SUPPORT FOR OFFSHORE MONOPILE INSTALLATION THROUGH THE TRENCH CUTTER TECHNOLOGY

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SUMMARY

Europe is currently facing an energetic revolution. Several offshore wind farm projects are currently under construction or under planning in North and Baltic Sea. Typical foundation structures for offshore wind farms are steel open-ended monopiles with large diameters up to 6 m. Currently, the monopiles are installed by driving with large impact hammers. However, there are many situations where pile refusal is reached, due to hard soil layers or erratic blocks. Driving and drilling technique is therefore applied. This manuscript briefly describes the trench cutter technology normally used for foundation works on land. Three case histories onshore and one offshore project are discussed and the evolution of the trench cutter technology for supporting the installation of offshore monopile is described.

1. INTRODUCTION

1.1 THE OFFSHORE WIND ENERGY IN EUROPE

According to [1] 293 new offshore wind turbines, in 9 wind farms, representing investments of around €3.4 billion to €4.6 billion, were fully grid connected between 1 January and 31 December 2012, totalling 1,166 MW, 33% more than in 2011. Once completed, the 14 offshore projects currently under construction will increase installed capacity by a further 3.3 GW, bringing cumulative capacity in Europe to 8.3 GW. Preparatory work has started on seven other projects, which will have a cumulative installed capacity of 1,174 MW. Installations in 2013 could be around 1,400 MW and for 2014 around 1,900 MW. Foundations were installed in 2012 in Global Tech 1, Nordsee Ost, Meerwind sud/ost, Riffgat, Borkum West II, Teesside, Gwynt y Mor, Karehamn. Additionally, preparatory work has begun at five more sites: Belwind Phase 2 and 3 (Belgium), Vertiwind (France), Dan Tysk, EnBW Baltic 2 (Germany), West of Duddon Sands (UK). Offshore wind development has been limited to waters shallower than 30 m in the North and Baltic Seas. At depths less than 30 m, the established monopile foundation technologies can be deployed without significant R&D effort. The average water depth of wind farms completed, or partially completed, in 2012 was 22 m and the average distance to shore 29 km. Both average water depth and distance to shore are expected to increase over the coming years. For many European countries, such as Denmark, the Netherlands, Germany, and the United Kingdom, these shallow water sites appear to be abundant, and should allow offshore wind installations to proliferate rapidly in the near term [2]. According to the DENA (Deutsche Energie-Agentur – stand at November 2012) four wind parks are currently operating (i.e. Alpha Ventus, BARD Offshore 1, ENOVA and Hooksiel) in North Sea, whereas in the Baltic Sea EnBW Windpark Baltic 1 and Rostock are the only ones. The wind farms currently in construction both in North and Baltic Sea reach water depths up to 45 m. Water depths is increasing also for the future “Round 2” offshore sites in the UK (up to 65 m) and planned offshore structures in Norway and Italy for water depths of 100 m or more [3]. However, when looking at wind farms currently under construction per sea basin, it is clear that the North Sea will continue to be the main region for offshore deployment (63% of total capacity). The Atlantic Ocean (22%) and the Baltic Sea (15%) will, however, continue to attract important developments, whereas no significant developments are expected in the Mediterranean Sea in the short term [1]. Typical offshore wind farms foundations are monopiles, gravity structures and tripods or jackets. According to EWEA, monopile substructures remained the most popular substructure type with 355 installed (73%) in 2012. 61 jacket foundations were installed, representing 13% of all newly installed substructures, followed by tripods (6%) and tripiles (5%). Finally 16 gravity based foundations were installed representing 4%. They are economic in relatively shallow water depths and have had acceptable dynamic characteristics for the range of soil conditions [3]. The monopile construction consists of a cylindrical hollow pile. The monopile is used in many European offshore wind farms in coastal areas and is suitable for structures in water depths up to about 20 m. Monopile can be installed easily and quickly. They are frequently installed as foundations for offshore wind energy converters, e.g. at Horns Rev in Denmark or Arklow Bank in Ireland [4]. For the use of more powerful wind turbines (6 MW) in deeper waters monopile designs are not suitable. Their use is economically up to water depths of about 15 meters. Another disadvantage of large diameter monopiles is that no proper design guidelines and installation methods are yet available. Large diameter also has problem of removal after completion of design life. The tripod consists of a central steel shaft connected to three cylindrical steel tubes supporting the main pile. The tripod is anchored with small stakes by ramming the seabed. Compared to the monopile foundation here, steel pipes are used with smaller diameter. It is possible to use tripod for marine depths exceeding 20 meters. Another advantage is the good foundation against the security of this pothole in a sandy floor. However, tripods are heavier and more expensive to manufacture than monopiles. The Alpha Ventus project is the only operating wind farm that employs tripod foundations [5].

The jacket is a steel truss structure that resembles the structure of conventional electricity pylons. On its four feet, the jacket is anchored with piles to the seabed. The jacket construction has already proven itself in the oil and gas industry in greater water depths. Through the lattice structure, 40 to 50% steel can be saved compared to the monopile. Thus, the project costs increase relatively for the use of this construction in greater water depths. The advantage of jacket substructures is that they are not very sensitive to wave loading as the structure attracts only small wave loads and is very stiff. The benefits of using the jacket foundation concept are found to be a lower wave load, a higher level of stiffness and lower soil dependency. The design will therefore be suitable for installations in deeper water or in waters with high waves and at sites with poor soil [6]. According to Kaiser and Snyder [5] 75% of the foundation types of offshore wind farms were monopiles, 24% concrete base and only 1% Jacket/tripod.

