Examples include:

- pipeline route investigations that traverse from deepwater to continental shelves;
- seabed investigations in areas of previous slope failures;
- investigations in the vicinity of iceberg gouges;
- investigations on rocky seafloors; and
- operations within the vicinity of sand waves.

Operations on steep slopes present additional challenges to the safe operation of seabed investigation equipment. Information on seafloor slopes is normally obtained from the interpretation of geophysical site investigations or 3D seismic data. This information should be made available during the early stages of equipment selection, if steep slopes can be encountered.

The capabilities (and where appropriate the limitations) of the proposed geotechnical investigation equipment to effectively operate on the expected seafloor slopes are normally the responsibility of the geotechnical contractor.

The client should familiarize himself with the capabilities of the proposed investigation equipment, and the potential impacts on the quality of the acquired data. Special deployment methods, and/or specialist investigation equipment, may alternatively be selected to ensure accurate data are acquired in a safe manner.

B.3.2 Factors affecting equipment performance on steep slopes

The client should consider the following factors in assessing equipment performance on steep slopes:

- the expected strength of the upper seabed at the proposed investigation sites, and whether the applied surcharge of the equipment can lead to seabed instability;
- whether the operation of the equipment, resulting in vibrations, additional torsional or vertical loads, could result in seabed instability;
- whether the ‘out-of-levelness’ of the template will impede the passage and operation of the drill string;
- the capacity to measure the height of the drill centre above the seafloor at the centre of the machine;
- the local variability of the slope, and whether this is likely to affect the capacity of the system to land and remain stable during drilling operations.

A large proportion of equipment currently available for marine soil investigations can safely operate on seafloor slopes of up to 5°. Wherever seafloor slopes are identified at an investigation site, due account of the practical operating capabilities of the selected equipment should be taken into consideration. It should be noted that the capacity for equipment to operate on seafloor slopes can be reduced where non-uniform (for example rocky) seafloor slopes are encountered.

Annex C
(informative)

Drilling and logging

C.1 Drilling methods

C.1.1 General

A variety of drilling methods and equipment are available. This part of ISO 19901 primarily considers rotary drilling techniques. Guidance can be found in ISO/TS 22475-2 and ISO/TS 22475-3 for further description of equipment and personnel for onshore/nearshore soil investigations (presented herein where relevant).

In rotary drilling, the rate of penetration (ROP) depends on a combination of the characteristics of the bit, the pressure and volume of flow of drilling fluid (mud pressure and mud flow), the normal force between the bit and the bottom of the borehole (weight on bit), and the characteristics of the material being cut. Depending on the objectives, the driller adjusts the combination of weight on bit, drilling fluid pressure and flow, and drilling fluid characteristics in order to advance the borehole.

When drilling from a floating vessel, cyclical variations in weight on bit (and hence soil disturbance) are induced by vertical motions at the drill floor. These motions are attenuated by employing a heave-compensation system. Appropriate equipment should be identified for the defined drilling objectives. Where optimal data quality is an objective, the hard-tie heave-compensation system offers a high performance option, particularly in softer soils.

Appropriate drilling equipment and methods should be identified for the defined drilling objectives. Within the two main modes of deployment (i.e. vessel-drilling mode and seafloor-drilling mode), the typical types of rotary drilling are:

— ‘open-hole’ or ‘core’ drilling;

— ‘uncased’ or ‘cased’ drilling;

— ‘riserless’ or ‘riser’ drilling.

C.1.2 Open-hole versus core drilling

In rotary open-hole drilling, sampling and *in situ* testing are performed on undisturbed material ahead of the bit by pushing (and other means such as percussion) specialized wireline tools through the open centre of the bit.

In rotary core drilling, core samples are recovered either as cores typically 1,5 m to 3 m long, recovered by a drop-in wireline coring system, or as long continuous lengths of core typically 6 m or more, recovered by pulling the complete drill string out of the borehole to recover the core barrel. However, in the latter case, a re-entry system is needed in order to re-enter the existing borehole to advance to the next core interval.

