1 **Title:** Review of long seabed samplers and criteria for new sampler design

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1 **ABSTRACT**

2 A cost efficient way of investigating shallow sediments and for collecting soils data for
3 many offshore geotechnical problems, e.g. anchoring of floating structures with suction
4 piles or evaluation of submarine slope stability, is to carry out seabed sampling to say
5 25 m below seabed and in addition perform seabed CPTUs to say 40 m. Based on a
6 review of data collated from the literature and from in house project experience at the
7 Norwegian Geotechnical Institute it was found that Kullenberg type piston core samples
8 give poor recovery and samples, which are increasingly disturbed as penetration
9 increase. This means that laboratory tests on these samples will give results that are not
10 representative of in situ conditions and will give incorrect parameters for foundation
11 design. Many different factors control the quality of the samples recovered but the need
12 for an effectively stationary piston a core retainer and improvements to the physical
13 sampler parameters, e.g. diameter / wall thickness ratio, cutting edge angle, inside and
14 outside friction are perhaps the most critical. The importance of each of these factors is
15 discussed in detail in addition to the need for instrumentation and the way to penetrate
16 the sampler. Recommendations are given in terms of criteria for the design of a new
17 sampler, which the authors feel will give better results than most samplers used in
18 practice today.

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20 **KEY WORDS:** site investigation, seabed sampling, long corers, sample quality

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1 **1. Introduction**

2 For many offshore geotechnical problems, e.g. anchoring of floating structures with
3 suction piles or evaluation of submarine slope stability, it is sufficient to determine soil
4 conditions to a depth of between 25 m and 40 m below the seabed (e.g. Lacasse and
5 Lunne, 1998). It is also important to get a comprehensive understanding of the geology
6 of the shallow sediments for most field developments. A cost efficient way of collecting
7 soil data is to carry out seabed sampling to about 25 m below seabed and in addition
8 perform seabed piezocone tests (CPTU) to somewhat deeper depths, e.g. 40 m.

9 Several long seabed sampling systems exist today but there are problems with most
10 of them (Lunne et al., 1998). The geotechnical quality and sample recovery ratio is in
11 most cases less than satisfactory. From a geological viewpoint the sample quality may
12 not be so important as long as the sample is representative of the complete profile.
13 However, this may not always be the case, since part of the soil profile may have been
14 lost in the sampling process (e.g. Buckley et al., 1994). Also several of the seabed
15 samplers available today are heavy and cumbersome to handle.

16 The objectives of this paper are to:

- 17 1. Briefly review available seabed sampling systems, with particular emphasis on fixed
18 piston long coring devices.
- 19 2. Assess the quality of the samples produced by some of these devices using the
20 results of soils tests published in the literature and unpublished data from the files of
21 the Norwegian Geotechnical Institute (NGI).
- 22 3. Discuss the influence of various sampler features and sampling parameters on
23 specimen quality.

1 4. Make recommendations for the design of an improved sampler, which should give
2 better recovery and sample quality than most available samplers used in practice
3 today.

4 **2. Need for high quality samples**

5 *2.1. General*

6 In general there are two aspects pertaining to soil sample quality. The first relates to
7 how the sampling disturbance influences the laboratory measured mechanical properties
8 of the specimen and the second to whether or not the sample is representative of the
9 depth from which it is thought to have been recovered (i.e. linked to core recovery
10 ratio). Both aspects will be dealt with here. Sample disturbance is caused by (Lunne et
11 al. 1997a, 1998):

- 12 1. Stress relief, when the sample is removed from the ground. If gas is dissolved in the
13 pore water then stress relief induced sample disturbance can be very significant.
- 14 2. Mechanical disturbance due to sample tube penetration and retrieval.
- 15 3. Techniques used to retrieve sample onto the ship deck.
- 16 4. Extrusion.
- 17 5. Transportation.
- 18 6. Sample storage environment.
- 19 7. Specimen preparation for laboratory testing.

20 If best available practice is applied the effects of items 3 to 7 can be minimized. In
21 cases where problems with gas coming out of solution are not an issue, the effects of
22 stress relief can be at least partly overcome by reconsolidating the specimen in the
23 laboratory to the best estimate of the in situ stress. Of primary concern here is
24 identifying the factors that cause mechanical disturbance and how to minimise them.

The issues of keeping the sample under pressure to avoid stress relief will not be discussed here.

2.2. Examples of the effect of sample disturbance on measured mechanical properties

Lunne et al. (1997a) report on a sampling comparative exercise carried out at NGI's research site at Lierstranda, near the city of Drammen in southern Norway. Samples were taken using the Sherbrooke block sampler (Lefebvre and Poulin, 1979), the 75 mm thin wall Japanese fixed piston sampler and the NGI 54 mm fixed piston sampler (composite type). Both the block sampler and the 75 mm sampler are well known to yield specimens of high quality (see for example Hight et al. 1992 and Tanaka et al., 1996). The 54 mm sampler includes an inner plastic liner, which results in a relatively crude cutting edge configuration, and thus the samples are often of comparatively poor quality. The geometry of this sampler is such that it compares with a range of offshore seabed samplers.

Some results of CAUC (anisotropically consolidated undrained) triaxial tests and CRS (constant rate of strain) 1D oedometer tests from a depth of 12.3 m are shown on Figures 1 and 2 respectively. At this depth Lierstranda clay has water content (by weight) of 35% to 40%, bulk unit weight of 18.5 kN/m³, plasticity index (I_p) of 16% and sensitivity of about 8.

From the CAUC tests it can be seen that the block sample is of significantly higher quality than the 75 mm piston sample, which in turn is of better quality than the 54 mm piston sample. The block sample shows the highest undrained shear strength (s_u), the lowest strain to peak and the highest stiffness. Its initial stress path (in shear stress, q , and effective mean stress, $t' = (\sigma'_{ac} + \sigma'_{rc})/2$, space as shown) has an inclination of 1 horizontal to 3 vertical. This is indicative of a high quality specimen that has retained its in situ structure.

1 Similarly the block sample CRS stress – strain curve shows a clear yield point
2 compared to the more rounded curves of the 76 mm and 54 mm piston samples. The
3 block sample gives the highest initial stiffness and highest preconsolidation stress (p'_c).
4 The consequences of using samples of low geotechnical quality is that laboratory tests
5 on these samples will give results that are not representative of in situ soil conditions.
6 Using parameters determined in this way can give foundation designs that are too
7 conservative and costly. In some cases unconservative design may result.

8 *2.3. NGI's criteria for evaluating sample disturbance*

9 Many techniques are available for the assessment of sample quality. These include
10 X-ray photography, measurements of initial suction in the sample, comparison of shear
11 wave velocity measured on the specimen with that obtained in situ and the assessment
12 of the stress / strain curves and parameters measured in oedometer or triaxial tests (see
13 for example Lunne et al. 1997a, 1998, Clayton et al., 1995 and Hight, 2000).

