} \tag{8.4}$$

with
- F_e: exciter force [N]
- $F_{e,max}$: maximum exciter force [N]
- F_z: centrifugal force [N]
- $F_{z,h}$: horizontal component of the centrifugal force [N]
- $F_{z,v}$: vertical component of the centrifugal force [N]
- t: time [s]
- ω: exciter angular frequency [rad/s]

The exciter force F_e changes continuously with rotation, resulting in a harmonic oscillation. The maximum value of the exciter force $F_{e,max}$ (also called the exciter force amplitude) is the product of the static moment and the square of the exciter angular frequency:

$$F_{e,max} = M_{stat} \cdot \omega^2 \quad \text{[N]} \tag{8.5}$$

with
- $F_{e,max}$: maximum exciter force [N]
- M_{stat}: static moment [kgm]
- ω: exciter angular frequency [rad/s]

As shown in Equation 8.5, the maximum exciter force increases quadratically with increasing rotational speed. If it was possible to operate a vibrator with a very fast rotational speed, then the exciter force would also be very large with a small static moment. In practice, however, this is not advisable for several reasons: for one thing the centrifugal force of individual eccentric masses increases so strongly with increasing rotational speed that the bearings would be overloaded in the long term. Also, not only the exciter force but also the frequency (and thus the rotational speed) is decisive for effective vibration. The frequency has to be adapted to suit the relevant soil type, and particularly with deep compaction with compaction probe, the effective frequencies are in a relatively low range of around 15 Hz [66].

8.1.1.4.3 Frequency

The exciter angular frequency ω (also called the angular velocity) is determined by the frequency f:

$$\omega = 2 \cdot \pi \cdot f \quad \text{[rad/s]} \tag{8.6}$$

and the frequency f can also be described depending on the rotational speed n:

$$f = \frac{n}{60} \quad \text{[Hz]} \tag{8.7}$$

with n: rotational speed [1/min]

The control of the frequency has a decisive influence on the quality of vibratory pile driving. If the highest possible penetration or extraction rate is to be achieved in non-cohesive soil, then the frequency should be set as high as possible [67]. If the frequency is set to the resonance frequency of the system (vibrator-piling element-soil system), then a resonance can be achieved, which results in an intensification of the oscillations. This principle is exploited in deep compaction with compaction probe [66].

The achievable frequencies of vibrators are – depending on the construction type of the vibrator – up to about 55 Hz, with the higher frequencies only being possible with small vibrators (mostly as excavator attachments).

8.1.1.4.4 Peak-to-peak amplitude

Another important factor is the peak-to-peak amplitude S. This denotes the distance between the two turning points (upper and lower position) of the oscillating system and can be calculated as follows:

$$S = \frac{2 \cdot M_{stat}}{m_{dyn}} \quad \text{[m]} \tag{8.8}$$

It should be noted here that the total mass of the oscillating system (also called the dynamic mass) m_{dyn} is composed of several components:

$$m_{dyn} = m_{vibrator} + m_{piling\ element} + m_{soil} \quad \text{[kg]} \tag{8.9}$$

The mass of the vibrator $m_{vibrator}$ included in Equation 8.9 does not relate to the total mass of the vibrator. It consists of the mass of the oscillating parts of the vibrator, that is the mass of the exciter block and the mass of the clamping system, which can also consist of several parts (e.g. double clamps, turning plate, T-bars). The values of these masses are normally available from the manufacturer's information and can be quickly determined.

The mass of the piling element $m_{piling\ element}$ can also be easily determined; tables are normally available with the corresponding weight data.

The determination of the mass of the soil that also oscillates m_{soil} is considerably less precise. It can only be roughly estimated for the planning of vibration works. As an estimation, the following values can be used [63]:

$$m_{soil} = \frac{2}{3} \cdot (m_{vibrator} + m_{piling\ element}) \qquad \text{for sheet piles}$$

$$\frac{1}{2} \cdot (m_{vibrator} + m_{piling\ element}) \qquad \text{for concrete piles}$$

The peak-to-peak amplitude is an important parameter in relation to the achievable pile driving progress. Only when the peak-to-peak amplitude reaches a minimum can the soil sticking to the piling element be loosened and the piling element start to move. This applies particularly in cohesive soil, in which a larger peak-to-peak amplitude is correspondingly advantageous. For productive vibrating, the peak-to-peak amplitude should always be at least about 6 mm [63], [47].

