Offshore rock investigations by a remotely operated submersible drilling rig with continuous drilling parameters recording (MWD)

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ABSTRACT

The submersible drilling rig presented in this paper was designed and constructed with the aim to allow conducting soil or rock characterization in offshore investigations in shallow water projects when short target penetrations are required. The system is instrumented with sensing elements allowing the full control of the operation in real-time for three different purposes: (i) positioning, (ii) continuous drilling parameters (MWD, measuring while drilling) and (iii) visual inspection. The suitability in sandy and silty soils was reported by Romero et al. (2012). The system is outstanding as an interesting alternative to traditional methodologies for rock investigations in relative shallow water projects where the knowledge of the first metres of rock profile is critical (e.g., pipelines, submarine interconnections, dredging, foundations). Some benefits of the system are presented in this paper, especially in ground models composed of a rock layer underneath a soil deposit or by rocks with variable strength with depth.

Keywords: Submersible drilling rig, Offshore rock investigations, Soil characterisation, MWD, Underwater exploration technology.

1. Introduction

The marine site investigation is a key factor for the correct development of any project that must be conducted offshore. There is a wide range of tools designed to get information of the seabed in case of soil, either in-situ tests or collecting samples. Nevertheless, in the case of a rocky seabed, the options are limited. Drilling vessels with heave compensation are available and are especially useful for deep-sea waters and large investigation depths. For nearshore projects, the use of jack-ups with onshore drilling equipment on board is also common but limited to the maximum length of the spuds. However, the cost of mobilisation of both systems is the main item in any geotechnical investigation and might be economically prohibitive. Therefore, there is a lack of a cost-effective system for shallow water projects when short target penetrations are required.

2. Geotechnical investigations. Deployment means

Marine spread selection is critical to gaining high quality data in a timely and cost-effective manner. Depending upon the specific site environmental conditions (wind, wave, current) and water depth, fixed platforms (jack-up rigs), anchored or dynamically positioned geotechnical vessels can be used. Appropriately equipped vessels can also deploy seafloor drills for applications such as cable route surveys (SUT-OSIG 2022).

2.1. Jack-up rigs

The geotechnical investigation platforms supported on the seabed are the most appropriate means of geotechnical investigation in areas of low water depths (<20 m). Depending on local conditions, it may be an alternative for water depths of up to 30 m. They are particularly suitable in case of large tides. On the platform it is possible the deploy drilling rigs by percussion and rotation, take samples of excellent quality and make in situ tests as in the onshore works. Moreover, large jack-up rigs have deck space for additional laboratory capacity and can even have accommodation units.

Jack-ups are weather sensitive, especially for moving from one investigation point to the next. Also, staff access is done once or twice per day. This operation requires good to excellent sea conditions, it is always a major HSE concern. Moreover, for large jack-ups the risk of foundation failure (punch-through and adverse leg penetration) is non-negligible. One of the most important limitations is that can only be moved when environmental conditions are within set limits.

2.2.Geotechnical vessels

Drilling operations from geotechnical vessels requires a complex system. A rotary head suspended from the derrick actuates the drill string. The sampling or test instruments are subject to a cable located around inside the drill string. After adjustment, these instruments are powered from the ship. When the operation finishes, the different devices are uploaded to the deck. Some elements of the scheme are not always present but are recommended to extend the operating range of the ship. Sometimes, the hull's internal bore (moon pool) is substituted with structures that position the tower away from the side of the ship .. To prevent damage to the material it is imperative that the ships used in the geotechnical investigation are fitted with motion compensation systems. Drilling must be isolated from the influence of the waves in all directions (movement in three directions, as well as balancing, steering and pitch). The effect of horizontal movements and rotations are usually compensated by dynamic positioning systems. The vertical or lifting movement is the most pernicious for being the cause of major changes in tension of cables and pipes for drilling activities. These effects are particularly harmful when performing a sampling or penetration operation by CPTu on the seafloor. In some cases, to avoid this problem, drilling operation from the vessel is assisted by a drill string clamp. This operation increases the cost and not all workers are prepared to do it. A common element in all geotechnical vessels is the heave compensator.

DP vessels with heave compensation can move fast between locations and are allowed for operations in marginal sea-state conditions. Nevertheless, the main drawbacks are the limited number of vessels in operation, the higher per diem cost than other options and the general unsuitability to shallow water operations and the difficult position-holding in high current areas.