1.2 MONOPILE REFUSAL

The bearing capacity of monopile comprises of end bearing resistance and shaft skin friction. The design guidelines for monopiles are based on the standard p-y method of American Petroleum Institute [7]. Many researchers have shown through finite element analyses that the standard p-y method overestimates the pile soil-stiffness of large diameter monopiles at great depths which may result in an insufficient pile length. If possible, piles should be driven to their full design penetration without the need to weld-on additional pile lengths, to drive insert piles, or to clean out the soil plug or drill below the initial refusal level of an open-ended tubular pile. [8] gave an example of times required for welding add-on lengths of 1.37 m OD tubular piles; they varied from 3 ¼ hours for 25 mm wall thickness to 10 ½ hours for 64 mm thickness. Such delays cause increased driving resistance due to 'take-up' (i.e. the increase of shaft friction). However, there are many situations where piles cannot be driven to their full penetration without the need for lengthening or for 'drilling-and-driving' techniques. Cleaning out the soil plug is an effective way of reducing the driving resistance, thus obtaining deep penetration, because of the elimination of base resistance. It is particularly advantageous for obtaining deep penetration into coarse soils; say to develop uplift resistance, to avoid excessive settlement due to vibration effects, or to reach rock-head. This is because the base resistance in a coarse soil represents the major proportion of the total resistance to the driving of the pile. Removal of the soil plug is not particularly effective for piles penetrating deeply into clays where the base resistance is only a very small proportion of the total resistance. Drilling out the soil within the pile does not reduce the external shaft friction of the surrounding clay [9]. Refusal may be also caused not only by the soil plug within the pile but also by erratic blocks typical of the glacial regions which are likely to be found in the glacial tills. This is the typical case of the Baltic Sea. Since the most common substructures used are monopiles (1,376 such foundations were fully installed at the end of 2012, which represent 74% of all installed foundations), BAUER Maschinen GmbH developed the trench cutter for supporting the offshore pile driving for large mono piles when pile refusal is prematurely reached.

2. THE TRENCH CUTTER TECHNOLOGY

The basic method is in use since the early 1960s and is used also for oil well and soil exploration drilling to maintain boreholes in caving soils without casing [10]. The large hydrostatic pressure resulting from several hundred meters of slurry allowed retention of oil or gas in oil wells until they could capped with valving to control the fluid flow rate.

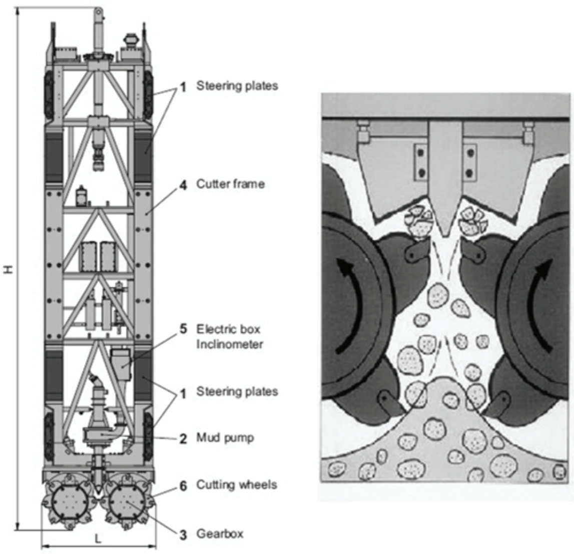

Figure 1: Trench cutter sketch

The trench cutter (Figure 1) is an excavating machine that operates on the principles of reverse circulation. It is made up of a heavy steel frame with two gear boxes at the bottom of the frame. Cutting wheel drums fitted with a series of teeth are fixed to the gearboxes; they rotate in opposite directions, break up the soil and mix it with the bentonite suspension. As the cutter penetrates, soil, rock and bentonite are conveyed towards the openings of the suction box, from where they are pumped by a centrifugal pump through the slurry pipe incorporated in the cutter's frame, via the mast head into the slurry conveying system to the de-sanding plant. There solid soil and rock particles are separated from liquid bentonite which is pumped back into the trench or for storage and later reuse. The torque output of the cutter wheels in combination with the weight of the cutter is sufficient to cut into any type of soil, to crush cobbles, small boulders or weak rock. The verticality of the trench cutter and thus the trench alignment are measured on two axes by means of two independent inclinometers. Data provided by the inclinometers is processed by a computer on-board the base carrier and displayed on-line. Adjustment of verticality in the two directions is carried out by a system of steering plates. Throughout the excavation process the rig's operator is prompted by the machine's software that calculates its status and indicates the most appropriate action take. All information can be downloaded on a "Panel Report" that can be printed after completion of each panel and used for quality assurance and quality management (QA/QM) purposes.

