Chairman's contribution: Deepwater production concepts

Contribution du président: Concepts pour la production par grands fonds

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SYNOPSIS: The theme for the Offshore Geotechnical Engineering discussion session for XII ICSMFE is "Planning and Design for Deepwater Foundations." In this and the abstracts immediately following are descriptions of deepwater oil production concepts and their respective foundation requirements. These topics will be presented in detail at the discussion session.

The challenges of foundation engineering for deep water are best introduced by a brief overview of the concepts being employed for permanent production facilities in these environments. These facilities incorporate two general categories of structural support systems: conventional bottom founded structures and compliant systems (which may be bottom founded or anchored). Conventional structures generally are relatively stiff with fundamental periods less than about 7 seconds. Compliant systems, on the other hand, are designed to have much longer periods of say greater than about 20 seconds. The dominant wave energy range of 7 to 20 seconds is generally avoided because of costs associated with achieving fatigue and overload resistance in this regime.

One of the major challenges of engineering for deepwater systems is the economic one. Because of the expense of even the most minimal facilities in deepwater, development can only be justified by relatively large fields. Generally, the most attractive scheme is to minimize the number of facilities in a field development. Thus, deepwater systems tend to be large, with a high concentration of wells and decks laden with processing and drilling equipment. However, in a number of situations minimum facilities have been found to be viable.

Conventional deepwater structures are, for the most part, extensions of shallow water concepts. The steel jacket is by far the most prevalent type of offshore structure with several thousand presently in existence. This is a spaceframe structure founded on steel pipe piles. Figure 1 shows a conventional platform for about 381 meters of water. The piles supporting this structure consist of main piles driven through the main legs and skirt piles driven through the sleeves attached near the bottom of the structure. The structures are typically barged to the installation site, launched, placed on bottom temporarily on "mud mats", and piles are then driven to permanently fix them to the ocean floor. The deck systems and facilities are normally placed after the foundation is secure. To date (1988), the Bullwinkle platform is the tallest such structure yet installed. It stands in 411 meters of water in Green Canyon Block 65 in the Gulf of Mexico. Its completed height will be 492 meters (to top of derrick) with a 122 m by 130 m base. The jacket weight is 45,000 metric tons. The project costs for development is reported to be in excess of $500 million (U.S.). Classifying this as a conventional structure may be a bit of an understatement; it certainly should not imply that innovation is any less important in such a design.

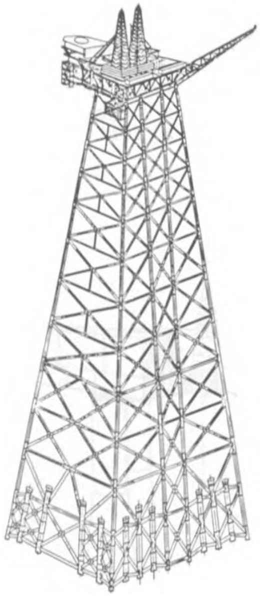

Figure 1. Conventional steel jacket structure.

Also falling into the conventional category are gravity structures - structures that achieve their stability through the use of shallow mat-like foundations and their large self weight to prevent overturning. A typical example is shown in Fig. 2. These structures have primarily been used in the North Sea, on hard glacial deposits, in water depths on the order of 150 meters or less. One of their attractive features is the large storage capacity that can be accommodated in the structure base. Recent innovations have extended this concept to deeper water and softer sediments using the deep skirt concept. Shear skirts on the order of 20 to 30 meters have been designed to mobilize deeper, stronger foundation soils. The Gullfaks C platform, currently under construction (1988), will be the largest of this class. It is intended for 216 m of water and the concrete skirts will penetrate 22 m into the seabed. The total concrete volume in the structure of 246,000 m^3 will make this the heaviest offshore structure yet installed. Gravity structures are towed to the site using self buoyancy and ballasted down to achieve skirt penetration. Deck systems and facilities are often carried out intact with the structure.