The drilling technique adopted is largely governed by the expected soil conditions, the requirement for sample quality, and required *in situ* testing. Open-hole drilling with sampling and testing by downhole tools is generally appropriate for uncemented formations, and for some weakly cemented soils or very weak rock formations (e.g. highly weathered chalk). Rotary core drilling is generally appropriate for cemented soils or rock formations, and can also be a good alternative in hard boulder clays, especially if recovery is more important than sample quality.

In some cases, a combination of the two techniques can be employed, with three different coring systems and procedures, given below, that can be adopted.

a) Pull out the open-hole drill string completely and run in a rotary coring drill string. This approach requires additional pipe handling, but maximizes core sample diameter and ensures that the most appropriate drill bit is always used for the formation encountered.

b) Pull the open-hole drill string back a short distance from the bottom of hole, then run a coring drill string through the centre of the open-hole string (termed 'piggy-back coring'). This approach requires some additional pipe handling, possibly an additional top drive unit, and the sample diameter is reduced, but borehole integrity is ensured and the most appropriate drill bit for the formation encountered can be used. This mode of operation requires a seafloor frame to be clamped onto the drill string in order to prevent the open-hole drill string from heaving within the borehole due to the motion of the vessel.

c) Drop a wireline core barrel through the open-hole drill string to latch into a specialized open-hole drilling BHA. This approach saves pulling or running any additional drill string, but requires continued use of the open-hole drill bit, which can be less appropriate for the formation to be cored and can result in poorer quality core sample and/or reduced recovery.

C.1.3 Uncased versus cased drilling

Most marine soil investigations are performed using equipment in uncased, open-hole rotary drilling mode, where a single tubular (the drill string) runs from the drilling platform.

At sites where borehole stability can be an issue (such as excess pore pressure regimes or very deep boreholes), or where project-specific objectives demand (e.g. 'piggy-back coring'), it can be necessary to install one or more casing strings prior to completing the borehole. Casings can be either specialized casing tubulars run separately, or drill pipes doubling as casing once a certain depth (or other criterion) has been achieved. Multiple concentric casing strings, reducing in diameter as the borehole advances, can be employed and specialized handling equipment and procedures can be required.

C.1.4 Riserless versus riser drilling

Most marine soil investigations are performed in riserless drilling mode, where drilling fluids and cuttings flow between the annulus of the borehole and the outside diameter of the drill pipe and end either at the top of the borehole (i.e. at seafloor) or at the top of the casing string. With riserless drilling (also termed 'total loss drilling' or 'drilling with fluid returns to seafloor'), all drilling fluid and cuttings exit the borehole in a plume which is either dispersed by sea-bottom currents, or from which cuttings settle out of suspension to form a mound in the vicinity of the borehole.

With riser drilling, a tubular casing extends from the borehole back up to the floating vessel or platform. This allows the recovery of drilling fluid and cuttings, either for recirculation, for retention of the fluids and cuttings (e.g. in areas where zero discharge-to-sea is required), or to sample the cuttings. Riser drilling requires specialized handling and processing equipment and procedures (see ISO 22475-1). In particular, care is needed to ensure that the elevated hydraulic pressure exerted on the borehole walls by the hydraulic head of drilling fluids between the water surface and the riser top does not lead to hydraulic fracture of the formation, which can lead to loss of drilling fluid into the formation and can compromise borehole stability or sample quality.