14 Early work (e.g. Andresen and Kolstad 1979) argued that the volumetric strain, ϵ_{vo} ,
15 induced when consolidating a sample back to the best estimate of in situ stresses was a
16 useful indicator of sample quality. For a high quality sample ϵ_{vo} should be close to zero.
17 Lunne et al. (1997a) evaluated which soil parameters were most systematically
18 influenced by sample disturbance. The conclusion confirmed that the volume change
19 when consolidating a sample back to the best estimate of in situ stresses is the best
20 indicator of sample disturbance. Lunne et al. (1997a) recommended to express the
21 volume change in terms of the change in pore volume relative to the initial pore
22 volume, $\Delta e/e_o$, because it is reasonable to assume that a certain change in pore volume
23 will be increasingly detrimental to the particle skeleton as the initial pore volume
24 decreases. [Note $e_o = (G_s/\rho_d)-1$, where G_s is the particle density or specific gravity and

ρ_d is the dry density.] In this paper therefore use is made of the disturbance index $\Delta e/e_o$ rather than ϵ_{vo} .

Since 1996 NGI has used $\Delta e/e_o$ to evaluate sample disturbance on a number of onshore and offshore consulting projects according to the sample disturbance criteria given in Table 1. These criteria seem to have worked well in distinguishing between good and poor samples for OCR (overconsolidation ratio = p'_c / σ'_{vo}) values below 3 - 4.

It must be remembered that the sample disturbance criteria proposed in Table 1 are mainly based on tests on marine clays with plasticity index in the range 10-55%, water content 30-90%, OCR = 1 - 4 and depth 0 - 25 m below ground level. For soils with properties outside this range, the criteria should be used with caution.

Based on the tests carried out at Lierstranda and various other sites the potential consequences of sample disturbance on two key design parameters, i.e. the undrained shear strength (s_u) and the constrained modulus (M = change in stress / change in strain in 1D oedometer tests), used for settlement predictions, are summarised on Table 2 (from NGI, 2002).

Results of CAUC or CRS tests that are in sample quality classes 3 and 4 (see Table 2) should not be used without correction. Results of tests in sample quality class 2 should be evaluated carefully before deciding whether it is necessary to correct the result or not. No correction is required for results of tests in sample quality class 1.

3. Overview of experience with fixed piston long coring devices

3.1. General note

Up to the early 1970's, the most common equipment used to recover sea-bottom soil samples were open drive gravity samplers with no piston. For a summary of developments up to the early 1980's, the reader is referred to the papers by Rosfelder and Marshall (1967), Schjetne and Brylawski (1979) and Holt and Ims (1985).

1 Sometimes the upper end of the sampler was fitted with a suction ball valve to keep the
2 sample in the tube during recovery. In soft clays open-drive gravity samplers can
3 normally penetrate 5 m to 6 m before plugging occurs. In stiff clays this may be limited
4 to 1 m (Smits 1990). Sample quality was often poor as evidenced by distortions in the
5 sediment layers or cracking. Recovery ratio (defined as actual recovered length over
6 distance tube pushed into soil) was frequently less than 70%.

7 Despite this, it is possible that simple gravity type cores give a more reliable
8 indication of the soil conditions at the sediment / water interface, due to disturbance
9 caused by a non-rigid piston and drainage problems with excess water (Silva et al.
10 2000). Similarly Skinner and McCave (2003) carried out some analyses of piston coring
11 and recommended that, in the absence of a truly recoilless fixed piston corer, the
12 preferred sampling procedure would be large diameter gravity coring to about 10 m
13 depth combined with piston coring below this.

14 3.2. *Piston corers (Kullenberg type)*

15 Because of the need to recover longer and less disturbed samples, piston corers were
16 originally introduced by Kullenberg (1947, 1955). These were considered as an
17 improvement on simple gravity type devices. The principle of operation of this
18 equipment is shown on Figure 3. Essentially it is the same as a gravity corer, which also
19 drops in free-fall from a limited height. However it has a lower end enclosed by a piston
20 until penetration starts into the soil. The piston is usually either directly connected to the
21 main cable or there is an independent piston cable (Weaver & Schultheiss, 1990). In
22 both cases, the piston can only remain approximately stationary, as it is dependent on
23 the movement of the vessel even if the influence is limited when working in deep water.

24 The problems, which are frequently encountered with the behaviour of the piston are
25 well identified and have been described by several authors e.g. Weaver & Schultheiss

(1990), Buckley et al. (1994) and Skinner and McCave (2003). These include improper placement of the piston at initiation of sampling, incoherent movement of the piston during coring and upward movement of the piston during retrieval of the corer. Behaviour of the piston is also dependent on the elasticity of the cable which tends to pull the piston upwards once the system is released by the counter weight. The induced accelerations are transmitted to the piston during coring resulting in irregular penetration rate and fluctuating cavity pressure below the piston inside the core liner. Frequently this induces the stretching of the sediments into the corer (Weaver and Schultheiss 1990).

A combination of these problems can result in “core shortening”, i.e. highly disturbed sediment cores, which are significantly shorter than the apparent depth of penetration (recovery rates are often reported close to 70%) or on the contrary “core lengthening”. Such data are in relation to observations of occurrence of core top losses, missing sediment sequences or sediment flow-in.

A considerable number of improvements have been made since 1947. These include:

- Larger core barrel diameter (up to 120 mm but typically 60 mm to 100 mm).
- Introduction of a core catcher.
- Measures to render the piston as immobile as possible by counteracting the heave of the survey vessel and the rebound of the cable caused by the release of the corer weight.
- Use of devices to monitor various parameters such as cable load.

3.3. Sophisticated Kullenberg type piston corers developed in USA and France

The sophisticated Woods Hole Oceanographic Institute (WHOI) giant piston corer (GPC) and jumbo piston corer (JPC) and the CALYPSO corer designed by the French

1 Institute for Austral Research and Technology (IFRTP) are essentially Kullenberg type
2 corers. However as there is significant experience of their use and as many
3 improvements have been made in order to increase specimen recovery and quality, they
4 are treated separately here.

5 Development of the US systems began in the early 1970's. The basic design of the
6 giant piston corer (GPC) was described by Hollister et al. (1973). Early improvements
7 were described by Driscoll and Hollister (1974). The first studies of geotechnical
8 properties of the sediments recovered by the corer were presented by Silva and Hollister
9 (1973) and subsequently by Silva et al. (1976) and Silva and Hollister (1976 and 1979).

10 During the lifetime of the GPC various modifications were made, particularly to the
11 core tube geometry and in particular the core head, the free-fall loop system and the
12 instrumentation. A core catcher was also included. No inner plastic liner was used but
13 the inside of the corer was coated with teflon in order to reduce friction. Driscoll (1981)
14 and Weaver and Schulteiss (1990) described the use of a parachute with the GPC in
15 order to minimise cable rebound effects on the piston. Cable rebound by the release of
16 the corer weight is restricted to that length between piston and parachute. A complex
17 system to minimise residual motion of the piston by an intelligent piston control system,
18 the so-called hydrostatic accumulator piston, was described by Driscoll (1981). Driscoll
19 and Hollister (1974) also described some problems with an "orifice effect" generated as
20 the piston travels through the barrel. This was relieved to some degree by ventilation of
21 the barrel section directly below the piston bearing plate. Silva (1999) and Silva et al.
22 (2000) described how sample quality could be poor in the upper 2 m of core due to
23 difficulties in draining away excess water and also due to disturbance caused by a non-
24 rigid piston. These authors therefore recommend that simple gravity type cores give a

1 more reliable indication of the soil conditions at the sediment / water interface and to
2 check any core loss in the parallel piston sample.

3 The jumbo piston corer (JPC) is essentially a lighter version of the GPC (Silva et al.
4 1999, Silva 1999, Young et al. 2000 & Silva et al. 2001). A significant improvement of
5 the JPC is that it incorporates an inner plastic liner which can be extruded from the fully
6 assembled core barrel. Core diameter is usually 102 mm.