With regard to the peak-to-peak amplitude, it should be noted that this is often confused with the peak amplitude. The peak amplitude A is half the peak-to-peak amplitude S, see Equation 8.10 and Fig. 8.10:

$$A = \frac{1}{2} \cdot S \quad [\text{m}] \qquad (8.10)$$

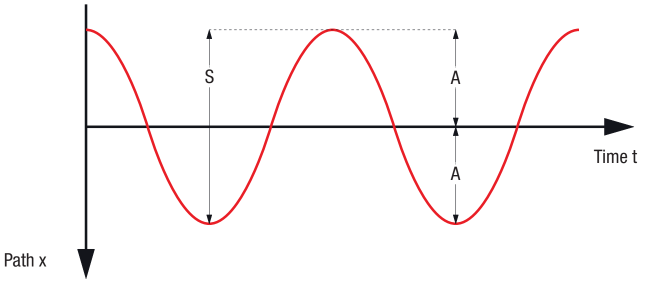


Fig. 8.10: Peak-to-peak amplitude and peak amplitude

Particular care should be taken to avoid this possible confusion in manufacturer's information sheets, above all when these are in English, since only the term “amplitude” is used in English. When choosing a suitable vibrator, it is necessary to differentiate the “peak amplitude” and the “peak-to-peak amplitude”.

Fig. 8.11: LRB 355 with MS-40 HFV

Another danger in the interpretation of information given in technical data sheets of vibrators is that the values always relate to only the freely oscillating system, i.e. neither the piling element nor the mass of soil that also oscillates are considered. Often the clamping system is also neglected since its selection depends on the choice of the element to be driven.

8.1.1.4.5 Acceleration

The acceleration a is another important parameter in vibratory pile driving. This can be calculated from the product of the square of the exciter angular frequency and the peak amplitude:

$$a = \omega^2 \cdot A \quad \left[\frac{\text{m}}{\text{s}^2}\right] \qquad (8.11)$$

The acceleration plays a decisive role in the reduction of grain-to-grain friction in the soil and thus to the reduction of the resistance to penetration of the piling element. For productive vibratory pile driving, the acceleration should be greater than 100 m/s² [47].

8.1.1.4.6 Surcharge

Another important parameter is the surcharge F_a, although this does not normally concern the vibrator but the carrier machine. Above all when the vibrator is leader-guided, this parameter should not be underestimated because it can then be controlled from the carrier machine. With free-hanging vibrators, it is not possible to change the surcharge during the driving process since the surcharge in this case is applied in the form of ballast slabs bolted to the spring yoke. With vibrators mounted on hydraulic excavators, the surcharge can be increased to a certain degree by pressing with the excavator boom.

Increasing the surcharge can normally lead to an increase of the penetration rate. At low frequencies, however, a heavy surcharge can lead to a stoppage of driving progress and this can happen suddenly, particularly in non-cohesive soils [80]. When a surcharge is applied, care should be taken that the peak-to-peak amplitude is not “stalled”. Above all in cohesive soils, there is a danger that soil sticks to the piling element and it can no longer oscillate sufficiently.

8.1.2 Deep compaction with compaction probe

In deep compaction with compaction probe, a special compaction probe is driven into the soil under vibration to compact it. The compaction is produced by driving in and extracting the probe, with the frequency being set to the resonance frequency of the oscillating system (vibrator-piling element-soil).