A number of compliant concepts have been suggested for deep water. The economics can vary significantly with water depth, operating environment, production requirements, and construction market conditions, making it difficult to generalize regarding conditions favoring selection of a particular system.

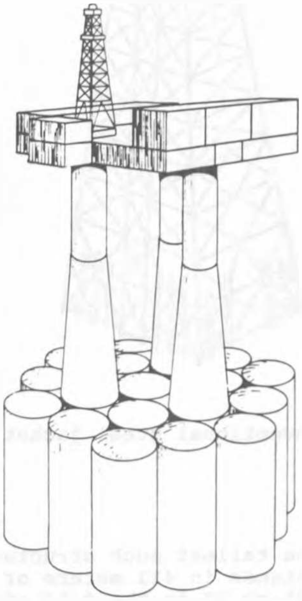

Figure 2. Conventional gravity structure.

One of the earliest concepts employed was the guyed tower. It consists of a relatively slender tower to support vertical loads and a system of guylines to provide a lateral restoring force. Support of the structure weight at the seabed can be through piles or a "spud can" which is seated in the soil. One of the most attractive aspects of the structure is that conventional drilling and production operations are employed. Only one full scale guyed tower has been installed to date, in the Gulf of Mexico Lena Field, in about 300 m of water. It has performed very much as expected and its reliability has been established. On the other hand, its complexity and cost have motivated a continuing search for improvements. Several other versions of compliant towers have been developed using different combinations of bouyancy, inertia, and tower flexibility to achieve compliance. One very promising concept that has evolved, applicable to a broad range of water depths, is the compliant piled tower (CPT). The CPT, shown in Fig. 3, consists of a slender tower supported by piles tied off to the tower well above the mudline. The piles behave like giant vertical springs providing the lateral restoring force, vertical support, and the resultant compliant behavior.

Another important class of systems are floating systems that are anchored to the seafloor. Certainly, the most publicized of this group is the tension leg platform (TLP). The concept typically employs a semi-submersible hull which is anchored with vertically tensioned members as shown in Fig. 4. This method of anchorage virtually eliminates heave, pitch and roll. The anchorage may be effected with piles but other concepts such as gravity foundations or "suction" caissons are under active consideration. At this writing, one TLP has been installed - in the Hutton

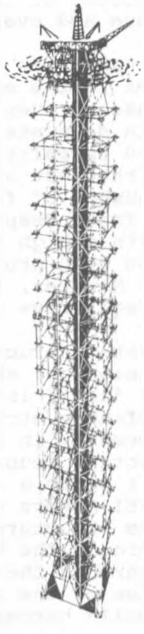

Figure 3. Compliant piled tower.

Figure 4. Tension leg platform.

Field in 146 m water depth. While this water depth would normally call for a conventional platform, the operator apparently used this development as an opportunity to establish the viability of the concept.

The Floating Production System (FPS) is another concept employing a floating vessel - normally a semi-submersible or a ship. The vessel is anchored to the seabed using a more traditional catenary mooring system. The anchors themselves may be drag anchors or other foundation concepts such as piles or caissons may be employed. Several floating production systems are now in service, perhaps the most notable being the recently installed facility in the Gulf of Mexico, Green Canyon Block 29 in 470 m water depth.

Finally, it should be mentioned that subsea production systems have many potential deepwater applications. The presently favored concept is a highly simplified system used in conjunction with more extensive surface facilities (existing platform). Foundation requirements are normally modest but often do have unusual design requirements such as the need to resist an eccentric, horizontal pipeline pull.

The foregoing constitutes a very brief survey of current deepwater production concepts. Clearly, this is a rapidly evolving area and one can expect to find new concepts as well as combinations of current concepts being employed. Foundation design requirements are highly varied. While piles continue to be the favored foundation concept for most applications, new economical ideas are rapidly emerging; and with the very high costs involved, innovation is more important than ever.