During the cutting process, soil material is continuously loosened, broken down and mixed with the support fluid. The slurry charged with soil material and cuttings is pumped to the surface by the mud pump and conveyed to the desanding plant via a ring main. There, the slurry is cleaned and subsequently re-circulated into the trench (Figure 2). The slurry used for these procedures is generally a mix of bentonite, water and suitable additives [10]. The walls are usually stable with a slurry pressure about 65 to 80% of the active soil pressure [11]. The slurry must be of sufficient viscosity that it does not easily drain out through the sides of the excavation. Slurry is obtained by using a mixture bentonite, barite and dispersing agent to reduce the tendency of the clay to floc [10]. The slurry mixture is a trial process in the laboratory, where water, clay and any other admixtures are mixed by trial until a slurry with the desired density ρ is obtained. Viscosity of slurry is measured by a Marsh funnel. Fresh slurry should have a minimum viscosity of 32 Marsh seconds, while in the trench the slurry viscosity should not exceed 65 Marsh seconds [12]. The property of slurry depends on the kind of work. It is important both in design calculation and in in situ quality control. However, the slurry density must be high enough to ensure trench stability. It is not unusual to require slurry densities, ρ, to be at least 0.240 g/cm^3 more than the density of the soils. Some specifications include a maximum slurry density ρ in the range of 1.28 to 1.36 g/cm^3 [13].

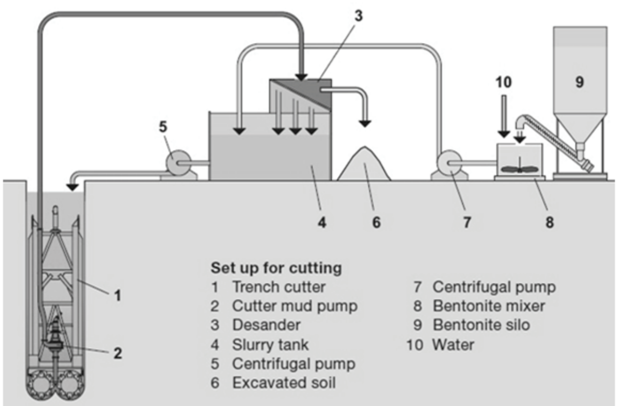

Figure 2: Principle sketch of the desanding plant

A hydraulically operated centrifugal mud pump is mounted just above the cutter wheels. The mud pump continuously conveys the slurry, charged with soil material and cuttings, to the surface and then to the treatment plant. In loose soil formations and when heavy slurries are used (e.g. single phase system), the capacity of the mud pump is crucial for the excavation output. The gearbox and the mud pump are protected against damaging ingress of bentonite slurry by a pressure equalization system.

For achieving optimum excavation outputs, BAUER trench cutter systems are provided with a particularly sensitive electronically operated crowd winch for controlling the crowd pressure. Depending on the strength of the soil, the control parameters used are either the cutter's speed of penetration (in soft soils) or the surcharge on the cutter wheels (in hard soils). The crowd system is electronically controlled and therefore easy and safe to setup and adjust. Selecting the most suitable type of cutter wheels is essential for cutter progress which is heavily dependent on the soil conditions. For the construction of soils of different widths, the cutter wheels are always exchanged with the appropriately sized set of cutter wheels. In addition, both the suction box and the cutter frame have to be adapted to the required trench width. The ridge forming between the two cutter wheels is cut away on all BAUER trench cutters by a patented flipper tooth (Figure 3).

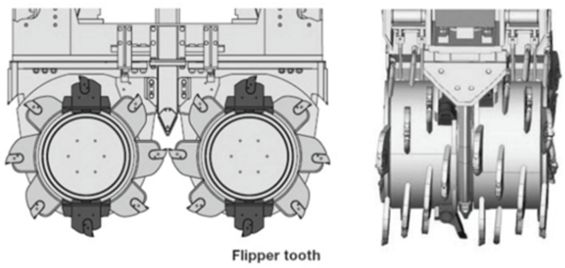

Figure 3: Flipper tooth of the cutter wheels

Several types of cutter wheels are used for different geological conditions. The standard set of cutter wheels (FRS) is equipped with tungsten carbide-tipped teeth. They are inserted into long teeth holders and can easily be replaced. Ejector plates, attached to the suction box, remove any spoil between the tooth holders, particularly in cohesive soils. Standard cutter wheels are primarily used in mixed soils. Round shank chisel-cutter wheel (RSC) are equipped with special round shank chisels. They are primarily deployed for cutting in cemented sands, conglomerates, cobbles, and weathered rock. The gapless distribution of cutter teeth across the entire cutter wheel ensures that the whole area under the cutter wheel is cut away, making it impossible for the cutter wheel to ground.

The roller bit-cutter wheel (HRC) has been developed for extremely hard rock formations (UCS > 120 MPa). The roller bits are arranged on the wheel in such a way that the entire rectangular cross section of the trench is cut. The central ridge below the gear shield is removed by flipper teeth. To generate the right amount of crowd pressure required by the roller bits, the main cutter frame is surcharged with additional ballast (Figure 4).