C.2 Selection of drilling equipment and procedures

C.2.1 Drilling equipment applicability considerations

In order to assess the applicability of a particular drilling spread of equipment for a given set of project-specific requirements, details of the equipment to be provided should include the following:

— operating platform description (i.e. floating or fixed platform, moonpool or over-side deployment, submersible drill rig) with nominal operating limits (i.e. sea/tide/current/wind);

— drilling system capacity, with drill mast/derrick height, weight capacity under the power swivel (i.e. maximum mass of drill string including drill collars and BHA), and details of draw-works heave-compensation system (type, maximum capacity, full-stroke length and usable-stroke length) if in floating vessel mode;

— specification of drill pipes and drill string handling system, with maximum length of drill string that can be handled and maximum pipe stand length;

— description of drill bits carried onboard, and rotary coring system (if any);

— details of the seafloor frame, and of its heave-compensation system (type, maximum capacity, full-stroke length, usable-stroke length);

— mud system details, with mud pump(s), mixing capacity, number and volume of mud tanks, maximum pumping rate;

— drilling parameter logging system (i.e. automated or manual, parameters logged, reporting format and system limitations);

— manning levels required on the drill floor, with location of controls for drilling and wireline downhole equipment, pipe and wireline tool handling systems.

Table C.1 offers guidance on drilling equipment characteristics relevant to particular project requirements. It can be used to help identify appropriate or inappropriate equipment.

Table C.1 — Drilling equipment selection considerations

Priority	Project-specific requirements	Principal drilling equipment selection considerations
1	Water depth and sea conditions	Seafloor drilling/vessel drilling/availability/hook capacity/power/heave compensation
2	Soil conditions	Open-hole/rotary coring/uncased/cased/riserless/riser/power
3	*In situ* testing and sampling	Open-hole (or combination)/seafloor reaction frame/heave compensation
4	Borehole depth	Uncased/cased/riserless/riser/power
5	Drilling hazards	Uncased/cased/riserless/riser/pilot hole/specialized equipment
6	HSE and extreme working environment	Specialized equipment (minimized manual drill floor interventions)
7	Environmental discharge	Riserless/riser
Modifier	Optimized data quality	Accurate heave-compensation/seafloor reaction frame
Modifier	Optimized data recovery	Working height (maximum length of downhole tool that can be handled)
Modifier	Optimized rate of progress	Power/mud flow

C.2.2 Drill bit selection

The selection of drill bit should be made based on the expected soil conditions, required drilling, logging, sampling and/or *in situ* testing techniques, and whether optimal sample quality or maximum rate of penetration (ROP) is required.

Where sampling or testing is required, an open-centred bit ('core bit') is used in open-hole drilling mode. For drilling without sampling or testing, a close-centred destructive drilling bit can offer greater ROP. Also available are drop-in 'centre' bits which latch into the BHA to convert an open-centred bit into a close-centred bit, and can subsequently be recovered by wireline overshot.

For open-hole drilling in uncemented marine soils, a drag bit is likely to be the preferred solution. The drag bit is particularly appropriate where it is expected to encounter clay strata (which can have a tendency to 'ball' and block the discharge ports of other bit designs, which can lead to bit damage and/or significantly reduced ROP). For other ground conditions (principally rock), ISO 22475-1 provides additional guidance regarding bit selection.

The following factors should be considered for drill bit selection:

— range of bits for the possible soil conditions, drilling problems and hazards that could be encountered;

— criteria for change of drill bit;

— positioning of drilling fluid discharge ports and bit geometry (i.e. the bit should be balanced to minimize the tendency of the borehole to deviate from the axis).

C.2.3 Drilling fluid

The function of the drilling fluid is twofold: to carry drill cuttings away from the cutting face, and to prevent the drill bit from overheating. However, depending upon its specific characteristics, the fluid can also serve a number of other functions:

— borehole advancement, i.e. cutting soil ahead of the bit by hydraulic action;

— borehole stability, i.e. formation of a stable 'cake' around the wellbore thereby helping prevent cave-in of the borehole walls, particularly in loose non-cohesive or over-pressured formations;

— prevention of drill cuttings from settling back to the bottom of the borehole while pumping is stopped, for example when running a sampling or *in situ* testing tool;

— control of hydrostatic pressure in the borehole.

Drilling fluids are typically based on seawater (or fresh water), and in many cases water alone is sufficient, provided the mud system is able to deliver adequate flow rate and pressure. When defining the drilling fluid to be used, consideration should be given to the potential for adverse chemical interactions of the drilling fluid (including seawater) on the soil, e.g. low salinity seawater with high salinity soil.