2.3.Existing seafloor drill rigs

Seafloor drill has significant advantages with respect to jack-up rigs and geotechnical drilling vessels due to the lower HSE risk since no personnel is involved during drilling operations and there is a significant reduction in pipe handling.

There are some existing systems in the market designed for subsea operations. However, all drilling machines were designed to sustain up to several kilometres of water pressure and with large target penetrations. While the machines may be conceptually similar, this water depth and maximum penetration results in far more expensive components, requiring larger investment and maintenance costs. Moreover, they are restricted to either wireline or drill-string perforation. These methods are both capable of perforating most terrains, but they have optimal performance in a more restricted set of circumstances (wireline in competent rock, drill-string in soft soil).

Because of carrying larger in-built costs and because the relative efficiency gains of seabed drilling are even larger in deep-water, these machines have oriented themselves to the deep-water market. The daily rates commandeered by the more commercially active systems are well above even those of geotechnical drilling vessels. At this point, they compensate for this by more efficient performance and, crucially in certain deep-water environments, by their weather resilience.

Maybe the main draw-back of these systems is that the assessment of samples is delayed until the drilling unit is recovered to deck. In case of low recoveries, the system must be launched back with no option to drill out in the same exact location, so a new test must begin. Moreover, it is necessary the use of a DP vessel with appropriate deck space and launch and recovery system to deploy.

3. Small submersible rigs

In the market, there are very few underwater equipment options adapted for shallow water circumstances and short drilling operations, a factor significantly beneficial for certain types of projects such as submarine cabling, dredging, etc. For the present study, a system (MiniDrill®) has been employed that facilitates rotational drilling operations in a single manoeuvre up to 6m in depth into the terrain.

The system is outstanding as an interesting alternative to traditional methodologies for rock investigations in relative shallow water projects (up to 200 m water depth) where the knowledge of the first meters of rock profile is critical (Romero et al. 2012).

The equipment is assembled within a self-supporting rectangular frame. The drill mast is mounted on top and is allowed an altitude rotation from 0º to º120º with respect to the base. The tower support structure occupies 8.4 m2, the length of the whole system with the tower folded in horizontal direction is 7.51 m. These dimensions allow the easy storage of the entire system and ancillary equipment within a 40 ft. container that is well suited for transportation purposes. The rig is landed on the seabed and hoisted from the support vessel using an A-frame or a deck crane. An umbilical connects the system to the vessel to provide remote control and power. Tensioned winches or vessels with dynamic positioning are employed to isolate the seabed system from the vessel motion. The allowable maximum penetration is 6 m with a sample diameter up to 113 mm, suitable to perform any kind of traditional laboratory test.

The selection of the set-up, the core barrel and the drill bit are a key parameter since the whole drilling is performed in a single run. Therefore, limited manoeuvres to increase recovery performance are available. This is particularly important in heterogeneous and fractured rocks as well as in seabed composed by weathered or altered rocks with variable strength, cementation, and weathering. If the expected material is soil, the core barrel and the drill bit must be configured for soil and will not be able to drill through the rock. The suitability for drilling in sandy and silty soils was reported by Romero et al. (2012). Otherwise, for the rock configuration, the soil will be washed out and lost due to the action of the rotation force together with the water jetting applied. The most homogeneous is the rock the most rate of recovery is achieved.

Figure 1. Submersible drilling rig (left), operator during drilling in a subsea borehole: visual inspection and drilling parameters visualisation in real time (centre) and positioning sensors for both the rig and the mast displayed (right)

3.1. Monitoring and control

The system is instrumented with sensing elements allowing the full control of the drilling operation in real real time for three different purposes: (i) positioning, (ii) drilling parameters and (iii) visual inspection. All data streams are transferred through the umbilical cable to the surface. Prior to the beginning of drilling operations, the stability of the rig is ensured by the positioning sensors and the inclination of the mast is defined depending on requirements. The operator is then able to control and modify all drilling parameters in real time to enhance drilling operations. Moreover, the control of all sensors allows ensuring that operations are done in a safe way without any risk of jeopardising the equipment.