Discussion leader's contribution: Deep skirt, suction caisson and other novel foundation concepts for deep water

Contribution de l'animateur: Jupe profonde, caisson ventouse et autres nouveaux concepts de fondation pour les grands fonds

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SYNOPSIS: Deep water deposits are often characterized with soft normally consolidated clays. This presentation paper will therefore concentrate on foundation principles developed to accommodate such soil conditions.

1 GRAVITY STRUCTURES WITH DEEP SKIRTS

One approach to foundation design in deep water was to construct a large foundation or to spread out the foundation area on multiple footings, like for example the Condeep T300 concept with three pods. However, a more attractive approach turned out to be long skirts which transfer the foundation loads down to stronger and less compressible soil on less total foundation area.

There may be practical or economical limits to the skirt depth, like for example available water depths at construction sites and along towing routes. There is, however, also a technical limit to how much the foundation area can be reduced. The foundation rotational stiffness is roughly inversely proportional to the third power of the foundation diameter. The stiffness will therefore decrease faster than the foundation area. The first natural period of the structure will approach the wave periods where significant energy occurs and excessive dynamic amplification of the wave induced response therefore sets a limit to the reduction of the platform foundation area.

A major part of the foundation design has therefore been to improve and develop the procedures for analysis of foundation stiffness which constitute an important boundary condition in the dynamic response analysis of the platform.

Although the foundation bearing capacity is performed following limiting equilibrium procedures where the loading is assumed to be static, the cyclic shear strength used in the analysis takes the complete cyclic loading history into account. The overturning moment loading predominates on a deepwater gravity platform, Fig. 1. Various rotational types of failure mechanisms must therefore be investigated as a part of the bearing capacity analysis.

Because of the high cyclic stresses concentrated below the edge of the platform, the procedure for bearing capacity analysis must also be able to take into account the effects due to redistribution of stresses in the soil. These high stress concentrations have also raised the concern that local plastic deformations and redistribution of stresses during cyclic loading could induce settlement of the platform. Consequently, practical procedures for the assessment of the different settlement components induced by cyclic loading were developed during the design studies of deepwater gravity platforms.

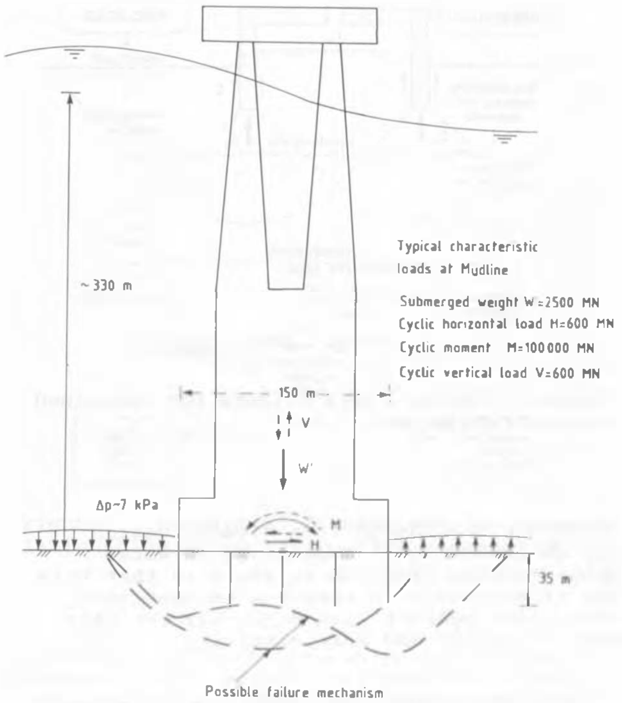

Figure 1. Geometry and loads for a typical North Sea deepwater gravity platform on soft clay.