If the drilling fluid is required to perform additional functions, then one or more additives can be included to give the necessary characteristics, e.g. the addition of barite to give a heavy 'kill mud' suitable for controlling a shallow gas event. Additives can be supplied in liquid or powder form, and specific mixing procedures should be followed (with due regard to HSE considerations). It may be necessary to periodically test samples of the mixed fluid to ensure that the desired consistency and viscosity characteristics are maintained across multiple batches.

For complex borehole constructions, or in difficult soil conditions, it is recommended to seek advice from experts regarding design of an appropriate drilling fluid programme.

C.3 Drilling operations plan

The drilling operations plan describes the process of considering and documenting the drilling activities relating to the soil investigation. The drilling operation plan may be documented in a stand-alone document (suitable for daily reference by the drilling crew), or may be part of the soil investigation execution plan in the PEP.

For the range of possible soil conditions, the drilling operations plan should describe the full sequence of activities and contingencies for each borehole, from initiation to completion. It should consist of the following basic components:

a) drilling equipment and operational details;

b) borehole construction plan, describing the sequence of borehole construction (with drill string details and drill bit selection), identification of possible drilling problems, borehole abandonment procedures and grouting procedures (if required), and contingencies or remediation options (e.g. in the event of stuck string or tool lost in the borehole);

c) mud plan, with the drilling fluid solution adopted and criteria for change of fluids;

d) requirements for recording drilling parameters (as appropriate);

e) sampling and *in situ* testing schedule and procedures;

f) shallow gas plan (where relevant, see C.4);

g) grouting plan (if required), with the grouting fluid/additives selected, grouting procedures and requirements for grout testing (i.e. grout cube crush tests and acceptance criteria).

C.4 Shallow gas

C.4.1 General

Shallow gas can pose a significant hazard to drilling operations, and efforts should be made to avoid release of gas into the sea and atmosphere. In order to minimize both the likelihood and consequences of such a release, a site specific assessment should be undertaken which should include the following:

— 'hazard assessment' for the specific location and planned activities, to identify the likelihood of encountering gas during the soil investigation;

— 'risk assessment', for the geotechnical vessel/platform, to identify zones of high, intermediate and low risk with due consideration of the consequences of gas release and mitigating measures.

C.4.2 Hazard assessment for specific locations

The site-specific hazard assessment is usually performed by the client, but it should be incumbent upon the soil investigation contractor to ensure that the hazard assessment conclusions are aligned with his own procedures and that the risks (probability x consequence) which the hazards pose to the planned operations are assessed properly.

The hazard assessment would typically consider the following:

— regional geology/desk study;

— site-specific geophysical data (considering type, quality, resolution and timing of the data acquisition);

— potential for changes since geophysical data acquisition (e.g. due to well-drilling activity);

— potential depth, pressure and volume of shallow gas;

— alternative sources of free gas, and gas characteristics (composition, toxicity, flammability, density);

— planned soil investigation activities, e.g. seafloor-mode operations, borehole drilling/sampling/*in situ* testing operations, pilot-hole drilling, distance to production infrastructure.

There are three possible outcomes of the hazard assessment for a specific location as listed below:

a) low probability of encountering gas;

b) intermediate probability of encountering gas;

c) high probability of encountering gas.

C.4.3 Risk assessment and gas procedures

C.4.3.1 Depending upon the hazard assessment outcome, all areas of the geotechnical drilling vessel/platform should be assessed, i.e. specific areas of potential gas release or accumulation identified, and area classification layouts for the vessel developed (guidance on hazardous area classification for drilling facilities is given in IEC 61892-7).

Typically, the risk assessment should consider

— specific activities, such as riser/riserless drilling, adding/tripping pipe, sampling/*in situ* testing, potential sources of ignition, soil sample handling, entry to confined spaces, etc.,

— consequences, e.g. loss of vessel buoyancy, vessel flooding due to rolling water, blowout, fire/explosion, poisoning (gas toxicity),

— proportional mitigating measures.