Figure 4: Roller bit-cutter wheels

The standard trench cutters BC32, BC40 and BC 50 are of similar construction. Their essential characteristic features are:

- Rigid main cutter frame;
- Shock absorber between gearbox and cutter wheels;
- Pressure equalisation on all key components;
- Watertight seals on all electrical boxes;
- Verticality control by individually controlled steering plates;
- Inclinometers for measuring the inclination in x- and y-axis;
- Gyroscope for measuring the rotation about the z-axis;
- High tooth forces due to the high torque generated by the gearboxes;
- Crowd control by way of a separately operated winch system;
- B-Tronic control and visualisation system with touchscreen terminal;
- B-Report evaluation software for data visualisation and production of cutter reports;

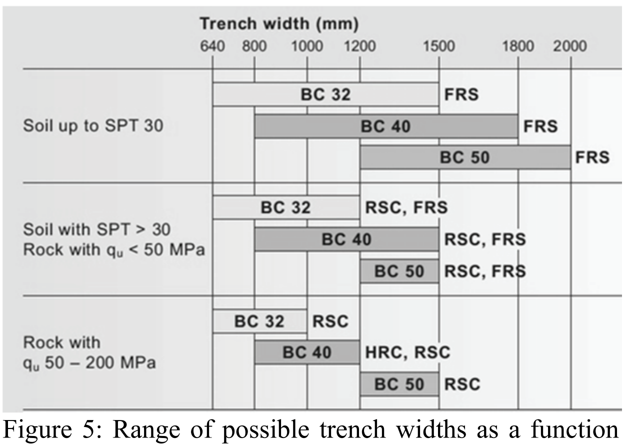

Figure 5: Range of possible trench widths as a function of soil conditions and type of trench cutter. FRS: Standard-cutter wheel; RSC: Round shank chisel-cutter wheel; HRC: Roller bit-cutter wheel

Figure 5 illustrates the range of possible trench widths as a function of soil conditions and type of trench cutter. It can be used as a pre-selection tool, but does not constitute a binding selection diagram.

An accurate determination is dependent on the operating weight of the cutter, the type of cutter wheels and above all, the detailed ground conditions (particle size, density, degree of cementation, abrasiveness, number and distribution of fissures, UCS). Table 1 summarises the technical data of the different trench cutters available.

	BC 32	BC 40	BC50
Overall height	9.5 m	12.6	12.7
Torque max.	81 kNm	100 kNm	120 kNm
Speed of rotation	0 – 25 U/min	0 – 25 U/min	0 – 25 U/min
Cutter length	2800 – 3200 mm	2800 – 3200 mm	2800 mm
Max. delivery rate, mud pump	450 m^3/h	450 m^3/h	450 m^3/h

Table 1: Technical specification of the trench cutters

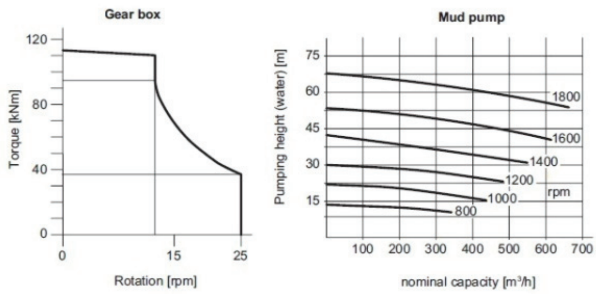

Figure 6: Characteristics curves of the trench cutter

3. THE TRENCH CUTTER TECHNOLOGY IN FOUNDATION ENGINEERING

Three onshore case histories are presented. In 2001 BAUER worked for a cut-off wall for Diavik diamond mine near the Arctic Circle in Canada using a BC 40 trench cutter, in 2005 it participated for a project for another cut-off wall project under extreme geological and geometric conditions to a depth of 120 m in Peribonka (Canada) using a CBS CBC 135 and in 2007 cut-off walls were excavated at the Red Dog Mine (Alaska).

3.1 DIAVIK DIAMOND MINE

[14] describes the construction of a 3800 m long temporary water-retaining dike under extreme conditions in the harsh northern climate to enable two of the

kimberlite pipes at the Diavik Diamond Project (Canada) reserve to be mined using open pits. All of the kimberlite pipes were planned to be mined initially using open pit techniques. In order to enable this, encircling dikes were built that are subsequently made water-tight by installation of a plastic concrete cut-off wall. Connection to the bedrock surface was accomplished by jet grouting the contact zone and fractures in the upper granite bedrock are sealed by pressure grouting. When the dike was built, and the water seepage cut-off components were completed, the pool that was created was pumped out. After dewatering, an average of 6 m of glacial soil deposits was removed from the planned mining area. During the construction of the diaphragm wall five different ground conditions were encountered:

- Crushed rock
- Till
- Frozen till
- Boulders
- Weathered granite

The project site was situated within the continuous permafrost zone of Canada, and permanently frozen ground occurs on all islands within Lac de Gras, near shorelines where the water depth is less than 2 m, and on the mainland. The ground surface only thawed to a maximum depth of 3 m in the summer. The original plan to excavate frozen till using hydraulic grabs, was quickly changed and the BC 40 Trench Cutter was substituted. The cutter was equipped with roller bits wheels, which worked satisfactorily from the outset. Boulders embedded in the till could be cut quickly enough to allow the cutter to reach the desired trench depth. This procedure still resulted in melting of the permafrost due to the thawing action of the warm bentonite slurry, and a progressive over-break resulted. Thus excavating a trench in permafrost became a time dependent process. Typical boulders consisted of hard granite, with an UCS averaging 115 MPa. Boulders measuring up to 1 m on a side were excavated with the hydraulic grabs, while larger boulders were cut by the trench cutter BC 40.
A total of 32700 m^2 of 80 cm thick diaphragm wall were built for the dike cut-off, using a two-phase procedure. Diaphragm wall support during the excavation was provided by means of a bentonite slurry, which was subsequently displaced by tremieing a plastic concrete mixture into the trench.