The calculation of traditional settlement components due to the submerged weight of the platform includes challenging aspects, due to the long skirts which act as piles and reduce the platform settlement compared to a foundation with shallow skirts. Different ways of reducing the settlement of the platform exist, e.g., deballasting or hydraulic surcharging of the soft soils within the skirt compartments.

Application of suction pressure within the skirt compartments provides huge forces that can help the penetration of the long skirts. The maximum suction that can be used is limited by "bottom heave failure", Fig. 2. However, the penetration force available usually exceeds the penetration resistance by an ample margin for the structures and soil profiles studied to date.

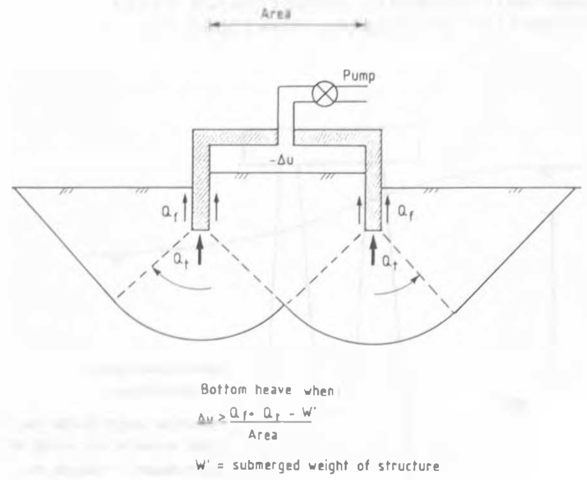

Figure 2. Bottom heave failure for undrained loading conditions.

A common conclusion from several design studies in soft soil conditions in water depths ranging from 200 to 350 m is that this type of structure is feasible to construct, install and operate within the current standards of safety and serviceability.

2 OTHER FOUNDATION STRUCTURES INSTALLED BY SUCTION

The principle for penetration of long skirts into a soft seabed by evacuating the water entrapped inside the cells gives possibility for several attractive areas of applications.

Since a very limited submerged weight of the structure is necessary for installation, the principle can be used to install long-skirted foundation structures for any purpose where a foundation or anchor is needed. Footings for each leg on a jack-up rig may be pre-installed on the sea bottom prior to the installation of the structure. Similar footings may be an attractive alternative to pile groups on jackets. Any type of protection structure for subsea installations can also be installed by this principle.

The concept has proved to be an attractive alternative to a piled foundation for a Tension Leg Platform (TLP) being considered in the North Sea. The idea is to install one independent anchor structure for each group of tethers which connect the platform to the sea bottom. The static tension load can be balanced by the submerged weight of the structure and additional ballast, Fig. 3. A cyclic component will add to the permanent load during a storm. Contingency requirements and the inclination of the tethers during peak loading will produce an eccentricity of the vertical load and a horizontal load component. In many cases it is therefore likely that a rotational sliding becomes critical in the bearing capacity analysis. The procedures developed for gravity platforms are fully applicable to this type of structure for analyses of bearing (holding) capacity, settlements and displacements.

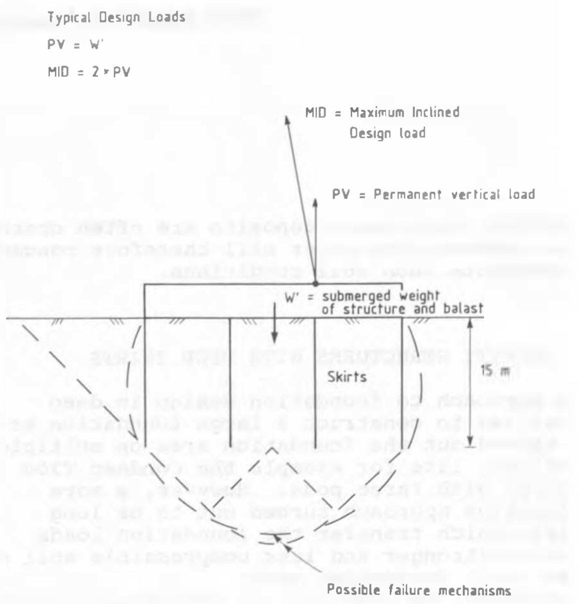

Figure 3. Geometry and loads for one of a TLP suction anchors on clay.