C.4.3.2 Even for a low probability of encountering gas, it is prudent to consider the implementation of residual risk mitigation measures. See C.4.3.3 regarding mitigation measures which should be considered.

C.4.3.3 In drilling areas with intermediate probability of encountering shallow gas or free gas, special procedures should include the following:

— safety meetings of all crew members;

— review of the duty watch/chain of command in emergency gas drill;

— conduct of move-off exercise;

— no hot work or smoking on deck;

— gas detectors (in the moonpool and in the derrick) and gas alarm;

— wind and current meters to ensure vessel is positioned optimally with respect to the wind and current to minimize accumulation of gas on deck;

— general look-out or dedicated bridge watch for bubbles surfacing in the vicinity of the vessel/platform;

— investigate the possibility of having heavy 'kill mud' available (together with rapid switch-in and high capacity pumping system).

— consider drilling a dedicated pilot-hole during daylight hours with a non-return valve in the lower part of the drill string and no running of downhole tools,

— as a precaution against gas through the drill string, maintain a safety valve on top of the power swivel while using wireline-operated downhole tools,

— as a precaution against gas outside the drill string, maintain offset between the drilling vessel and the borehole (based on wind and current conditions). Typically, soil investigation operations can continue with horizontal offsets of around 5 % to10 % of water depth,

— suspend all non-essential crane operations,

— monitor penetration and pump pressure consistently.

If a shallow gas risk is identified, specialized training can be required not only for the drill crew but also for all crew members, consisting of a course on shallow gas preparedness (drill crew), shallow gas induction (all crew), and regular gas alarm drills (all crew).

C.4.3.4 In drilling areas with high probability of encountering shallow gas, further precautions such as the following are recommended in addition to those in C.4.3.3:

a) non-return valve in the lower part of the drill string while drilling and pulling pipe;

b) TV camera and/or sonar mounted on the seafloor frame or ROV;

c) pulling the sampling/testing tool out of the soil by lifting drill string while the downhole tool is latched into the BHA (with special attention to the swabbing effect when pulling tools out of the soil;

d) *in situ* gas measuring system, in order to ensure early warning before the gas-charged layer is penetrated;

Depending upon the source, characteristics and severity of the gas hazard, and on the drilling equipment employed, a variety of additional equipment can be considered for use in mitigation.

Examples of such equipment are:

— gas diverter on top drive unit;

— shear rams;

— mud valve;

— non-return valve in BHA;

— annular preventer on top drive (allowing the wellbore to be sealed with wireline tools in the hole);

— isolated moonpool chamber (with fresh air duct or HVAC system);

— zoned drill floor equipment;

— automatic shut-off for unzoned ship's equipment on gas alarm;

— personal portable gas detectors;

— breathing apparatus;

— intrinsically safe communications system.

C.5 Borehole geophysical logging

C.5.1 General

The geophysical logging of a borehole can provide an invaluable additional data set, and a variety of different parameters can be measured, recorded or inferred. A number of tools are available, some for in-pipe measurements and some for open-hole measurements [see Digby (2002) and ISO/TR 14685 for further information].

When defining a suitable geophysical logging scope of work, some of the following aspects should be considered:

a) required measurement types;

b) minimum number of measurements per logged depth section;

c) required sequence, direction and rate of travel for logging;

d) accuracy class for depth below seafloor, which should be given in project specifications according to Clause 6;

e) required correlations between measurements;

f) number of tools or length of logging section per run;

g) length of rat hole drilled;

h) whether a compensated logging line is required.

If a radiation-type logging system is planned, a qualified radiation protection supervisor should be onboard the soil investigation vessel, and operational procedures for these tools should be established to address the following:

— handling of radioactive sources in accordance with applicable regulations;

— heave compensation of wireline tools;

— contingency procedures to recover tools lost in the borehole or on the seafloor;

— contingency procedures in the event that it is impossible to recover a radioactive tool from the borehole (typically grouting).