The plastic concrete mix design that was used, produced a 28 day compressive strength of 2 MPa and consisted of the following proportion of components:

- cement 58 kg
- bentonite 40 kg
- water 412 kg
- fine aggregate, 0-8 mm 668 kg
- coarse aggregate, 8-16 mm 668 kg.

3.2 PERIBONKA DAM

The Peribonka dam is located in the province of Quebec (Canada). The project involved the construction of a main earth dam across a main and secondary valley, two main dikes and a hydroelectric generating Run-of-River station with an estimated capacity of 385 MW. BAUER constructed a plastic cut-off wall in unusually complex ground conditions through deep alluvial deposits that form the dam foundation. The wall, successfully completed, is exceptionally deep, about 116 m at one point. The bedrock, where it was keyed, underlies coarse highly permeable alluvial deposits, and formed a buried valley with steeply sloped flanks, creating further difficulties. The geotechnical properties of the soil showed an extremely deep 60-m-wide valley in the bedrock underlying the riverbed alluvium. The canyon-like fold, a glacial gully, was filled with cobbles and boulders, with dimensions of up to 1 m within a sandy matrix with zones of high permeability. There were further challenges, such as the almost vertical flanks and overhangs of the bedrock, and concentrated boulder zones. In addition, the granite and anorthosite at the site had measured strengths in the range of 120 to 180 MPa, and occasionally in excess of 200 MPa. To mitigate the risk of instability, BAUER, grouted the alluvial zones in the gully section, creating a section 10 m wide with a depth of 120 m along the dam axis. The grouted soil body had the advantage of preventing erosion. Besides the cut-off wall and the alluvium grouting, some other challenging geotechnical measures were:

- Intensive drilling in the glacial gully section to identify the contour of the bedrock, as well as the location of large boulders in the dam axis;
- Bedrock consolidation grouting;
- Soil improvement by vibro-compaction of the alluvium layer and the dam base to mitigate the extent of settlements and risks of liquefaction due to seismic activity;
- Installing a ground water lowering system during construction to control potential rising river water levels.

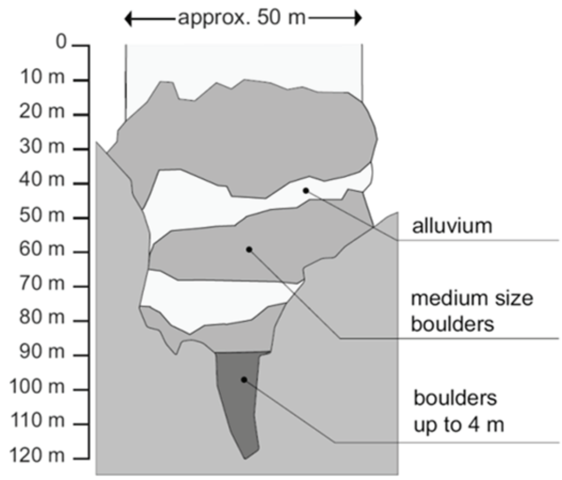

Figure 7: Geological conditions of glacial gully section at the Peribonka dam (Canada)

BAUER used “tubes à manchette” to grout the alluvia within the glacial gully. The main concern here was the risk of a limited penetration range of the grout and the grout intake quantities. Cut-off walls were constructed in several areas of the dam. Here only the exceptionally deep wall in the glacial gully of the main river valley was considered. This wall’s width ranged from 1200 mm to 1500 mm, with 116 m maximum depth, with a total area 12000 m^2. Based on the originally assumed rock profile in the glacial gully, it was expected that the wall would reach a depth of more than 120 m at its deepest point, and constructed a cutter prototype especially for the project. The wall depth necessitated additional measures for the verticality control to ascertain interlocking of the panels. Considering the complicated soil conditions, BAUER adapted the cutter direction control plates to allow longer stroke lengths, thus increasing the correction efficiency. Besides standard online monitoring and logging systems for parameters such as the deviation in both axes, depth, penetration progress, torque of each wheel and retention force acting at the hook, the largest cutter was further equipped with a gyroscope that monitored eventual rotations in the panel excavation. As a technical solution the cut-off wall was originally designed with a limited rock keying of the individual panels, over less than a half of their length, to facilitate its execution in the gully section against very steep rock slopes. The resulting “windows” underneath the non-embedded panel base were to be subsequently treated by cement or chemical grouting, depending on the groutability of the soils found. BAUER proposed an alternative which, making use of advanced cutter technology, allowed for a full embedment of the panels into the rock to avoid the risks associated with such deep “windows” (Figure 8).

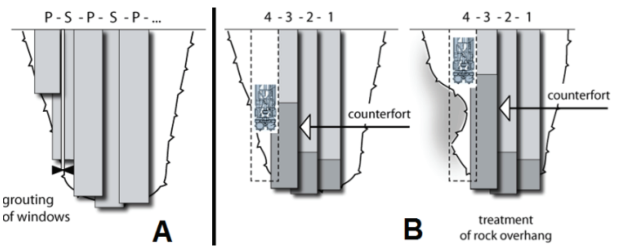

Figure 8: Left original proposal for the project, cut-off wall combined with cement grouting; right the BAUER’s proposal using cut-off wall fully embedded in rock

The deviation and torsion of the cutter frame were monitored by real-time measurements conducted by the two inclinometers and the gyroscope installed on the cutter frame, enabling the cutter operator to correct any deviations during the excavation. Finally, the alignment of the trench was controlled by ultrasonic cross-hole measurements.