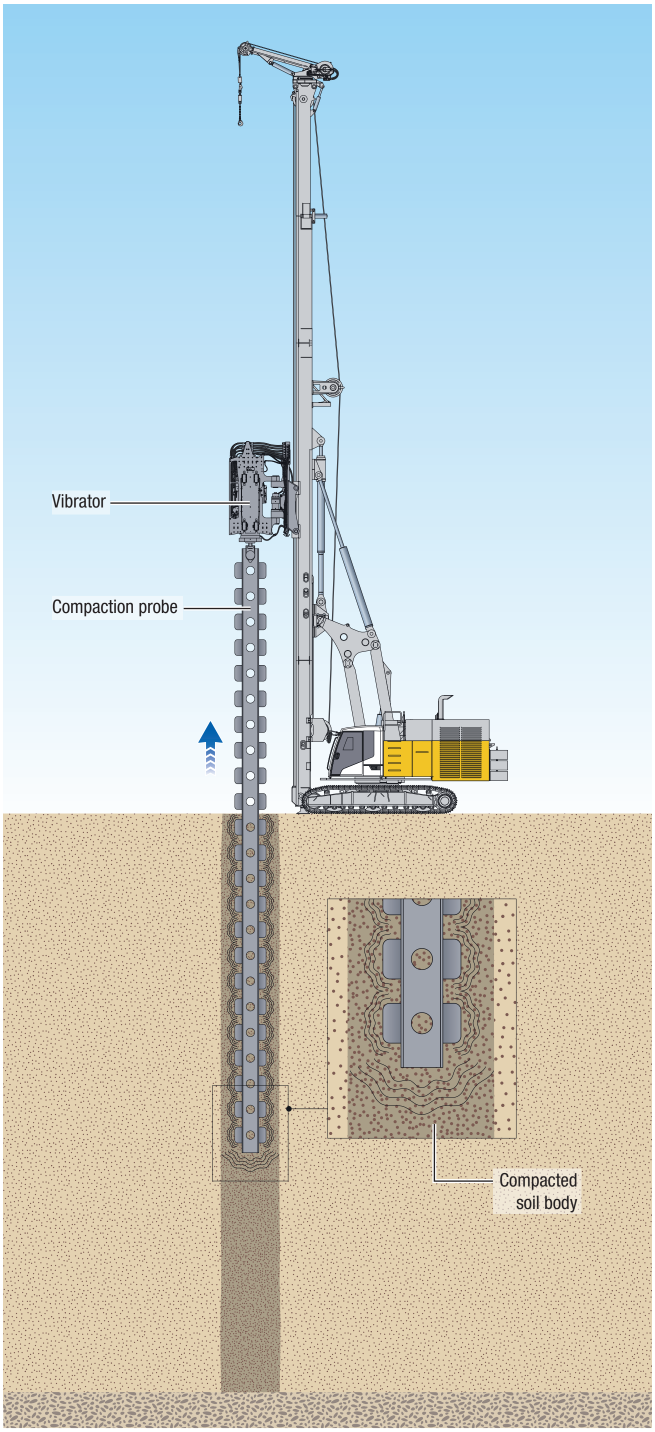


Fig. 8.12: Process principle of deep compaction with compaction probe

This achieves resonance, which leads to an intensification of the oscillations in the soil. For this reason, this process is also described as resonance compaction. Alternative descriptions are the MRC process (Müller Resonant Compaction) [98] or the Vibro-Wing method [13]. In order to optimise the control of the frequency, oscillations at the surface can be measured with geophones so that the frequency can be adjusted during the compaction process.

The sequence of operations for deep compaction with compaction probe is as follows (see also Fig. 8.14):

After positioning the compaction probe at the starting point, the vibrator is started. The compaction probe is then driven down to the required depth with a high frequency (> 30 Hz). If working with a leader-guided vibrator, the greatest possible surcharge is applied here. The high frequency and surcharge while vibrating are intended to ensure the quickest possible insertion. When the final depth has been reached, the crowd force is stopped and the frequency of the vibrator is slowed until the resonance of the system of vibrator, piling element and soil is achieved. This frequency is about 15 Hz [66], depending on the soil type. Then the oscillations intensify and the maximum possible vibration energy can be applied to the soil by the compaction probe. Finally, the compaction probe is extracted, for which the frequency of the vibrator has to be increased again since otherwise an excessive pull force would be necessary. Compaction can then be carried out again in a higher position.

Due to the reduction of the void ratio in the soil under vibration, a sink crater is created around the compaction probe. This crater is then filled with a non-cohesive material, mostly sand, gravel or a mixture during or after the phases of compaction and extraction.