C.5.2 Reporting of results

The report on logging results should include as a minimum:

— characteristics of the borehole geophysical logging system;

— details of borehole conditions according to Clause 7;

— open-hole logging versus in-pipe logging;

— sequence, direction and rate of travel of the logging probes in the borehole;

— accuracy class for depth below seafloor;

— presentation of results;

— definitions, formulae, assumptions and limitations of derived parameter values and applied correlations between measurements.

Annex D
(informative)

In situ testing

D.1 CPTU/CPT equipment and procedures

Guidance on the CPTU/CPT procedure and interpretation can be found in Lunne et al. (1997) and Schnaid (2009).

Cone penetrometers with dimensions outside the standard range may be used for special purposes, e.g. an enlarged cone for increasing the accuracy of the measurements in very soft clay. In such cases, it should be reported that non-standard equipment has been used. In Tumay et al. (1998) and Watson and Humpheson (2005) it is shown that, for some penetrometers, the measured cone resistance, q_c, can increase when carrying out a CPT/CPTU with a smaller cone diameter.

Empirical correlations developed for standard size penetrometers are not necessarily applicable/valid for penetrometers outside the allowable range, and should be used with caution in the absence of parallel testing using standard size equipment.

In some cases, important information can be obtained by carrying out tests at non-standard rates. If such tests are carried out, results should be clearly marked noting that non-standard rates have been adopted.

As covered in 8.3.4, it is important to correct cone resistance for pore pressure effects. It is also possible to correct the sleeve friction for pore pressure effects if pore pressures at the top and bottom of the sleeve have been measured or can be assumed.

The corrected sleeve friction can be determined from:

$$f_t = f_s - \frac{\left(u_2 \times A_{sb} - u_3 \times A_{st}\right)}{A_s}$$

where:

f_t is the corrected sleeve friction, in MPa;

f_s is the measured sleeve friction, in MPa;

A_s is the area of friction sleeve, in mm^2;

A_{sb} is the cross sectional area of the bottom of the friction sleeve, in mm^2;

A_{st} is the cross sectional area of the top of the friction sleeve, in mm^2;

u_2 is the pore pressure measured between the friction sleeve and the cone, in MPa;

u_3 is the pore pressure measured above the friction sleeve, in MPa.

This correction requires values of u_2 and u_3 and these parameters should preferably both be measured if this correction is to be made.

NOTE u_3 can be estimated from u_2 using correlations given by Lunne et al.(1997).

These corrections are most important in fine-grained soils where the excess pore pressure during penetration can be significant. It is recommended to use corrected values of the test results for interpretation and classification purposes.

D.2 Documentation of reference readings for CPTU/CPTs

D.2.1 CPTU/CPT, ball and T-bar tests in non-drilling mode

The following recommended procedure is applicable in non-drilling mode. Figure D.1 shows an example of results obtained during a CPTU in non-drilling mode.

With reference to Figure D.1, the test can be divided into the following time stages:

— Stage 1-2 - Initial acquisition of reference readings from all sensors at deck level. The reference readings should be recorded once the output signals from the sensors are stable. This should be undertaken with the cone penetrometer and rods at a temperature as close as possible to the seafloor temperature.

— Stage 2-3 - Lowering of probe to seafloor.

— Stage 3-4 - Recording of all reference readings once the probe is located at (but not in contact with) seafloor. The reference readings should be recorded once the output signals from the sensors are stable.

— Stage 4-5 - Penetration into seabed.

— Stage 5-6 - Extraction of the probe until it is located again at (but not in contact with) seafloor.

— Stage 6-7 - Recording again of reference readings from all sensors at the seafloor. The reference readings should be recorded once the output signals from the sensors are stable.

— Stage 7-8 - Recovery of the push frame and probe to deck level. Visual inspection of the probe for any damage, soil adhesion to probe, damaged or dirty seals, etc.

— Stage 8-9 - Taking final reference readings from all sensors at deck level. The probe should remain in a vertical orientation during these measurements. The reference readings should be recorded once the output signals from the sensors are stable.