3.1.1. Positioning

The need for accurate positioning throughout all phases of a project cannot be overlooked. Positioning of each vessel or Jack up, and associated sensors and equipment, is an essential prerequisite to ensure that all subsequent surveys, investigations, and structures are all confirmed to be accurately positioned and each must use the same predetermined coordinate reference (SUT-OSIG, 2022). The positioning on the seabed may be recorded by using an USBL or, alternatively, by using a GPS receptor and a pressure transducer in case of very shallow water projects. The frame is fully instrumented with two tiltmeters and a compass. Hence, the accurate position can be verified before starting the drilling, allowing the re-positioning of the system in a more stable or flat area if necessary. Moreover, the relative inclination of the mast is also recorded with a tiltmeter and might be fixed at any position between 0 and 90º in case non-vertical operations are required.

3.1.2. Visual inspection

A digital camera is mounted on the frame within a sealed compartment to enable visual inspection of the positioning and drilling operations. This is particularly useful when the rig is located over a rocky outcrop. All data is digitally stored and visualised in real time.

3.1.3. Drilling parameters

A detailed recording of all aspects relevant to the drilling operation are monitored and displayed in real time: applied torque, rotational speed, thrust, mast-parallel displacement, flow rate and pressure of the flushing medium (Figure 2). The accuracy of the transducing system is such that the depth below the seafloor can be estimated with less than 5 cm uncertainty. In case of a low recovery due to a seabed composed of rocks with variable strength, the drilling parameters allow estimating the profile and to identify the boundaries between different layers. An example is in Figure 3. The grey solid patterns indicate sections with high strength. It highlighted the differences on drilling parameters, especially on thrust and penetration ratio between layers with different strength. In this borehole, only high strength samples were recovered while weathered rock and soil was washed up. Nevertheless, the depth of each sample was correctly established based on drilling parameters.

In geotechnical investigations for pipelines or dredging projects where the ground model is composed by a rock layer underneath a soil deposit, the thickness of the soil and hence the depth of the interphase between soil and rock might be a key parameter to estimate the volume of material to be dredged and the suitable burial depth of the pipeline, among some other reasons. In these cases, the drilling parameters might be of particular interest to determine with high accuracy changes on ground behaviour since the soil will be washed up and only rock samples will be recovered. An example is in Figure 4. The first 43 cm were not recovered due to the system set-up, but the soil thickness was defined by high accuracy using the drilling parameters. This recording might be also used to detect fractures within the rock and its thickness.

3.2. Sampling devices

For sampling, the submersible drilling rig can adapt different sampler systems according to the expected ground conditions and project requirements:

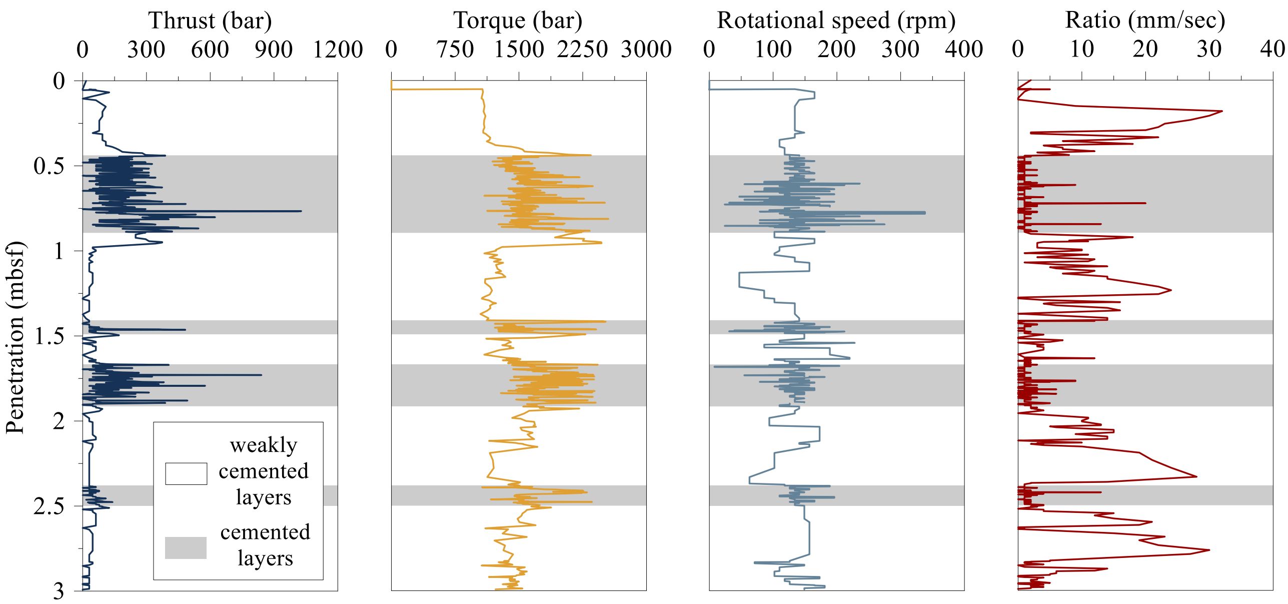

Figure 2. Drilling parameter of a 3 m depth borehole composed by rocks with variable cementation degree.

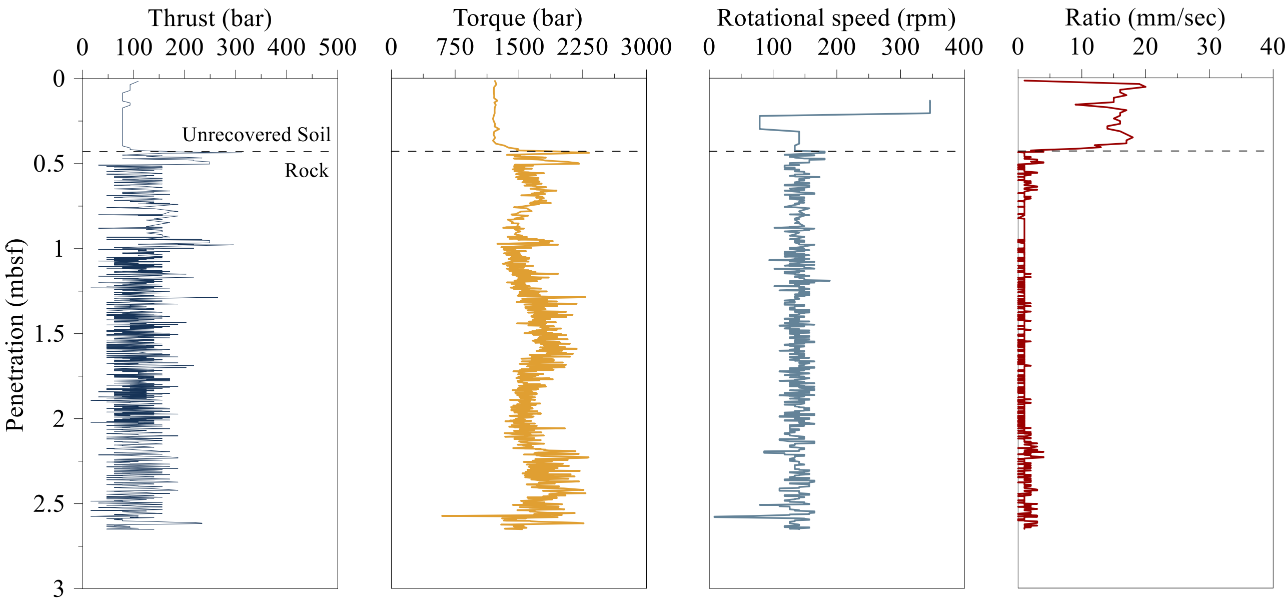

Figure 3. Drilling parameters of a 2.66 m depth borehole composed of rocks underneath a soil layer. They allow defining the thickness of the soil layer even if the soil was washed up during drilling.

- Double system or double tube core barrel system. This tube comprises a 1,5-3-6 m core barrel composed by two concentric tubes and a bearing arrangement in the core barrelhead.
- Triplex system or triple tube core barrel system. It comprises a 1,5-3-6 m core barrel consisting of three concentric tubes and a bearing arrangement in the core barrelhead.

A transparent PVC liner is used to recover the sample when unloading the rig back to deck. It allows a preliminary rock analysis on board including RQD, TCR, sample description, etc. or even a full analysis and some laboratory tests if it is available on board. Otherwise, the inner core is cut into smaller sub-samples to facilitate its transport to the onshore laboratory for a further analysis. Allowable sample diameters are suitable for most of the common laboratory tests.