Fig. 8.13: Deep compaction with compaction probe

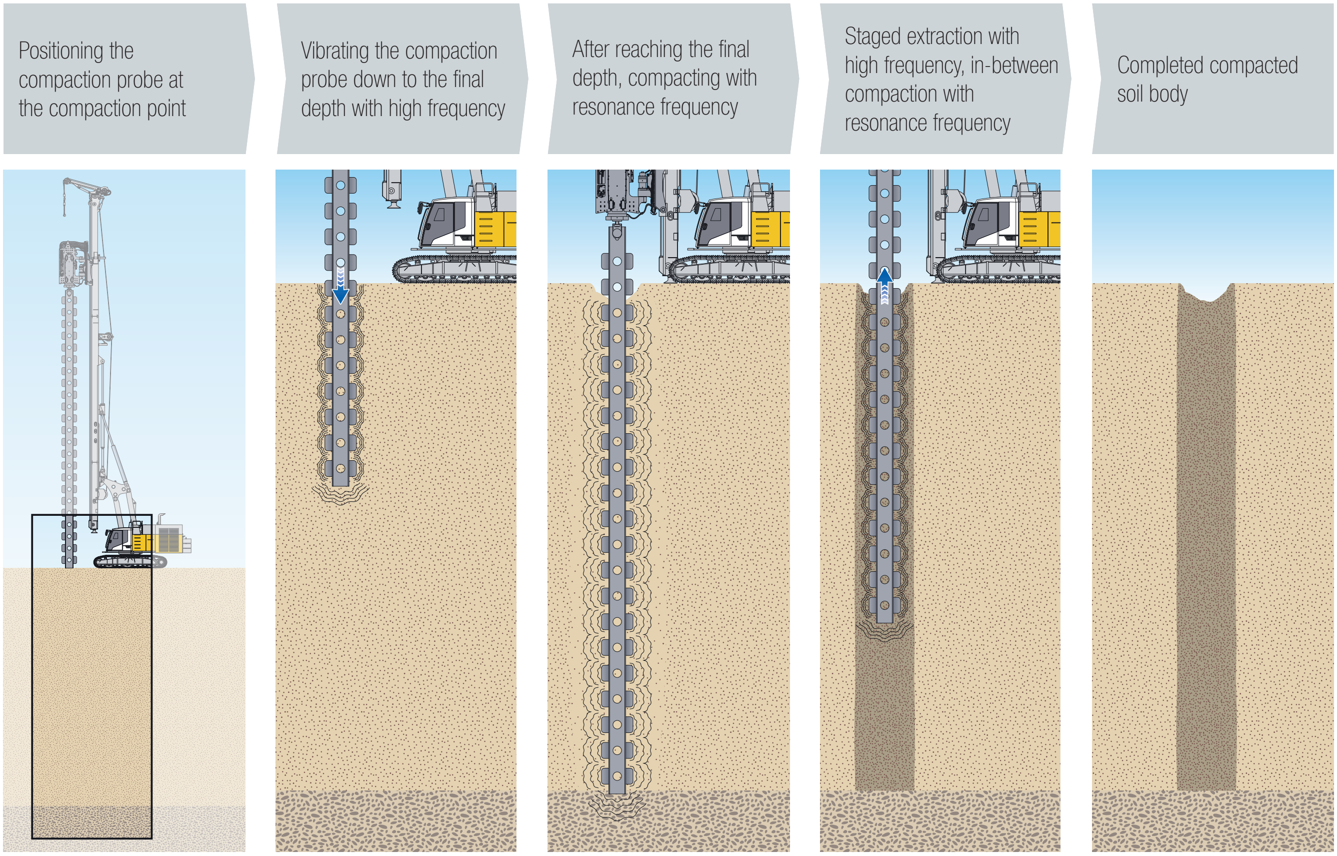


Fig. 8.14: Procedure for deep compaction with compaction probe

8.1.3 Deep compaction with casing

Deep compaction with casing is a ground improvement process, in which a temporary casing is driven into the soil with the assistance of a top vibrator and then a material in the form of sand, gravel, crushed stone or concrete is added. The displacement of the soil from the driving of the casing has already compacted the soil in advance in most cases and improved its load-bearing capacity. The addition of extraneous granular material and/or hydraulic binders, or also the use of concrete or the insertion of a geotextile in the casing with subsequent filling leads to a strengthened column after extraction, which can both bear loads and in certain cases drain water.

The usual casing diameters in practice for deep compaction using a top vibrator are between 300 and 800 mm, in a few applications even up to 1,500 mm.