Panelist contribution: Deep water integrated geoscience studies

Contribution de panelist: Etudes intégrant les sciences de la terre pour les grands fonds

ALAN G. YOUNG, Fugro-McClelland, Houston, Tex., USA

SYNOPSIS: Deepwater site investigation requirements have motivated the development of integrated geoscience studies. These studies provide not only high quality design data but an understanding of regional site conditions.

The first offshore geotechnical investigation for an oil and gas production platform was performed in 1947 in six meters of water off the coast of Louisiana. The equipment and techniques used for the foundation boring were the same as those commonly employed for buildings on land. Technical and operational advances now allow studies to be conducted in water depths in excess of 1,000 m. Unlike earlier investigations, the geotechnical engineer today works closely with other marine specialists such as geologists, geophysicists, and geochemists. The results of studies by this geoscience team are integrated and a model is developed which explains the significance of the engineering properties of the sediments and the potential geologic constraints on the design and installation of foundations.

The stages of a typical deep water integrated geoscience study are as follows:

(1) review of existing data and planning of field phase,

(2) geophysical data acquisition field survey, and collection of samples of seafloor soils,

(3) initial geophysical, geological, and geochemical data interpretations,

(4) geotechnical field investigation and collection of deep-soil samples for engineering, geologic and geochemical testing,

(5) extensive geotechnical, geological, and geochemical laboratory testing, and

(6) final integration, synthesis, and analysis of all data.

The engineering properties, environmental conditions, and geologic processes on the continental shelves are reasonably well understood in most instances. The new challenge for deep water geoscientists will be to understand geologic processes that have formed the sediments, the distribution of new sediment types, and their importance relative to marine foundations. Good engineering design requires both a knowledge of the engineering properties of foundation materials and an understanding of the risks to construction and operation of production facilities from the deep water environment.

Geologic features of the deep water continental slope in the Gulf of Mexico which are more prevalent than on the adjacent continental shelf include: (1) slope instability, (2) gas-charged sediments, (3) active faulting, and (4) steep and irregular slopes. Careful study of the geologic phenomena in the proposed area of construction is needed to assess whether they represent "hazards" to the facility or merely "engineering constraints" which can be compensated for in design and site selection. Deep water integrated geoscience studies typically follow a work plan such as illustrated in Figure 1. This plan allows the geoscience team to develop an initial model defining the geologic structure, stratigraphy, and geologic history of the site. With subsequent acquisition of geotechnical data, the engineering significant of the features can be judged in the context needed to achieve safe and economical long-term performance of marine foundations.

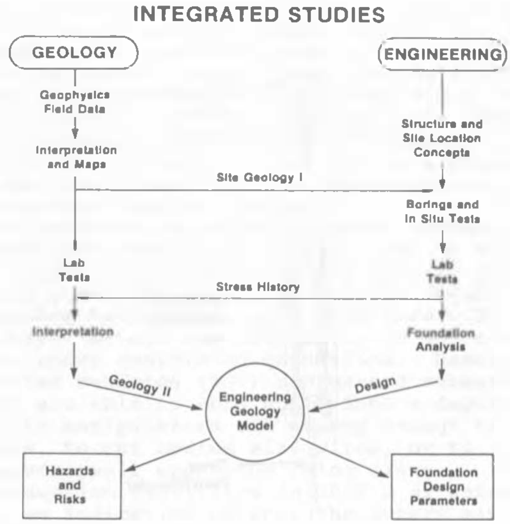

Figure 1. Conceptual diagram showing interrelationships among engineering and geology.