3.3 RED DOG MINE

[15] describe the work involved in the design and construction of a cut-off wall along the Back Dam of the existing tailings impoundment at Red Dog Mine, Alaska, which is one of the world’s most efficient open-pit zinc and lead mines.

The completed cut-off wall was about 1500 m long and up to 45 m deep. The geotechnical conditions of the site was fill material which was encountered on the haul road, cofferdam and overburden stockpile. The waste rock fill material was generally silty gravel with occasional boulders and cobbles. Fill materials of the overburden stockpile consisted generally of Kivalina shale. The native soils was colluvial and alluvial material (organic soil, ice-rich soil, silty clay and sandy gravel). The shale bedrock underlying the colluvial and alluvial material was weathered near the contact surface becoming fresher with the depth. RQD values were generally 20%. Rock strengths varied from weak (R2) to very strong (R5), according to the field estimates of uniaxial compressive strength of intact rock by [16]. The estimated UCS was up to 150 MPa. However, the majority of bedrock encountered during the geotechnical investigation (about 75%) had UCS values of 50 MPa. The cut-off walls were designed to be keyed about 1 m into the apparent low permeability bedrock, i.e.$1x10^{-6}$ cm/sec [15].

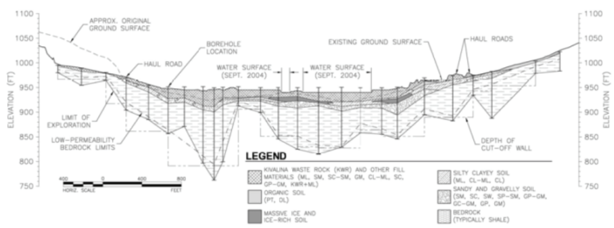

Figure 9: Geological section of the Cofferdam [15]

The configuration of cutting wheel used for full scale production at Red Dog was the RSC wheel. These wheels can cut a variety of rock hardness encountered for the majority of conditions along the Back Dam alignment, although they are likely not the optimum configuration for the cutting of the overburden soils. The other two widely used wheel configurations include the flat tooth wheels and bullet tooth wheels.

- Flat tooth wheels are extremely efficient in soft rock and clay like conditions as they are able to cut and scoop large quantities of material, but are unproductive for the R2 (weak) to R5 (very strong) rock that made up 60% of the cutting on the Back Dam alignment.
- Bullet tooth wheels are a configuration of large conical shanks with multiple carbide tips capable of grinding and cutting large columns of R4 (strong) to R6 (extremely strong) rock.

Despite the presence of some very hard rock at Red Dog, this configuration was not considered for the project due to the large thickness of overburden in some of the holes and the preponderance of mainly R2 (weak) and R3 (medium strong) rock across the site.

Attempts were made to correlate productivity of excavation to rock strength, however insufficient data on rock strength was available to make this possible. The Back Dam cut-off wall included the construction of a total of 39000 m^2 of wall over four construction seasons, with an average productivity per 12 hour shift of about 78 m^2 of wall. The cut-off wall depths ranged between 15 and 48 m.

4. OFFSHORE EXPERIENCE WITH THE TRENCH CUTTER TECHNOLOGY

[17] reported experience of the cutter system in the field of diamond sampling off the coast of Namibia. A full scale trial was carried out for BHP in the spring of 1993 at a test site in Germany. The two most important questions which, amongst others, had to be clarified were whether the cutter was capable of breaking down larger stones and cobbles and whether diamonds with a higher specific gravity could be lifted by the mud pump. For this purpose, cobbles of up to 300 mm diameter were placed in the test pit and mixed with steel bolts and nuts. The mixture was subsequently excavated by a standard BC 30 cutter and separated into its components by a screening plant.

The test clearly demonstrated that all types of cobbles could be broken down by the cutter wheels and even metal particles with a very high specific gravity could be lifted and conveyed by the mud pump. Based on these test results and the findings of the preceding comprehensive study, BAUER were awarded the contract for the development of a special cutter sampling tool in July 1993. The main parameters for the sampling tool were specified as follows:

• Sampling area	3.40 m^2
• Sampling depth into seabed	max. 6 m
• Max. water depth	165 m
• Total weight of tool	65 tons
• Overall dimensions of tool	5 x 4 x 15 m
• Capacity of centrifugal pump	700 m^3/h
• Max. cobble size through pump	120 mm

The tool was lowered onto the seabed through a moon pool in the centre of the mother vessel measuring about 6.5 x 6.5 m. The two counter rotating cutter wheels with 200 kNm torque each cut an area of 3 x 1.2 m (up to 3 x 3 m are possible). The material mixed with seawater was then pumped to the separation plant on board the vessel Geomaster with a capacity of approximately 700 m^3/h. Cutter wheels and mud pump were mounted on a special cutter frame and connected by wire ropes and hydraulic hoses to the vessel. An outer frame with four telescopic legs supported the cutter vertically on the uneven seabed and allowed a controlled penetration of the tool up to 6 m into the diamond bearing ground. The tool required a total power installed of approximately 800 kW. All hoses, the 6-inch mud hoses as well as the hydraulic hoses, were stored and compensated on drums on board suitable for a water depth of up to 200 m. Launch and recovery of the tool was effected through the moon pool of the vessel and the 25 m high, special designed drill tower. The 65 tons sampling tool had been commissioned in early 1994 in Cape Town. After intensive testing the sampling programme of more than 4000 holes could be successfully completed by January 1995 (Figure 10).