4. Compound parameters

The analysis of an individual drilling parameter to get any relationship with rock characteristics is not evident. Consequently, several compound parameters have been proposed which combine two or more parameters into energy or strength parameters. These relationships tend to smooth the profiles and increase their physical meaning thus improving interpretation by practitioners (Laudanski et al. 2012). Among the most relevant are the alteration index and specific energy (Pfister 1985), the Somerton index (Somerton 1959), the normalised energy (Nishi et al. 1998) and the specific energy (Teale 1965).

The Somerton Index (Sd) was proposed in 1959 after the author realised that the ultimate compressive strength was not a reliable rock strength parameter for general rotary drilling correlations (Somerton 1959). Therefore, this index was proposed as a “strength parameter” which could provide a good correlation between advance rate, rotation rate and the effective weight on the bit (Viana and Coelho 2007). The Sd is presented in Eq. (1):

$$S_d = W_{net}\sqrt{\frac{w_d}{V_d}} \qquad (1)$$

Where W_{ent} is the effective weight on the bit, w_d is the rotation rate and V_d is the advance rate.

This parameter has been extensively used to qualitatively assist in the delineation of geological profiles. Moreover, its suitability in other contexts such as on the determination of the evolution of the jet grouting resistance with curing time has also been demonstrated (Viana da Fonseca 2015). In this study, the Somerton Index was calculated immediately after the drilling rig was recovered on deck, serving as an initial characterization of boreholes prior to the conventional sample description and laboratory tests conducted onshore. Additionally, along with the drilling parameters, it served as a QA/QC measure for the data. Thus, this parameter can facilitate critical decision-making onboard, such as moving the vessel to the next location, retesting for specific reasons or even increase the project scope incorporating additional boreholes to enhance ground characterization.

5. Case study

An offshore geotechnical investigation for an electrical interconnection was conducted in the Mediterranean Sea. The primary objective was to investigate the distribution, the nature, and the geotechnical and mechanical properties of the bedrock to facilitate the cable routing, the cable burial risk assessment (CBRA) and the cable installation assessment. The scope included double locations composed of Cone Penetration Test (CPTu) and sampling with vibrocorer. Rockcorer tests were also conducted in rocky outcrops or in locations with minimal soil thickness. Tests were performed along the route up to a target depth of 3 m. For rock coring, double and triple core barrel systems were used depending on the expected ground conditions with the aim to increase the recovery and get high-quality samples for rock description and laboratory tests.

Although the soil above the rock was generally washed-up during operations, the drilling parameters allow a detailed definition of its thickness, thus determining the top boundary depth of the rock. They also provided reliable information regarding variations in rock characteristics with depth, including different degrees of weathering, cementation, or discontinuities. The operator was able to improve the drilling performance by adjusting the parameters in real-time. The recovery ratio was generally acceptable. Samples were initially described on board, then sorted in a dedicated container to preserve their properties and finally transported to the laboratory for further analysis.

The Somerton Index was utilised to characterise the ground and to delineate variations among the different rock types encountered along the route. Six types of rock were identified: sandstone, biogenic rock, mudstone, conglomerate, limestone, and dolomite. Different degrees of weathering were observed, with samples generally described from slightly to moderately weathered according to ISO 14689-1:2005 standard. The characteristic profile of Somerton Index with depth for the six rock types is shown in Fig. 4. In some cases, the Sd profile remains relatively constant with depth, indicating rock homogeneity. However, in conglomerate and dolomite, a major variability with depth is evident due to fractures and weathered sections. The Unconfined Compressive Strength (UCS) determined from laboratory tests has been also included in the graph to allow a visual comparison between both "strength parameters".