Conventional high resolution seismic and side-scan sonar geophysical methods commonly used on the continental shelf will not generally provide the quality of seismic data needed in water depths greater than 400 m. To fill this need, geophysical methods have undergone significant technical improvements. Present deep-tow seismic equipment allows data acquisition in water depths up to 3,000 m and in areas with steep and irregular seafloor slopes. Continued improvement in seismic tools will further enhance deep water surveys by: (1) improving the cost effectiveness of survey coverage, (2) expanding the use of digital data acquisition, and (3) improving real-time data processing, image enhancement, and feature extraction. Future developments of seismic tools that can operate from autonomous vehicles are needed to improve deep water geophysical surveys to avoid the operational difficulties associated with long, deep-tow cables operated from oceanographic vessels.

In the last decade, geotechnical equipment and drilling vessels have undergone major improvements allowing investigations to be performed in water depths up to 1,100 m. Dynamically-positioned geotechnical drill ships have been built and operated with a fixed derrick, a hydraulic power swivel for rotary drilling, and motion compensated drill and lift lines to operate a seafloor reaction frame as shown in Figure 2. A variety of high quality sampling equipment have also been constructed and operated in both "downhole" and "seafloor" modes. To overcome some of the analytical complications associated with stress relief and disturbance to soil samples, in situ testing systems have been constructed that allow testing with instrument systems which include: (1) cone penetrometers, (2) vane shear devices, (3) pressuremeters, and (4) piezometers.

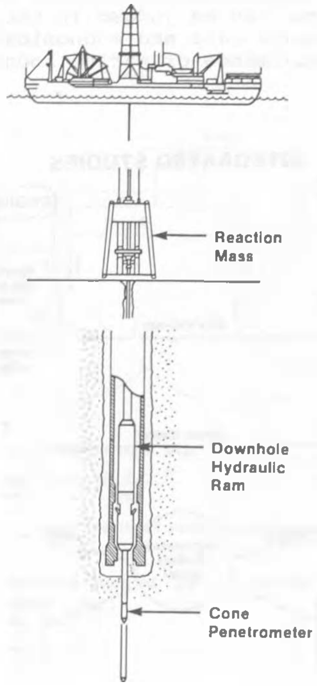

Figure 2. Dynamically-positioned geotechnical drill ship and specialized in situ testing equipment.

To circumvent the high cost of operating dynamically-positioned vessels to acquire shallow-penetration soil data, a new system has been recently developed that can be operated as a tethered seafloor platform from a smaller oceanographic vessel, Figure 3. This "mini-probe" test device features a thrusting unit that uncoils and straightens a steel rod while it thrusts the rod to seafloor penetrations up to 13 m. An instrumented probe on the end of the rod is used to measure in situ sediment properties. The system also has the capability to be operated from a remotely-operated vehicle (ROV) and use the ROV's data and power system while it maneuvers independent by the surface-support ship. The challenge is to extend the capability of this system to deeper seafloor penetrations and into deeper water.

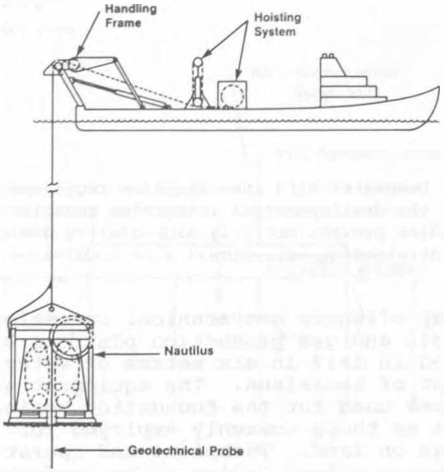

Figure 3. Deployment of a compact tethered seafloor platform.

Great technical strides have been achieved in the last decade that allow high quality geoscience data to be acquired in water depths up to 1,000 m. As marine development moves into even deeper water, the practical "doer" and state-of-the-art "researcher" must combine their talents to develop the new technology required for this frontier environment. Although these studies will be much more operationally difficult and technically complex, past experience indicates that the necessary technology can be developed to accommodate the move into even deeper water.