8.1.3.1 Vibro columns

For the production of a vibro column, a single-walled steel tube, called the casing, is vibrated down to the final column depth and then filled with granular material (mostly sand or gravel). The length of the casing is determined from the required column depth plus a projection above ground level for the attachment of the vibrator. In the simplest case, the

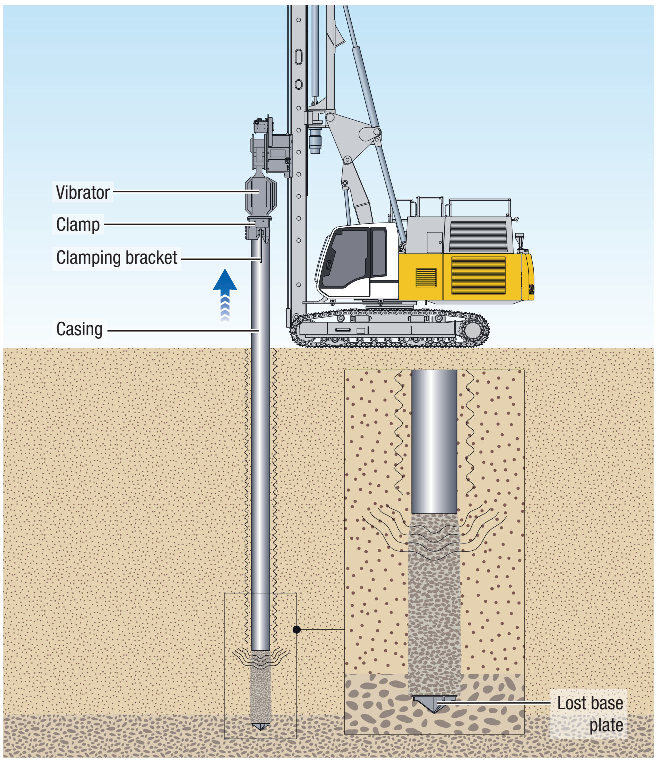


Fig. 8.15: Process principle of vibro columns

casing is a steel tube open at the bottom. This is closed at the lower end with a base plate before being vibrated in; the base plate remains in the soil after extraction. Before driving with vibration, the head of the casing must be fitted with a central clamping bracket, if one clamp is used or two clamping brackets welded to the sides, if two clamps are used, with appropriate strengthening of the casing, in order to clamp the vibrator to it.

It is however also possible to clamp the casing directly with the clamps of the vibrator, in which case the head of the casing should be strengthened with sheet metal. If the casing is driven in with a ring vibrator, it is clamped with the clamping inserts below casing end so that it projects past the ring vibrator.

The production of a vibro column is carried out in the following phases (see Fig. 8.16).

Firstly, the lost base plate is positioned at the column point. Then the casing, which is clamped by the vibrator clamps via the welded-on clamping brackets, is positioned on the base plate. After positioning the casing, the vibrator is started and the casing is driven in, supported by the crowd force of the crowd system. The system components vibrator, clamps, casing and base plate are a collectively acting, vertically oscillating system, with the base plate sealing under pressure through the resistance of the soil during vibrating. It must be ensured that the crowd force always acts on the casing so that the base plate cannot be lost. Only this can prevent soil entering the casing.

As the casing is vibrated into the soil, the soil changes into a pseudo-liquid state through the vibration and is displaced to the sides into the surrounding soil by the base plate and the following casing. This is similar to full displacement drilling with the open system where the soil is displaced by the drive tube, the displacement body and the drill bit [85]. This means that the soil around the casing is already pre-compacted by the vibration.

After the final depth has been reached, the vibrator is switched off, the clamps are opened and the vibrator is lifted from the casing.

Then the casing is filled with the additional material, normally with a wheel loader or telescopic handler. For this purpose, it may be necessary to fit a special receiver hopper to the casing in order to simplify filling with the wheel loader bucket. The fill material, mostly sand, gravel or a mixture of the two, should be as dry as possible or only have slight moisture content in order to prevent clump formation in the casing. After the casing has been filled with the fill material, the vibrator is mounted on the casing again and clamped.