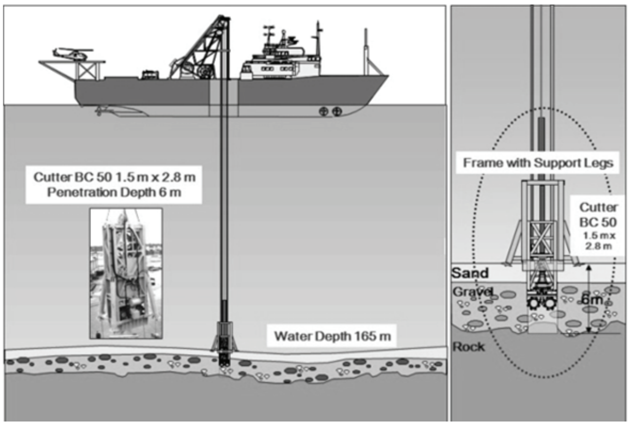

Figure 10: Sketch of the diamond sampling off the coasts of Namibia

The application of the trench cutter technique is now discussed in the light as alternative or support to the offshore pile driving. It is possible in the glacial submarine sediments to encounter erratics of big dimension (volume of at least one m^3), transported by a glacier to its present site during the ice age, which would impede the proper pile installation. The pile would be driven to refusal and that would impede the reaching of the design depth. The trench cutter might be used in order to mill the rock. The torque output of the cutter wheels in combination with the weight of the cutter is sufficient to cut into any type of soil, to crush cobbles, small boulders or rock. From a jack-up barge, the trench cutter would be immerged in the water by means of a crane (i.e. MC 128).

The trench cutter, usually used in the foundation engineering, has an approximate weight of 48 tons, trench length between 2.8 and 3.2 m. The flow rate of the pump is 450 m^3/h. The gear box has a torque of 120 kNm, with a speed of rotation of up to 25 rpm. Once reached the problematic site within the pile, by means of a special guide frame (Figure 11) the cutter tool is able to move in the two directions (± in the x direction) within the borehole to specifically cut the erratics which impede the pile driving and it is also able to rotate of ± 90° within the borehole.

The verticality of the trench cutter and thus the trench alignment are measured on two axes by means of two independent inclinometers. Data provided by the inclinometers is processed by a computer on-board the base carrier and displayed on-line. The trench cutter, together with the guide frame, might also be able to clean out the soil plug. The BAUER trench cutters are designed for depths up to 250 m. From a jack-up, which can be used in water depths up to 150 m, the trench cutters can be used for supporting long monopiles, as well (up to 100 m).

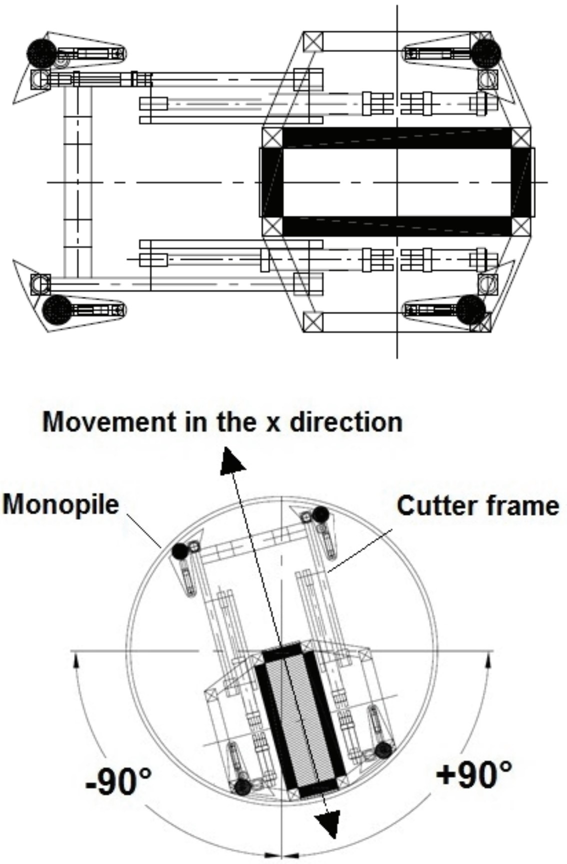

Figure 11: Guide frame and trench cutter for monopile support. The weight of this template is about 30 tons

Another option to use the trench cutter for offshore monopile installation is the application of the circular trench cutter (CTC) technology (Figure 12).

This kind of technology is suitable only for rock sea-beds, as found for instance off the coasts of Korea. It is well-known that driving pile in weak rock (e.g. calcarenite or mudstone) carries high risks in terms of premature refusal, exceedance of fatigue criteria or pile tip buckling. Besides, in strong rock conditions (e.g. limestone, sandstone or granite) it is almost impossible to drive piles. The idea of this new approach is not to directly excavate the entire monopile. It is rather to create a ring where eventually the steel tubular structure is inserted and possibly the steel/outer rock layer is grouted.