Panelist contribution: Pile foundations in deep water
Contribution de panelist: Fondations sur pieux par grands fonds

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SYNOPSIS: Piles have been the favored foundation concept for the majority of offshore facilities. New advances in technology promise to maintain the viability of pile foundations in water depths of many hundreds of meters.

The first offshore piled structure, designed for oil production purposes, was installed 43 years ago in the Gulf of Mexico. It was a wooden jacket platform located in 6 m water depth. Since this time the oil prices have increased, justifying the viability of deeper structures. At this writing (September 1988), the foundation template of the "Jolliet Tension Leg Well Platform", in 543 m of water, Green Canyon Block 184, Gulf of Mexico, is the deepest structure yet installed.

The main differences between shallow and deepwater piled foundations are notable, not only regarding the installation procedures and equipments, but also the geotechnical design. Deepwater foundations have resulted in larger and more problematic foundations, as a consequence of the following:

1. While shallow platforms are located on continental shelves where smooth seabeds are usual, structures deeper than 200 m are situated on continental slopes. Gradients on the order of 2^{o} to 10^{o} or more, can introduce slope instability problems.
2. The further from the shore, the superficial layers tend to be more cohesive, highly plastic and with a reduced degree of consolidation. These are normal to underconsolidated soft clayey soils with low shear strength.
3. Conventional platforms in deepwater have greater pile head loads due to self weight and more severe environmental conditions, and
4. In tropical areas seawater temperatures lower than 8^{o} to $4^{o}C$ can be encountered only in deep waters, that provide conditions for hydrate condensation occurrences mixed in the soil mass, causing potential local foundation instabilities.

In general, two basic piling philosophies have been used: driven piles for the majority of the foundations since the earliest installations, and drilled and grouted piles, more applicable for special cases (i.e., carbonate soils) or for foundation reinforcement (insert or bell piles). Driven piles started with wooden piles which were installed using free-fall hammers. Piles have changed so much and today steel open-ended pipe piles up to 2.5 m (o.d.) are the most common type, sometimes reaching 160 m one-piece length to be driven to 110 m penetration (the longest pile on record is 300 m including 6 add-ons welded offshore, while the deepest are 142 m penetration). In addition, new concepts have been applied, such as specially driven and grouted solutions. In at least one case, for large diameter pipe piles, the old closed-end pile was reintroduced. Both of these applications were in calcareous sand.

To accompany design requirements hammers had to have increased energy output and were improved accordingly. Starting with steam and diesel hammers, with or without followers, the most recent advance came in the late 70's with hydraulic hammers capable of both surface and underwater driving. In spite of hydrostatic pressure, updated underwater models with nominal energy up to 3000 KNm can drive in depths beyond 2000 m of water. Energy loss is a typical problem to be minimized by improvements in ram/anvil/follower/pile system geometry. Underwater handling/stabbing operations could be improved by use of thrusters in the near future.

For drilled and grouted piles, it is possible to use direct or reverse circulation methods, with seawater or bentonite mud as drilling fluid. Reverse circulation introduces advantages in hole wall stability, but due to air-lift pressure limitations, have not been efficient for deepwater foundation. The use of a 2.1 m (o.d.) drill bit is a record. On the other hand, drilling rigs using direct circulation have no limits.

For handling piles and inserts, hydraulic clamps were developed to lift loads up to 10 MN. Instead of relying on umbilicals, remotely actuated release mechanisms permit deepwater tasks to be performed more efficiently. Divers may operate up to 400 m of water under restricted conditions. Remotely operated vehicles (ROV) and manned submarine units are able to work up to 1500 m depths. Vehicle manipulators are strong enough to open valves, to cut medium size wires, or to maneuver small apparatus using claws.

Production facilities in 2000 m of water give an indication of what the future may hold.