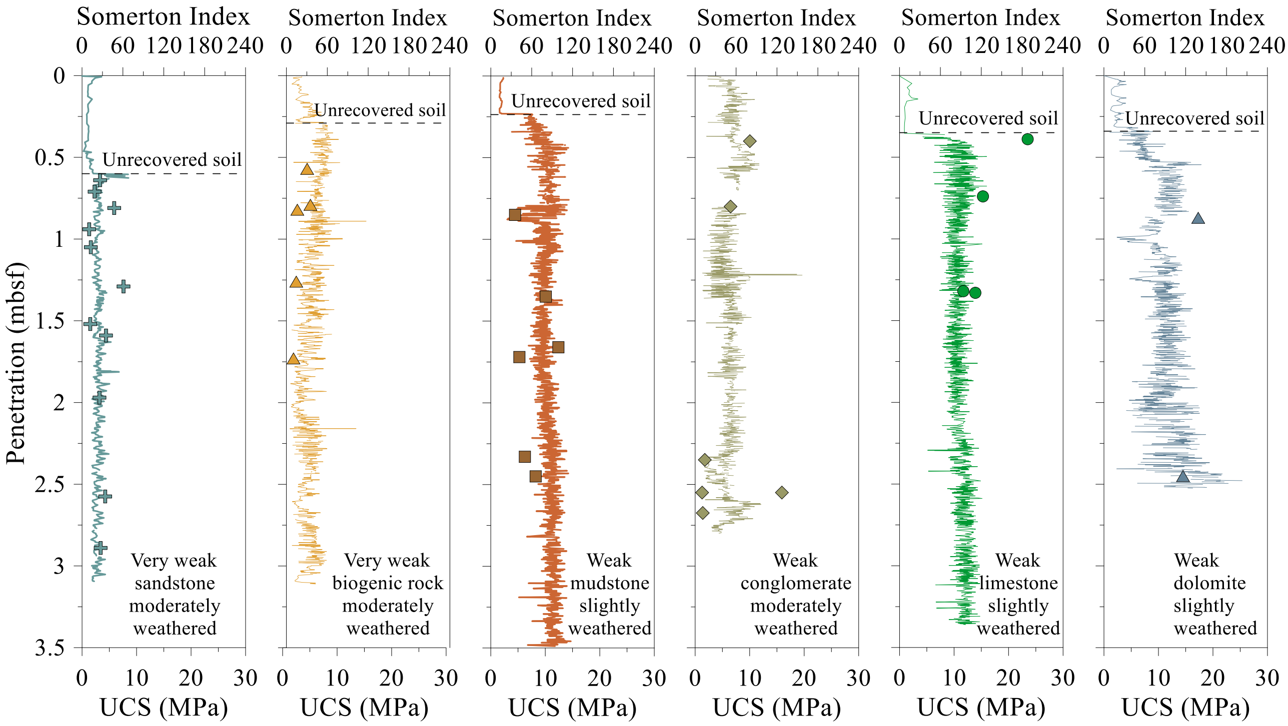

Figure 4. Characteristic profile of the Somerton Index for each rock type. The UCS is also included.

A good correlation is generally observed between both parameters. The Somerton Index provided valuable ground information in a simple and fast way. The averages are similar in three rock types: mudstone (85), limestone (89) and dolomite (84). On the other hand, they are slightly lower in the other rock types: sandstone (24), biogenic rock (38) and conglomerate (50). There is a clear relationship between the increase of the Somerton Index and the increase of the average UCS.

It must be considered that there are some limitations for selecting samples for UCS tests such as the minimum size requirement, which might be of relevance, especially in moderately to completely weathered samples and fractured rocks. These factors might lead to non-representative results. In contrast, the Somerton Index provides a continuous parameter that is valuable for identifying variations in rock conditions with depth. Although the comparison between individual values from continuous compound parameters might show considerable scatter due to variations in rock conditions, the low target penetration and general homogeneity across different rocks encountered enable a direct comparison between both parameters.

While all tests were conducted using rotary coring with continuous sample recovery, integrating compound parameters such as the Somerton Index in offshore projects could lead to a revaluation of survey scope. This could involve combining these tests with destructive boreholes specifically performed to obtain the drilling parameters. The rotary coring tests are time-consuming and often require repetitions due to low recovery rates. Conversely, destructive drilling enhances efficiency, allowing to perform a major number of locations with the same timeframe. It is considered that a suitable combination of both techniques could lead into more representative and accurate ground models.

The Somerton Index and UCS values for each rock type are shown in Fig. 5. The symbol represents the mean of both parameters. The range between the minimum and maximum UCS value is depicted alongside the standard deviation, serving as a statistical measure to quantify the dispersion of the Sd.