7 A useful summary of experience with both the GPC and JPC was given by Young et
8 al. (2000) and Silva and Bryant (2000).

9 *3.4. Ocean drilling program advance piston corer (ODP – APC)*

10 Skinner and McCave (2003) suggest that: “perhaps the most successful design of a
11 recoilless piston corer is the APC of the Ocean Drilling Program” (Storms 1990).

12 Unlike the cable-deployed systems, the ODP-APC is deployed from a rigid drill pipe
13 surmounted by a heave compensator to eliminate drill-string motion and uses
14 hydrostatic pressure to “fire” the core barrel into the sediment past a piston. Although
15 very successful, this corer design is highly specialized, requiring a drilling vessel for its
16 deployment.

17 *3.5. STACOR stationary piston corer*

18 Perhaps the most advanced gravity corer is the French STACOR, which was
19 originally developed by IFP (Institut Français de Pétrole) with the aim to:

- 20 • increase the sample diameter and to recover a larger volume of sediment with a
21 less disturbed central area,
- 22 • increase dimensions and weight of the corer so as to increase the available
23 energy and thus allow deeper penetrations in different types of soils and
24 • achieve an effectively stationary piston.

1 It was described in detail by Montargès et al. (1983, 1987)) and Fäy et al (1985,
2 1988) and is based on the principle of the sphincter corer developed by Kermabon and
3 Cortis (1969). It was, until recently, operated by Geoclean and is now operated by Fugro
4 France following its acquisition of Geoclean's geotechnical equipment. It introduces an
5 effectively stationary piston by attaching the piston to a seabed frame by a cable running
6 over pulleys at both ends of the core barrel as shown on Figure 4.

7 The base plate is 1.5 m in diameter and is made of a tubular steel frame. STACOR
8 has been employed in water depths of up to 5800 m and has taken 34 m long cores in
9 favourable conditions. It has been deployed over the aft of a supply vessel with an A-
10 frame, over the side by rotating in a davit or through the moon pool of a drilling vessel
11 with a derrick. Some special features of the sampler are as follows:

- 12 • Length of core pipe: up to 35 m. Limited to 30 m by Fugro.
- 13 • Diameter of core pipe: OD: 170 mm; ID 130 mm.
- 14 • Diameter of plastic liner: OD: 125 mm; ID 105 mm.
- 15 • Plastic pipe made of PVC or reinforced resin.
- 16 • Ballast weight: up to 5.5 tonnes. Recently Fugro has limited the total operational
17 weight to 4 tonnes to be compatible with vessel size.
- 18 • Overall weight with 35 m pipe: 5 tonnes to 10 tonnes

19 At a predetermined distance above the seabed, a counter weight triggering system
20 causes free fall of the device so that the corer pipe can penetrate into the soil. It is then
21 pulled out of the soil by a cable, which is allowed to uncoil freely during the free fall
22 and penetration of the corer. This main hoisting cable connects directly to the corer head
23 and is thus decoupled from the piston. Skinner and McCave (2003) acknowledge that
24 STACOR yields sediment cores of excellent quality, but suggest it suffers from some
25 practical drawbacks, for example its particularly time consuming deployment.

1 The British Antarctic Survey (BAS) developed a long piston coring system very
2 similar to STACOR in 1992 for use on the research vessel James Clark Ross
3 (www.antarctica.ac.uk). It was apparently successfully used on several cruises.
4 However no formal reports or papers were produced on the results. Recently BAS have
5 passed the equipment on to researchers at the Southampton Oceanography Centre who
6 are redeveloping the equipment.

7 3.6. *Piston corers driven by hydrostatic water pressure*

8 An early design for such a device was presented by Rosfelder & Marshall (1967).
9 Smits (1990) described a system, which was developed for the Hocus project, and was
10 used in 275 m water depths in the French Mediterranean. The corer was driven by
11 hydrostatic water pressure with some reaction provided by a seabed frame. It was
12 designed to take a continuous sample of 0.27 m in diameter and of length 10 m to 15 m.
13 The tip of the core barrel had a cutting head with an outside friction reducer and a built
14 in core catcher, which was deployed when the core was retracted from the sediment. To
15 the knowledge of the authors, the sampler has apparently not found any practical use,
16 despite the fact that several very interesting ideas were described by Smits (1990).

17 A similar device, called Starfish, was proposed by Marine GeoSystem (Bienvenu &
18 Bessonart 2001). Again it consists of a double tube isolated at the top end by a sealed
19 piston and sealed at the bottom end. For penetration into the soil a differential pressure
20 is created by a reversible water pump, which applies hydrostatic pressure on the top
21 piston.

22 **4. Sample quality from long seabed corers**

23 4.1 *Experience with Kullenberg type samplers*

24 Significant experience of sampling with Kullenberg type piston corers exists.
25 However not all of this experience has been reported in such a way that a quantitative

assessment of the resulting sample quality can be made. Therefore in this paper, the experience is sub-divided into some general points, sample recovery and those examples where a quantitative assessment of the quality can be made using the parameter $\Delta e/e_o$.

4.1.1. General

In some early work, Flaate and Janbu (1975) compared sample quality of Kullenberg piston samples (up to 6 m long), gravity cores (up to 2.5 m long) and samples obtained from NGI's gas operated piston sampler (described by Andresen et al., 1965) taken in the 500 m deep Hardangerfjord. Sample disturbance was found to increase with depth with the Kullenberg and gravity cores being somewhat more disturbed than the gas operated piston samples. Flaate and Janbu (1975) characterised the degree of disturbance of the lower portions of the Kullenberg and gravity core samples as "severe" and attributed it to friction between the sample and tube wall.

Olsen et al. (1986) reported on a study of Kullenberg type piston cores from 31 sites in the Mid – Atlantic Upper Continental Slope. Substantial disturbance effects on measured preconsolidation pressure were found. For shear strength testing the SHANSEP approach (Ladd and Foott, 1974) was used to overcome disturbance effects. Buckley et al. (1994) reviewed six years of archive data at the Atlantic Geoscience Centre in Dartmouth, Canada. Much of their data concerned normally consolidated sediments sampled using Kullenberg type piston corers. They found large departures from the expected strength profile. In particular, in silty soils and in laminated clays / silts, they found large shear strengths at the base of piston cores. It was suggested that coring stops when "binding" within the core cutter leads to high frictional stresses causing a degree of densification. Long (2002) also found that sampling silty soils using a sampler with a poor cutting head geometry leads to

densification. These authors also found that the sedimentation rates determined from the cores could be very misleading.

4.1.2. *Sample recovery*

There are several examples in the literature of experience with the GPC and JPC at Wood's Hole Oceanographic Institute. With the GPC, cores of length up to 31 m, have been recovered from water depth up to 5800 m (Silva and Bryant 2000). The JPC cores were recovered in water depths of up to 2385 m (Silva et al. 2000). Holister et al. (1973) report recovery rates of between 76% and 87% for work in the Gulf of Maine. Silva et al. (1976) reported core recovery rates of between 58% and 97% for work on the Bermuda Rise. Similarly Driscoll et al. (1989) give details of 43 cores recovered from the Canadian Arctic, where the recovery ratio varied between 0 and 99% with an average of about 60%.