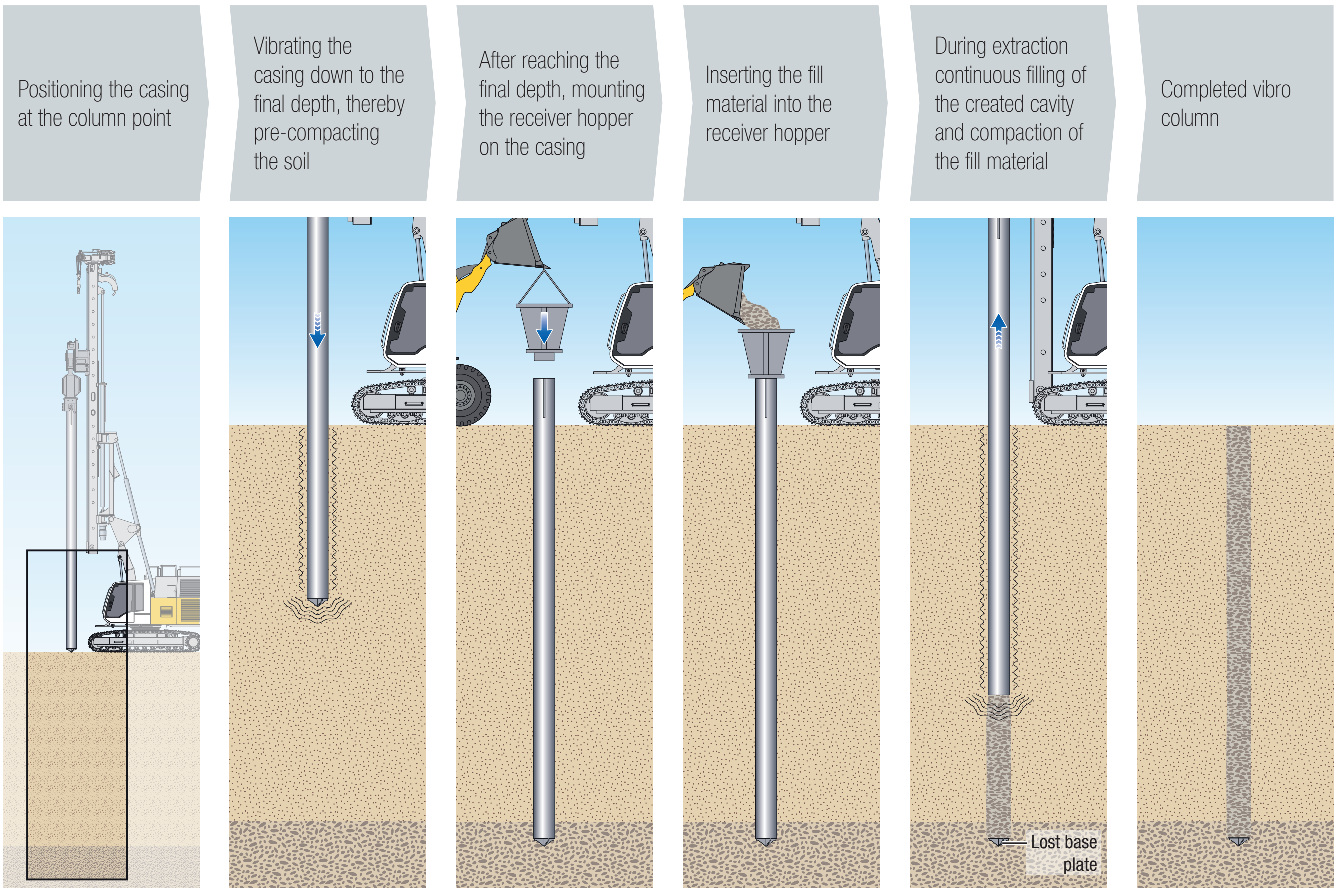


Fig. 8.16: Procedure for the production of vibro columns with top vibrator

Then the casing is extracted under vibration. As the casing is extracted, the base plate detaches from the casing and remains in the subsoil as a lost plate. The fill material flows out of the casing into the created cavity and fills it. The vibration during extraction additionally compacts the fill material in the casing. After the casing has been extracted, the compacted vibro column is complete and surrounded by pre-compacted soil as a result of the vibration. Then the carrier machine can be moved to the next column point.