Site-specific linear correlations through origin were proposed for each rock type. It is important to note that these equations might not be applicable in other projects due to the relationship between UCS and Sd is based on the mechanical response of the rock for a specific drilling set up rather than its classification. Different degrees of weathering or fractures, for example, could lead to different correlations. The comparison between UCS and Sd was not conducted with the example shown in Fig. 4, but with the correspondent borehole from which the sample was extracted and the UCS test performed. The slope of these correlations varies from 0.0735 for biogenic rock to 0.1849 for limestone, while the coefficient of determination ranges from 0.72 for conglomerate to 0.92 for mudstone. In some cases, only a few laboratory tests are available so results should be interpreted with caution. Site-specific correlations are graphically represented in Fig. 6 and detailed in Table 1.

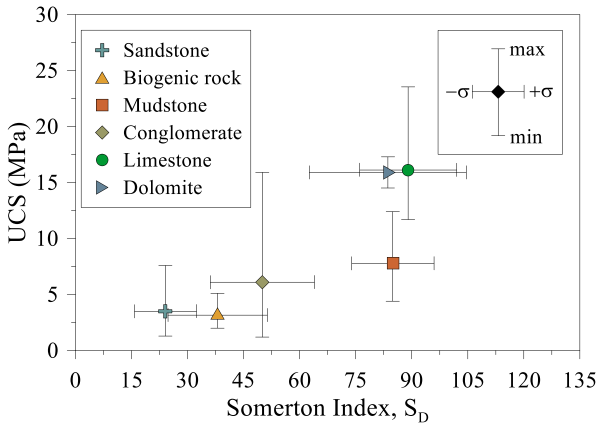

Figure 5. Variation in Somerton Index and UCS.

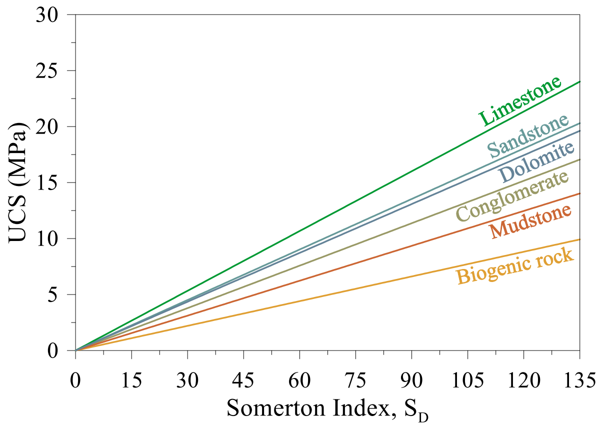

Figure 6. Site-specific correlations defined.

Table 1. Summary of the correlations obtained for each rock type.

	Average Somerton Index, S_d	Standard deviation	COV	Average UCS (MPa)	Correlation	R^2
Very weak SANDSTONE moderately weathered	24	8	0.33	3.5	UCS=0.1504 Sd	0.80
Very weak BIOGENIC rock moderately weathered	38	14	0.37	3.3	UCS=0.0735 Sd	0.92
Weak MUDSTONE slightly weathered	85	11	0.13	7.8	UCS=0.1039 Sd	0.92
Weak CONGLOMERATE moderately weathered	50	14	0.28	6.1	UCS=0.1263 Sd	0.72
Weak LIMESTONE slightly weathered	89	13	0.15	16.1	UCS=0.1849 Sd	0.87
Weak DOLOMITE slightly weathered	84	21	0.25	15.9	UCS=0.1454 Sd	0.91

6. Conclusions

A submersible drilling rig was designed for characterising soil or rock in offshore investigations, particularly for shallow water projects with short target penetrations. The system has been extensively used in recent years for electrical interconnections, dredging, pipelines, and foundations.

The paper likely elaborates on specific benefits of the system, especially for ground models that have a rock layer beneath a soil deposit or consist of rocks with variable strength depth-wise. The ability to accurately characterise these complex ground conditions can lead to more informed decision-making in various offshore projects.

A case study was presented, in which the Somerton Index, derived from continuous drilling recording parameters (MWD), was utilised to characterise different rock types encountered. This index, serving as a "strength parameter," was compared with UCS results from laboratory tests. Site-specific correlations were defined for the different rock types.

It is presumed that incorporating rotary coring along with destructive drilling in offshore research could improve the investigations and lead to the development of more accurate and representative models of the ground.

Clearly, standardising the tools and drilling techniques would enable comparisons and local correlations of results across various locations and among different researchers.

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