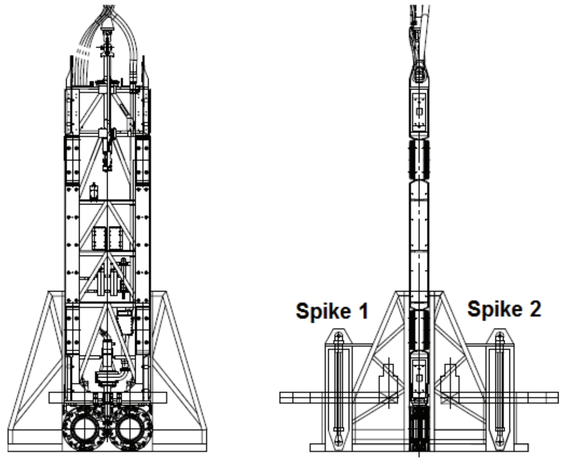

Figure 12: Circular Trench Cutter (CTC) technology

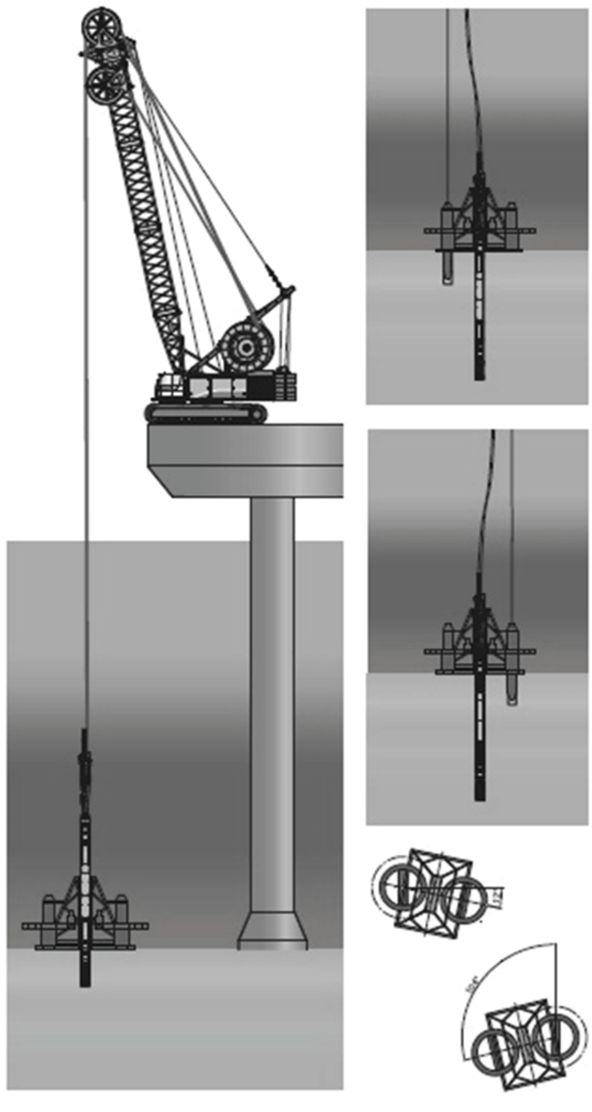

Figure 13: CTC working scheme

From a jack-up barge the CTC with the template is deployed on the seabed. Circular trench panel excavation then begins with the trench being excavated in discontinuous sections or "panels" using a BAUER trench cutter BC. Panel excavation is carried out in a predefined sequence to enable the construction of clear joints. This is achieved by constructing alternate "primary" panels first, followed by the excavation of the intermediate "secondary" or "closing" panels (Figure 13).

The length of a single bite panel is 2.8 m or 3.2 m (determined by the geometry of the machine). Minimum panel width is 640 mm and can be increased according to the required geometry of the circular trench to ensure the accurate installation of the monopile.

The verticality of the trench will be measured in the panel axis and perpendicular to the panel axis by means of two independent inclinometer systems that are mounted on the trench cutter. The B-Tronic system records the inclination of the tool in the excavation and correlates it with depth.

Once the excavation of the circular trench is finished, a prefabricated monopile is lowered into the trench to the depth required by the specifications. After the monopile is lowered into the trench it is located at the correct position by supporting it with a certain template. Once the monopile is within the trench, grouting can commence. One or more mixers are running in parallel operation. The mixer delivers continuously grout to the pumps. The grout is pumped through high pressure flexible hoses and must be arranged on deck from the Mixing/Pumping Plant to the inlet arrangement of the monopile. Once the grouting started, grout must be supplied to the trench locations at a certain rate to ensure sufficient pouring. Pumping is continued until the calculated amount is filled into the annuli. The number of hoses will be determined primarily based on the diameter of the individual trench to be grouted. Final verification of complete filling and over flow of grout should be surveyed.

The used grout must meet the required specifications in terms of workability and required strength. The mix design is usually finalised after the performance of trial mixes. Additives such as plasticizers or retarders may be included in the mix as required. On-site sampling and testing of grout usually consists of:

- The amount and frequency of sampling and testing should be specified in the contract specifications.
- The flow rate of the grout must be determined 5 minutes after mortar production using a flow channel.

During the grouting process the actual consumption of grout is plotted against the theoretical volume and is included as part of the panel records.

5. CONCLUSIONS

BAUER Maschinen GmbH is currently developing different offshore technologies for supporting pile installations. One of these technologies is the trench cutter technique. Based on forty years onshore foundation engineering experience, BAUER already proved to be able to work in offshore field in water depths up to 165 m. By a jack-up barge a trench cutter can be deployed within the pile and move in any direction with its special guide frame. By means of its cutting wheels the boulder or the hard layer can be milled. Pile driving can be further carried out. The CTC technique is a new innovative method in order to install monopiles in rock seabed conditions.

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