Buckley et al. (1994), who also used the same sampling equipment, found an average core recovery of about 67% for their 6 years of data. They also found that recovery rate decreased with increasing water depth. A significant proportion of the cores (17%) exceeded the apparent penetration depth. This suggested either unreliable penetration records or considerable occurrence of "flow in".

4.1.3. *Quantitative assessment of quality of Kullenberg type cores*

Table 3 gives a summary of available data for tests on specimens from Kullenberg piston corers, where it is possible to quantitatively assess sample quality using the parameter $\Delta e/e_o$, as discussed above. In general data is available from work in the US on the GPC and JPC and from unpublished data from NGI's files. As can be seen from Table 3 the types of clay tested vary significantly from the Storegga North Flank clay with I_p in the range 20 – 30 % to the very plastic Gulf of Guinea clays ($I_p = 50 - 100\%$).

1 Silva and Hollister (1973 and 1979) and Silva et al. (1976) discussed the quality of
2 specimens recovered using the WHOI GPC. Typical maintained load oedometer tests
3 for specimens on the Eastern Bermuda Rise (4 km to 5 km water depth) are shown on
4 Figure 5a (Silva et al. 1976). Based on X-ray images, visual observations of the core
5 and some 1D oedometer stress – strain curves, the authors suggested that the quality of
6 the specimens is “good”. However, if the criteria developed by NGI, as discussed
7 above, were applied, the quality would be described as “good to fair” to “poor” ($\Delta e/e_0 =$
8 0.06 to 0.08).

9 Similarly Silva et al. (1999, 2000) discussed specimen quality for JPC samples.
10 Some 1D oedometer tests results for a site in the Gulf of Mexico with water depths of
11 1400 m to 1930 m are shown on Figure 5b (Silva et al, 2000). The authors used both the
12 NGI criteria and the disturbance index criterion of Silva (1974) to assess specimen
13 quality. The NGI method classifies one sample as “good to fair” and the other four
14 samples as “poor”. In contrast the Silva (1974) technique indicates that the samples
15 have a “small amount of disturbance”. Silva et al. (2000) concluded that “the overall
16 evidence, especially the shape of the consolidation curves and X-ray images show
17 evidence that the core samples are of good quality”.

18 The NGI data was obtained from recent consulting projects, where NGI carried out
19 laboratory tests on long cores, of the Kullenberg type, taken by various companies /
20 institutions.

21 An attempt has been made to assess overall sample quality by plotting $\Delta e/e_0$, for all
22 seven sites on Figure 6. For the US data (Figure 6a) the $\Delta e/e_0$ values are generally
23 constant with depth and generally fall in the “poor” category with some in the “good to
24 fair” zone. Both the Gulf of Guinea – Site 3 and Gulf of Mexico (RGD and JPC corers)
25 (Figures 6b and 6d) show a very similar trend of the parameter $\Delta e/e_0$ increasing

1 consistently with depth. For both cases the sample quality can be described as “poor to
2 very poor” below 5 – 7 m. The Storegga North Flank Calypso specimens (Figures 6c)
3 do not indicate a clear increase in $\Delta e/e_o$ with depth but all laboratory test results indicate
4 the sample quality to be “poor to very poor”. For all three cases there is no clear
5 difference between the $\Delta e/e_o$ values determined from the different laboratory tests.

6 *4.2. Experience with STACOR*

7 *4.2.1. General and core recovery*

8 Fäy et al. (1985) summarised some French experience with STACOR for work in
9 the Gulf of Lyon (1983), in the Madeira Abyssal Plain and in the Nares Abyssal Plain
10 (1985). Penetration was apparently measured by observing mud marks on the core
11 barrel on retrieval on deck. Recovery ratio varied between 71% and 99% with an
12 average of 93%. According to Fäy et al. (1985), a recovery ratio of 95% is the criterion
13 for a good quality core sample. For the work described above an average recovery ratio
14 of 95% was achieved except in 7 of the 18 cases where the corer was operated as a
15 Kullenberg type.

16 Since 2001 STACOR has been largely used in deep waters for commercial purposes
17 offshore West Africa. Borel et al. (2002) reported on these experiences. A total of 42
18 cores, with penetrations of 12 m to 22m with an average of 18 m were recovered. Water
19 depth varied between 200 m and 1400 m. Penetration and total core length tended to
20 decrease linearly with the increase in net CPTU cone resistance gradient. For 30 cores
21 where the recovery ratio could be adequately defined, the value varied between 85%
22 and 105% with an average of 94%. Borel et al. (2002) regarded this as an excellent
23 result.

4.2.2. *Quantitative assessment of STACOR core quality*

For this purpose data is available from both NGI's files for two projects in the Gulf of Guinea (GoG), and from the work of Borel et al. (2002) who used the NGI disturbance criterion to assess the sample quality, mostly from oedometer tests. A summary of the results is given on Table 4.

For the NGI work the $\Delta e/e_0$ values are plotted on Figures 7a and 7b. In the case of GoG Site 1, where the samples were recovered using the thin walled version of STACOR, all tests indicate the samples to be in the "very good to excellent" to "good to fair" sample quality category. There is also no trend of any increase with depth of the parameter $\Delta e/e_0$. For GoG Site 2, where the thick walled version was used, high values of $\Delta e/e_0$ were measured and these can be seen to increase with depth in the same manner as for the Kullenberg samples shown on Figure 6.

Borel et al. (2002)'s results are compared with those from the NTG deep-sea corer (a Kullenberg type corer) and with borehole piston samples (Fugro's Dolphin or XP equipment) in Figure 8. The distribution of the STACOR $\Delta e/e_0$ values centre on 4% (0.04) with most of the values being in the range 2% to 6%. There is also no obvious change in sample quality with increasing penetration depth. The NTG deep-sea corer shows less favourable results with $\Delta e/e_0$ value worse than 7% and shows a significant decrease in quality with depth. Similarly the borehole piston sampler shows variable and frequently poor results.

4.3. *Present state of the art with long seabed corers*

As an example of the present state of the art in sample quality as recovered from long seabed corers, all available data from NGI's experience, is presented in Figure 9. This comparison is made as all of the laboratory testing was carried out by NGI to a standard set of procedures. No distinction is made between test type or Kullenberg

1 sampler type. It is recognized that the specimens were obtained by different personnel.
2 Although somewhat speculative as they draw on so little data, the following indicative
3 conclusions can be made:

- 4 • Kullenberg type piston core samples give samples that are increasingly disturbed as
5 penetration increase. A likely explanation for this is that as the corers penetrate
6 deeper the inside friction increases and more stress is transferred to the portion of
7 soil in front of the tip of the sample tube. Thus increasingly larger strains are
8 induced in the soil being sampled and thereby sample quality is reduced.
- 9 • Using a truly fixed piston, as is the case for the STACOR thin walled sampler,
10 seems to have the potential to give a very significant gain in sample quality,
11 especially for the deeper part of the core.
- 12 • These are also some difficulties with STACOR, particularly in relation to the
13 manner in which the piston is attached to the seabed frame by a cable running over
14 pulleys, which penetrate into the seabed, and with the details of the cutting edge of
15 the sampler.

16 Therefore there is a clear motivation to develop an improved long seabed corer
17 based on the current offshore experience as outlined above and on extensive work that
18 has been carried out for onshore sampling systems.