The filling volume of the casing is to be matched to the volume of the loosely inserted fill material, which is greater than the volume of the compacted vibro column after extraction. For this purpose, it is necessary to make the casing slightly longer than the intended column length. Another possibility is to weld a receiver hopper with the corresponding fill volume onto the casing. Then it is necessary to weld extra clamping brackets to the hopper to fix the clamps.

It is also possible to use a mechanically activated hinged vibration tip fixed to the lower end of the casing instead of a lost base plate, see Fig. 8.17. This vibration tip must be constructed so that it can be opened by a mechanical apparatus over the full cross-section after insertion of the fill material. It is opened immediately at the start of extracting the casing so that the fill material can flow out of the casing into the created cavity.

Fig. 8.17: Mechanically activated hinged vibration tip

8.1.3.2 Vibro-replacement columns

Another process for the production of granular columns is vibro-replacement. Similarly to vibro-replacement with a dry bottom feed vibroflot (see Chapter 7), compacted columns can be produced by adding coarse-grained material from bottom to top. The principle is based on driving a steel tube, the so-called casing, into the soil under vibration, filling it with material and then alternatively extracting a certain length and driving down again for a part of the length. This presses the emerging fill material firmly into the surrounding soil at the sides. The end result is a filled and compacted granular column up to ground level.

The construction of the bottom of the casing, or the vibration tip at the lower end of the casing, the construction of the receiver hopper at the upper end of the casing and the clamping brackets to connect with the clamp are very varied. There are different versions, some of which are patented. For this reason, this chapter describes a possible construction variant, which is used in normal practice. The system consists of a casing, at the lower end of which a mechanically activated hinged vibration tip is fitted. At the upper end of the casing, a reservoir is welded on as receiver hopper, into which fill material is inserted. There is also a clamping bracket welded on to connect the casing with the clamp of the vibrator.

It is also possible to use ring vibrators for the production of vibro-replacement columns. Then the casing is clamped in its

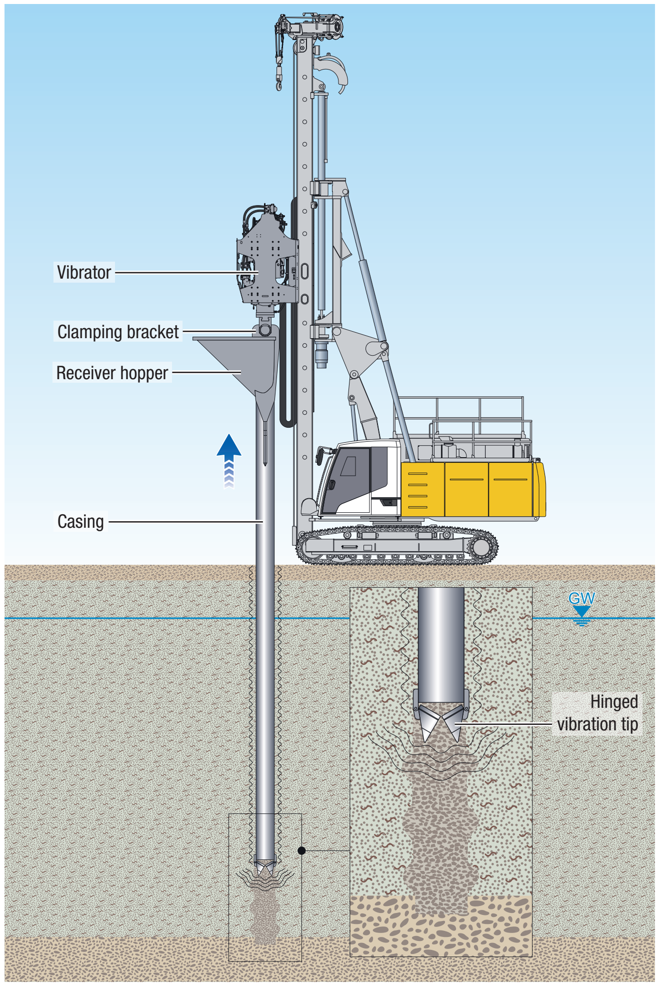


Fig. 8.18: Process principle of vibro-replacement columns