19 **5. Influence of various parameters on sample quality**

20 *5.1. General*

21 In order to identify how long seabed sampling quality can be improved the influence
22 of various parameters on the performance of long piston corers will be reviewed. The
23 purpose is to arrive at recommended criteria for the design of a new sampler. This
24 discussion will be sub-divided into that on:

- 25 • physical characteristics of the core barrel, e.g. the cutting shoe and inside liner,

- 1 • special features of the sampler, especially the piston and core retainer
- 2 • techniques for penetrating sampler into the seabed.

3 *5.2. Physical characteristics of the core barrel*

4 Much of this work was carried out for short land based sampling tubes. However the
5 findings apply equally here. The sampler characteristics, which are of most importance,
6 are its:

- 7 • diameter,
- 8 • wall thickness (or area ratio),
- 9 • cutting shoe angle,
- 10 • inside clearance,
- 11 • inside friction and
- 12 • outside friction.

13 Extensive literature exists on these topics. Of particular importance are the work of
14 Hvorslev (1949), Kallstenius (1963), Lefebvre & Paulin (1979), La Rochelle et al.
15 (1981), Andresen (1982), Hight et al. (1992), Lunne et al. (1997), Tanaka and Tanaka
16 (1999). Much of the work described in these references consists of comparative studies
17 of the performance of various piston and block samplers in well documented soils in
18 various countries.

19 In addition there has been considerable recent advances in numerical modelling of
20 the effect of sampling. Important early work was carried out at MIT by Baligh (1985)
21 and Baligh et al. (1987) who developed the Strain Path Method for the assessment of
22 sampling disturbance. More recent research by Clayton et al., 1998 is perhaps the most
23 representative of the behaviour of real samplers.

24 These researchers extended Baligh's work, via a finite element approach, to assess
25 the influence of various parameters of real soil samplers on sample disturbance.

Disturbance effects were evaluated by examining sample tube centreline strains. The validity of their numerical technique was first established by bench marking the results against those reported by Baligh (1985).

In particular they studied five different sampler geometries as shown on Figure 10. Samplers 1 to 3 were meant to represent the standard open drive “U100” tubes used in the UK. Samplers 4 and 5 are thin walled push samplers and have no inside clearance. In their analyses, the method of driving the sampler and friction between the soil and the sampler were not modelled. Predicted axial strains for the 5 samplers are shown on Figure 10. Again, like in the previous work, the geometry of the sample tube has a significant effect on the output, with Samplers 4 and 5 clearly being superior. An interesting finding of this work is that, in the case of these two latter samplers, no tensile strains are induced.

Clayton et al. (1998) also systematically studied the effects of various parameters on sample quality and the results of this work are presented on Figure 11. Note the very significant effects of inside clearance ratio and area ratio on specimen quality. As pointed out by Hight (2000) an implication of this work is that it suggests that, if inside clearance is omitted, tensile strains during sampler penetration will be eliminated and thus sample quality will be improved.

A detailed review of all the sampler characteristics influencing mechanical damage was carried out by NGI (2002) and the findings are summarized as follows and on Table 5.

5.2.1. Sample diameter

As early as 1949 the influence of sample diameter was recognised by Hvorslev (1949) who stated: “there can be little doubt that the disturbance of the soil during sampling operation decreases with increasing diameter”. In the interval since Hvorslev

(1949) was published, numerous other work has been done to confirm his findings. The influence of diameter on sample quality led to the development of large diameter block samplers for inshore use such as the Laval and Sherbrooke samplers (La Rochelle et al., 1981 and Lefebvre & Paulin, 1979 respectively).

The findings of the various studies are summarised diagrammatically on Figure 12 from Andresen (1981). As a result of this work sampling tubes having a diameter of 75 mm are commonly used in many countries for onshore sampling.

For deepwater corers a diameter as large as possible is recommended. However in order to allow practical weight handling on deck a diameter of between 100 mm to 120 mm is recommended.

5.2.2. Effect of reducing specimen diameter

From the theoretical work reported above it seems that some trimming of the sample prior to laboratory testing would be beneficial in order to utilise the part of the sample least subjected to strains. NGI recently tried out a new 75 mm thin wall piston sampler at their Onsøy test site (Nerland and Hermann, 2002. Personal communication to the authors). The s_u values determined on the trimmed samples were about 15 % higher than the untrimmed samples. However, the s_u values found from very high quality Sherbrooke block samples are still 8 – 9 % higher than the values from the trimmed samples.

5.2.3. Wall thickness (Area ratio)

Clearly the sampling tube has to be thick enough to resist distortion while it is pushed into the ground. For onshore work, tubes 2 mm to 3 mm thick are commonly used in many countries. Stacor, for example, has a core barrel which tapers from 20 mm to 15 mm towards the cutting edge. The giant piston corer has a wall thickness which varies between 6.4 mm and 19.1 mm.

A sampling tube must also be thin enough to minimize the disturbance of soil caused by displacement when the tube is pushed into the ground. The amount of soil displacement depends on the area ratio of the tube. Area ratio (C_a) is defined as:

$$C_a = \frac{D_e^2 - D_c^2}{D_c^2} \quad (1)$$

where D_e and D_c are the internal and external diameter at the sample cutting edge respectively. There have been many studies into the effect of C_a on sample quality. These include the analytical studies of Clayton et al. (1998), see Figure 11, which confirm that the axial strain imposed on the specimen during sampling increases with increasing C_a . For seabed samplers, it will not be possible to maintain low values of C_a because of the need to have a relatively thick core barrel so as to resist the installation stresses and to incorporate a liner. Typically C_a is in the range 40% to 50% for seabed samplers. ISSMFE (1981) reported on a survey of C_a values permissible in various countries throughout the world. These values varied between 4% and 20% with an average of about 12%. This report concluded that a C_a value of less than 13% is recommended but values up to 15% may be adopted depending on the soil conditions.

For long seabed samplers, mainly because of the need to have a liner, it is not possible to have such low C_a values. It is recommended that the cutting edge wall thickness be in the range 3.5 mm to 5 mm and that the area ratio is less than 17%.

5.2.4. Cutting shoe angle

As pointed out by Andresen (1981), Clayton et al. (1995) and others the effect of C_a on sample disturbance is linked closely to the cutting edge angle (β). If this is sharp then high quality specimens can then be recovered despite having a large area ratio, see Figure 13. (This figure is intended to be for demonstrative purposes only and needs to be treated with caution). Broms (1980) also recognised the close link between β and

1 area ratio, C_a this and suggested the combinations of the two parameters given on Table
2 6 below, which he said should give similar levels of sample disturbance:

3 Hight (2000 & 2001) strongly emphasised the importance of having a sharp cutting
4 edge angle. He showed that for both Bothkennar clay and the Nile estuary clays very
5 high quality samples could be obtained with thin walled fixed piston samplers with a
6 cutting edge angle of 5° . Indeed for Bothkennar clay he suggested that these samples are
7 equivalent in standard to those obtained from a Laval sampler. Long (2003) made a
8 similar finding for the Bothkennar laminated facies. The theoretical work, particularly
9 that by Clayton et al (1998), also concluded that cutting edge angle was a key parameter
10 in sample quality, see Figure 11.

11 If the cutting edge angle is too sharp then it will be damaged easily during sampler
12 penetration and handling. For the practical reasons discussed above, deep water corers
13 will have high values of C_a . Therefore it will be necessary to keep β as low as
14 practically possible and certainly to a value less than 10° . A value of 5° is recommended
15 for soils most susceptible to disturbance. For practical reasons a range of cutting shoes
16 should be available in order to deal with various soil types and the specific project
17 requirements.

18 5.2.5. *Inside friction*

19 For long sea bottom corers inside friction will play a critical role in the length and
20 quality of the core recovered. Although inside friction can cause sample disturbance it
21 will also help to retain the sample in place. Therefore if efforts are made to reduce
22 inside friction, other precautions such as the introduction of a core retainer are necessary
23 to ensure good sample recovery.

24 Work onshore has suggested that the use of sliding liners inside the sampler tubes is
25 useful for the purpose of reducing inside friction. Several stocking type piston corers

1 have been developed primarily for use on land (see for example Kjellmann et al., 1950
2 and Begemann, 1971). However it is felt that operation of these systems is too
3 cumbersome for offshore use.

4 Kallstenius (1963) conducted a series of experiments to measure the friction
5 between various materials and clay. He showed brass to have least friction, followed by
6 plastic, lacquered steel and finally stainless steel. Plastic (PVC, fibre- glass reinforced
7 polyester and cellulose acetate butyrate or CAB) inner liners are also frequently used in
8 composite sampler systems. With today's choice of various plastics, with or without
9 fibre-glass, teflon and a variety of composites, there should be potential to find a
10 smooth-surface material strong enough for the purpose.

11 5.2.6. *Inside clearance*

12 As described above, friction within the inside wall of a sampling tube is one of the
13 principal causes of disturbance of cohesive soils. This frictional force can be reduced by
14 making the cutting edge of the sampling tube slightly smaller in diameter than the rest
15 of the tube. Inside clearance ratio (C_I) is given by:

$$16 \quad C_I = \frac{D_i - D_c}{D_c} \quad (2)$$

17 where D_i and D_c are the internal diameter of the sample tube and of the cutting edge
18 respectively.

19 Broms (1980) and Andresen (1981) described how a large clearance ratio permits
20 swelling of the sample and the opening of fissures and thereby reduces the maximum
21 shear stress. For non-swelling soils, down to a depth of 20 m, these authors
22 recommended C_I to be in the range of 0.5% to 1%. Broms (1980) also reasoned that for
23 soils with ratio of in situ effective horizontal/ effective vertical stress (K_0) of less than
24 1.0, the adverse effects of inside clearance would be less than those of inside and

1 outside friction. Clayton et al. (1995) concurred with the views of Broms and
2 considered clearance to be a “necessary evil”. ISSMFE (1981) suggested the same
3 values as Broms for non-swelling soils, and state that if C_1 equals 1% to 3% then it is
4 too big. The theoretical work (see Figure 11) also suggests that, if inside clearance is
5 included, C_1 should ideally be less than 0.5%.

6 Recent work on short onshore samplers has suggested that sample quality can be
7 high if there is no inside clearance, provided the tube has a sharp cutting edge angle
8 (Hight, 2000). In Japan the 75 mm sampler and in the UK the ELE 100 mm samplers
9 have been adopted as standard and both have no inside clearance. Similarly the high
10 quality Laval sampler has no inside clearance. Recent practical experience with this
11 sampler has suggested that, in very soft to soft clays, inside clearance is not necessary
12 since the excess pore pressures generated at the sample perimeter are sufficient to
13 lubricate the sampler during driving (La Rochelle et al., 1981, Clayton and Siddique,
14 1999).

15 It seems unlikely that the benefit of omitting inside clearance for short onshore
16 samplers applies also to long sea bottom corers. Measures therefore must be taken to
17 minimise inside friction. If inside clearance is used, C_1 should be less than 0.5%.

18 5.2.7. *Outside friction.*

19 There are two aspects to the influence of outside friction on sample quality, i.e.:

- 20 • mechanical disturbance to sample,
- 21 • effect on penetration force required.

22 Eide and Andresen (1977) stated that although significant advances were made in
23 sampler design for the purpose of eliminating inside friction, “sample disturbance will
24 result in spite of all these precautions because of the excessive friction which is built up
25 along the outside of the sampling tube”. They suggest that these frictional stresses are

transmitted to the soil below the cutting edge, thus disturbing the soil even before it enters the sampling tube.

Kallstenius (1963) also recognised the importance of outside friction and suggested the effects could be lessened by:

- constructing the sampler with smooth and hard material,
- ensuring sampling is carried out in one continuous operation,
- using a reamer or friction breaker above the sampler and
- the use of paint or lubrication.

Especially for a sampler using static push relative to a frame on the sea bottom it is advantageous to reduce the required penetration force as much as possible. In this way the required reaction and penetration force can be reduced. It is also important that the required pull-out force is not excessive. Mechanical friction reducers are used in CPT practice for reducing rod friction (see for example Lunne et al., 1997b). For CPT testing it has been found very efficient to use a 15 cm² cone together with 10 cm² rods. The same principle may be used for the sampler; see Figure 14, where the sample tube is enlarged some distance back from the cutting edge in order to house the core retainer.

In CPT testing the injection of drilling mud or water to reduce the rod friction and hence the total penetration force is well known. An example from Canada is shown in Lunne et al, (1997b). It illustrates that the effect is a reduction of the order of 50% by using drilling mud injected into the soil from holes in the rods. The principle of outside flushing was also suggested by Rosfelder and Marshall (1967). They proposed to use the water escaping on top of the barrel during sample penetration for flushing in what they called a "self-jetting barrel".

5.3. Special features of the sampler

5.3.1. Core retainer

1 It is prudent to avoid the use of a core catcher if this is possible, as it will normally
2 disturb the sample to a degree, which depends on its shape and stiffness. However,
3 inclusion of a core retainer increases the chance of recovering a sample. Also if a
4 sampler with extremely small inside friction is used the weight of the sample must be
5 carried by the core retainer and the suction under the piston. There is little or no
6 published work, which quantifies these effects systematically for different core catchers.

7 Ideally the soil should not be affected by the presence of the core retainer and it
8 should only be activated on tube recovery. It will need to be reopened when the sample
9 is to be removed. Water should be allowed to enter so as to avoid the development of
10 suction. Ideally the core retainer should help cut the sample. Andresen (1981) suggested
11 that although the introduction of a core retainer is difficult for thin walled piston
12 samplers, it is possible with composite samplers as extra space is available. Kjellman et
13 al. (1950) described the core catcher, which is used in conjunction with the Swedish foil
14 sampler. Eight vertical steel bands are retained within channels embedded in the
15 sampler wall during penetration. When the full depth has been reached, the steel bands
16 are released and pushed into the soil. The bands subsequently support the core nearly on
17 its whole end surface.

18 As discussed above, the enlarged sampler cross section required to house the core
19 retainer can have beneficial effects as regards minimising outside friction.

20 5.3.2. *Piston*

21 Andresen (1981) summarised the main functions of the piston as being:

- 22 • It prevents the entry of displaced excess (remoulded) soil both prior to and during
23 sampler penetration.
- 24 • It allows the creation of a vacuum over the sample, which helps prevent sample loss
25 during withdrawal.

1 • The force created by this vacuum helps to effectively reduce inside friction between
2 the sampler and the soil.

3 Smits (1990) also described how the presence of a piston creates suction on top of
4 the sampler, which then overcomes inside friction and maximises the length of sample
5 recovered.

6 For Kullenberg type, long sea bottom corers, problems with the behaviour of the
7 piston are frequently encountered, as has been discussed above in the section on
8 experience with these samplers. Buckley et al. (1994), for example, concluded that the
9 mechanical reasons for core disturbance due to problems with the piston are complex
10 but include:

- 11 • improper initial placement of the piston,
- 12 • improper estimates of the length of the slack wire,
- 13 • cable rebound, contraction and oscillation after tripping and,
- 14 • fluctuations in cavity pressure.

15 Smits (1990) pointed out that, even for the most sophisticated equipment, the piston
16 is only fixed relative to the reference frame. In soft sediments, if the driving force is
17 simply the corer weight, the frame tends to settle because of the pressure reduction
18 below the piston. If the core barrel is forced into the sediment with the frame providing
19 the reaction, the pressure reduction below the piston is internally balanced, but the
20 frame tends to rise because of increasing resistance to penetration by outside friction.
21 This penetration resistance can be greatly reduced by appropriate design of the cutting
22 head and can certainly be made smaller than the accumulated inside friction, which
23 causes the frame settlement in the case of the core penetration by weight.

24 NGI's experience with various deepwater corers (Figures 6, 8 and 10) confirms the
25 essential requirement of an effectively stationary piston for projects where the soil

mechanical properties and / or identification of the core depth are important. From practical experience it seems that, in order to achieve this, one good solution is to use a sea bottom frame.

5.3.3. *Inner liner*

It is possible that the high suction pressures developed beneath the piston in long sea bottom corers will cause implosion of the liner systems, particularly for plastic liners. Buckley et al. (1994) observed that cellulose acetate butyrate (CAB) liners occasionally imploded in the mid core region (total liner length was about 15 m). This was attributed to a severe reduction on internal cavity pressure below the piston. Data loggers installed in the piston showed that once sediment flow-in occurred the reduced cavity pressure was somewhat relieved. Liner sections should also be of perfect cylindrical shape and join well together.

6. Techniques for penetrating sampler into the sea bed

Although no comparative studies exist, a review of the literature suggests that in order to obtain high quality samples, sampler penetration should be by means of steady pushing rather than by gravity, hammering / percussion or by vibration. Early work by Hvorslev (1949) showed that the sampler drive should be rapid (>1 cm/s) and continuous. This approach minimises friction. Kallstenius (1963) also found that friction increased if the sample tube push was interrupted for more than a few seconds. Broms (1980) stated that if the penetration rate is too low then inside friction can be excessive and will contribute to sample disturbance. Hvorslev (1949) intuitively suggested an optimum rate of 2 cm/s. Andresen (1981) stated that if the penetration rate is less than 0.17 cm/s (0.1 m/min.) then significant adhesive forces can build up. Andresen (1981) also pointed out that ideally sampling should not be interrupted. Pushing speed should be constant, as friction will increase if the sampling is interrupted

for more than a few seconds. As pointed out above the successful ODP-APC corer advances at very rapid speed.

Nonetheless, it is recommended that, for practical purposes in order to be compatible with cone penetration testing equipment, sampler penetration be achieved by means of steady pushing at a penetration rate of 2 cm/sec. Sampler penetration by gravity can also be used for practical purposes.

7. Instrumentation to monitor penetration and recovery

7.1. Penetration and recovery

It appears that one of the greatest uncertainties with seabed sampling is to know the exact penetration of the sampler. This is generally evaluated based on mud marks on the core barrel when this is brought back to deck after sampling. If mud has been washed away or the sampler has dragged on the sea bottom this measurement is highly uncertain. The measurement of penetration can be made in several ways. One approach is the use of echo sounders. If the sampler is penetrated with reference to a seabed frame it is also possible to consider other types of measurement for penetration, e.g. utilising the same mechanical principles as for CPT rigs. The optimal system to use will depend on the actual sampler deployment system.

7.2. Other measurements to monitor performance of sampler

In order to improve control of operations during sampling, which may have bearing on the sample quality, consideration should be given to measuring the following parameters:

- speed of penetration: e.g. by accelerometers for free fall type gravity sampling, or by mechanical means if penetration is static relative to a seabed frame,
- inclination of the core barrel,
- suction below the piston,

1 • force in wire keeping piston in place,

2 • penetration force (and possibly pull-out force) if static pushing is used,

3 **8. Summary and recommendations including proposal for making prototype** 4 **sampler**

5 *8.1. Summary*

6 Information has been collated on long seabed coring from the literature, in house
7 project experience at NGI, and from colleagues especially in France and the US. This
8 information has been combined with a detailed review of the factors thought to be most
9 important for sample recovery and sample quality from a geotechnical viewpoint.

10 It is concluded that in order to obtain high quality samples with recovery ratio larger
11 than 95 % it that the recommendations listed in Table 5 and summarized in Figure 14
12 should be followed. Most important are the following factors:

13 • piston should be stationary relative to sea bottom

14 • cutting shoe should be sharp, 5° is recommended for soils susceptible to sample
15 disturbance

16 • area ratio should be smaller than about 17 %, combined with sufficient length to
17 increased diameter as shown in Figure 14

18 • inside friction should be as small as possible.

19

20 *8.2. Recommended development work needed to give input to final design of a new* 21 *sampler*

22 In order to optimise design of a new sampler suggested tasks are as follows:

23 1. Investigate soil / sampler friction for different material types, using ring shear
24 tests or other tests that allow large deformations. Ring shear tests can also be

1 used to investigate the effects of stopping the sampler penetration or pushing the
2 sampler in a series of strokes or by pushing with different rates.

3 2. Carry out further numerical analyses to complement previous work, specifically
4 to optimize the design of the lower thin walled part of the cutting shoe and the
5 enlarged section of sampler required to house the core retainer and to reduce
6 outside friction.

7 3. Develop a detailed design of a core retainer / cutter. It should be designed so that
8 no additional strain is imposed on the soil during sampling.

9 4. Design a new piston.

10 5. Testing of any new prototype should first take place at a well characterised
11 onshore site prior to testing at a well known offshore site.

12 In addition to the design of the sampler itself, it should be recognised that the
13 deployment and sample handling is extremely important. The successful use of a
14 new sampler is very much dependant on a well thought of handling approach.

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1 *Table 1 Proposed criteria for evaluation of sample disturbance (Lunne et al. 1997a)*

Overconsolidation ratio, OCR	$\Delta e/e_o$			
	Very good to excellent*	Good to fair*	Poor*	Very poor*
1 – 2	<0.04	0.04-0.07	0.07-0.14	>0.14
2 – 4	<0.03	0.03-0.05	0.05-0.10	>0.10

2 *The description refers to the use of the samples for measurement of mechanical properties.

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5 *Table 2 Consequences of sample disturbance on soil design parameters (NGI, 2002)*

Sample quality class	s_u (CAUC) % of perfect sample	M (σ'_{vo} to p'_c range) % of perfect sample
Very good to excellent	> 95	> 90
Good to fair	75 – 95	60 – 90
Poor	< 75	40 – 60
Very poor	< 50	< 40

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9 *Table 3 Summary of experience with Kullenberg type long seabed corers*

Sampler type	Location	Water depth (m)	Depth range ¹ (m)	w/w _L /w _P ³ (%)	$\Delta e/e_o$	Test type ²	Reference
GPC	East Bermuda Rise	4000-5000	1.6-11.5	?	0.06-0.08	IL Fig. 6a	Silva et al. (1976)
JPC	Gulf of Mexico (Auger)	850	0-30 (14.6)	60-140 LI 0.7-1.4	0.08	CRSC Fig. 6a	Young et al. (2000)
JPC	NW Gulf of Mexico	1500-1900	10.7-14.3	≈90 ≈95 ≈40	0.06 – 0.10	CRSC Fig. 6a	Silva et al. (2000)
JPC	NW Gulf of Mexico	1630	0.14-0.25	>100 ? ?	0.01-0.016	CRSC/IL Fig. 6a	Silva et al. (2001)
Jumbo	Gulf of Mexico Site	1650	4 – 16	53-97 57-93 24-35	0.045-0.13	CRSC/DSS/CAUC Fig. 6b	NGI files
Calypso	Norwegian Sea (Storegga, North Flank)	1270	6 - 21	30-60 40-60 20-30	0.105-0.17	CRSC/DSS Fig. 6c	NGI files
RGD	Gulf of Guinea Site 3	960-1140	1 - 17	116-145 120-131 46-49	0.005-0.19	CRSC/CAUC Fig. 6d	NGI files

10 Notes: 1: Samples may be longer, depth range given is that over which NGI has tested samples.

11 2: CRSC = constant rate of strain consolidation; IL = incrementally loaded oedometer;

12 DSS = direct simple shear; CAUC = anisotropically consolidated undrained triaxial

13 3: w = water content, w_L = liquid limit, w_P = plastic limit, Ip = plasticity index, LI =

14 liquidity index

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1 **Table 4** *Summary of experience with STACOR*

Sampler type	Location	Water depth (m)	Depth range ¹ (m)	w/w _L /w _P ³ (%)	Δe/e ₀	Test type ²	Reference
STACOR (thin wall)	Gulf of Guinea Site 1	>500	9 - 17	82-104 - -	0.033-0.050	CRSC Fig. 7a	NGI files
STACOR (thick wall)	Gulf of Guinea Site 2	>500	7 - 14	90-175 110-170 30-50	0.087-0.233	IL Fig. 7b	NGI files
STACOR	Gulf of Guinea; Dalia Field (Angola).	200-1400	12-22	I _p 70-140 Fines > 85 Organic 5-15	0.01-0.12	CRSC/IL Fig. 8	Borel et al. (2002)

2 Notes: See Table 2

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5 **Table 5.** *Summary of factors influencing sample quality and recommendations (NGI, 2002)*

Sampler feature	Ideal situation	Limitations	Alternative solutions	Recommendation	Note	Importance Factor*
Sample diameter	As large as possible	Weight handling on deck		100 to 120 mm diameter	Advantage to trim down sample	2
Ratio wall thickness to sample diameter	B/t as small as possible	Strength of barrel and liner space between		Area ratio < 17% Cutting edge wall thickness 3.5 – 5 mm	Should be considered together with length to increased dia. (Figs. 13 and 14)	1
Cutting shoe angle	As small as possible	Prone to damage during operation		5° for most susceptible soils	Should vary with soil	1
Inside friction	As small as possible during sample cutting	Weight of sample during withdrawal	-smooth material -inside clearance <0.5%	Smooth material /coating	Soil / plastic ring shear tests recommended to find best material	1
Outside friction – cutting shoe	As small as possible		-smooth hard material -low area ratio	Smooth material		2
Outside friction barrel	As small as possible	Must be some distance from barrel tip	-friction reducer -smooth material -surface paint -water flushing	Possibly combination	Soil/steel ring shear tests recommended to find best material	2
Piston	Stationary relative to sea bottom	Possible settlement of seabed frame	-STACOR solution -NGI solution	Stationary relative to sea bottom		1
Core retainer	Not felt by soil during sampling Cut sample and carry weight	Available diameter of core barrel				2
Penetration	One steady long and quick push at about 2 cm/s		Hydraulic cylinder Wheel drive Hydrostatic push		To be evaluated by owner of equipment. Gravity / free fall may be acceptable.	2
Instrumentation	Measure penetration in real time plus other parameters		Echo sounders, mechanical measurements	Depends on deployment system		2

7 * Importance factor in relation to sample quality. In range 1 to 3, where 1 = Essential, 2 = very important
8 and 3 = important
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1 *Table 6. Recommended cutting edge angles with various area ratios for 75 mm*
2 *samplers (Broms, 1980)*

Area ratio, C_a (%)	Cutting edge angle, β (Deg.)
5	15
10	12
20	9
40	5
80	4

LIST OF FIGURES

Figure No.	Caption	Reference / File name
1	CAUC tests Lierstranda clay at 12.3 m	Lunne et al. 1997
2	CRS tests Lierstranda clay at 12.3 m	Lunne et al. 1997
3	Operating principle of Kullenberg type piston corer	Fäy et al. 1988
4	Principle of STACOR fixed piston corer	Fäy et al. 1988
5a	1D consolidation test results from GPC specimens	Silva et al. 1976
5b	1D consolidation test results from JPC specimens	Silva et al. 2001
6	Sample quality Kullenberg samplers	Laptop/Papers+ D(X)/Longsampler/Kullengerg.grf+xls
7	Sample quality STACOR – NGI database	D(X)/Longsampler/STACOR.grf +Kullenberg.xls
8	Profile of STACOR $\Delta e/e_0$ with depth	Borel et al. 2002
9	Comparison between sample quality Kullenberg and thin walled STACOR - NGI database	D(X)/Longsampler/AllNGI.grf +Kullenberg.xls
10	Predicted axial strains for five different cutting shoe geometries	Clayton and Siddique, 1999
11	Effects of area ratio, inside clearance and outside cutting edge angle	Adapted from Clayton et al., 1998 & Hight, 2000
12	Relationship between sample diameter and degree of disturbance	Andresen, 1981
13	Relationship between disturbance, cutting edge angle and area ratio	Andresen, 1981
14	Outline design of ideal sampler cutting head	NGI (2002)

Figures for Long seabed sampler paper by Lunne and Long

Figure 1 CUAC triaxial tests Lierstranda clay at 12.3 m (Lunne et al., 1997)

Figure 2 CRS oedometer tests Lierstranda clay at 12.3 m (Lunne et al., 1997)

Figure 3 Operating principle of Kullenberg type piston corer (Fäy et al., 1988)

Figure 4 Principle of STACOR fixed piston corer (Fäy et al. 1988)

Figures 5a and 5b. (a) 1D consolidation test results from GPC specimens (Silva et al., 1976) and (b) JPC specimens (Silva et al., 2001) 1D consolidation test results from GPC specimens

Figure 6. Sample quality Kullenberg samplers

Figure 7. Sample quality STACOR - NGI database

Figure 8

Profile of STACOR $\Delta e/e_0$ with depth (Borel et al., 2002)

Figure 9. Comparison between sample quality Kullenberg and thin walled STACOR - NGI database

Figure 10 Predicted axial strains for five different cutting shoe geometries (Clayton and Siddique, 1999)

Figure 11 Effects of area ratio, inside clearance and outside cutting edge angle (Adapted from Clayton et al., 1998 & Hight, 2000). See text for definitions.

Figure 12 Relationship between sample diameter and degree of disturbance (Andresen, 1981)

Figure 13 Relationship between disturbance, cutting edge angle and area ratio (Andresen, 1981)

Figure 14. Outline design of ideal sampler cutting head (NGI, 2002)