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APPARENT OVERCONSOLIDATION AND ITS IMPLICATIONS FOR SUBMARINE LANDSLIDES

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\textit{Highlights}

- The existence of AOC is related to the formation of a structured sediment, generated mainly by processes of secondary consolidation and aging.
- The structuring of the sediment by secondary consolidation is generated mainly when the sedimentary process is slow and continuous.
- Sediment structuring by aging would only occur in the most superficial samples and would later be masked in the deeper samples.
- The weakening that occurs immediately below the superficial layer due to AOC will facilitate the development of plane superficial slides.
The development of this type of instability generates a subsequent stabilization of the ocean floor and, consequently, a lower recurrence of large landslides in these areas.

Abstract

In recent years, apparent overconsolidation (AOC) has been observed in the most superficial sections of the sedimentary column of the seabed. AOC has been detected in sediment samples taken from deep and shallow waters, independent of the source area. Although the origin of this phenomenon remains controversial, it seems to be linked principally to physical-chemical bonds and ionic changes that cause strong attractions between particles.

This work uses an experimental approach based on standardized oedometer tests to study the presence of AOC in surface sediments and its disappearance at depth. The results obtained show that the existence of AOC is related to the formation of a structured sediment generated by both secondary consolidation and aging processes.

In addition, the results obtained facilitate a discussion of how AOC influences the potential development of plane translational slides. The development of this type of instability in areas affected by AOC generates a subsequent stabilization of the ocean floor and, consequently, a lower recurrence of large landslides in these areas than would be expected from a sedimentary process with no AOC.

Keywords: apparent overconsolidation, submarine sediment, sub-bottom, submarine landslide
1 Introduction

Consolidation is the reduction of sediment volume caused by the dissipation of excessive pore pressure that occurs as sediments are buried, and which, in turn, generates an increase in the effective pressure to which they are subjected. Oedometer tests of consolidation performed on undisturbed samples (Terzaghi and Peck, 1948) enable the determination of pre-consolidation pressure ($\sigma'_p$), in other words, the maximum effective pressure that the sediment has supported and which is mechanically equivalent to the transition between the elastic and the elastic-plastic behaviour (Wood, 1990).

If we compare the pre-consolidation pressure ($\sigma'_p$) obtained in an oedometer test with the effective pressure that the sediment supports in situ due to the weight of the sedimentary column ($\sigma'_{vo} = \Sigma \gamma' * h$), we find three types of sediments: (1) normally consolidated sediments ($\sigma'_p = \sigma'_{vo}$), i.e., those that have been subjected to a vertical effective pressure due solely to the weight of the sedimentary column that existed at the time of sampling; (2) overconsolidated sediments ($\sigma'_p > \sigma'_{vo}$), i.e., those which have endured effective vertical pressures higher than those provided by the weight of the sedimentary column at the time of sampling; and (3) underconsolidated sediments ($\sigma'_p < \sigma'_{vo}$), i.e., sediments that present a pore pressure excess that has not been dissipated and, therefore have not been consolidated due to the effective pressure of the current load.

Overconsolidation of marine sediments is generally related to erosive processes or mass movements that remove part of the sedimentary column; this mechanism is called mechanical overconsolidation (MOC). However, for decades, geotechnical studies of marine sediments have shown that in the seabed, the most superficial samples of the sedimentary column (generally less than 5 m deep) present, in many cases, pseudo-consolidation or apparent overconsolidation.
(AOC); in other words, the test results confirm that these sediments are overconsolidated, although this cannot be explained by a geological process of sedimentary column loss. In many cases, this AOC of the seabed is also associated with a peak strength, as in this zone the detected undrained shear strength (according to \textit{in situ} penetration tests or laboratory tests) is higher than expected.

One of the first studies in which this phenomenon was detected was the MOHOLE project (Hamilton, 1964; Richards and Hamilton, 1967), performed near Guadalupe Island in the North Pacific. In these early works, an explanation for the phenomenon was suggested to be interparticle bonding, which occurs through chemical cementation, although in cases where this chemical cementation was not observed, slow sedimentation was offered as an alternative explanation because this leads to the apparent aging of the sediment (Leonards and Ramiah, 1960). In the same decade, Bjerrum (1967) studied Norwegian marine clays and proposed that secondary consolidation, chemical activity (cation exchange), and cementation were responsible for this increased surface sediments strength.

Subsequent to those initial works, AOC began to be observed in most of the ocean floor. Keller and Bennett (1973), studying samples of clay from the northeastern Equatorial Pacific, found overconsolidation in the most superficial samples and invoked incipient cementation of the surface sediment to explain this. However, these authors questioned the accuracy of the results due to the disturbance of sediments caused by the drilling techniques; this particular explanation was one of the first to be postulated to describe this phenomenon. In the work of Silva and Jordan (1984), samples collected from the NW Atlantic and North-Central Pacific using different techniques, i.e., box, standard piston, giant piston (large-diameter), large-diameter gravity, and Kasten gravity corers, were analyzed. Based on the results obtained, the authors confirmed that
the phenomenon is seen independently of the sampling technique. More examples of AOC have been detected in subsequent works, once again independently of the sampling technique used: (1) deep sounding (Bryant and Bennet, 1988; Dadey and Silva, 1989; Dugan and Daigle, 2011; Guo et al., 2013); (2) gravity corer (Baraza et al., 1990; Brandes et al., 1996; Veyera et al., 2001; Anandarajah and Lavoie, 2002); (3) piston corer (Roberts and Cramp, 1996; Lafuerza et al., 2012; Yenes et al., 2012); (4) box corer (Brandes et al., 1996; Roberts and Cramp, 1996; Veyera et al., 2001; Yenes et al., 2016); and (5) determination of geotechnical properties in situ (Baltzer et al., 1994; Sultan et al., 2000; Le, 2008). We can therefore conclude that the phenomenon of overconsolidation in the first sections of the marine sedimentary column is not an artefact resulting from a particular sampling technique or the disturbance of sediments caused by sampling.

AOC has been detected both in deep-water samples (e.g., 3862 m of water column in Dadey and Silva (1989), south of Greenland) and in samples taken in shallower areas (e.g., 60 m of water column in Dan et al. (2007), on the Nice continental slope). In addition, the phenomenon also seems to be independent of the sediment source area, as it has been identified in samples clearly influenced by continental contributions (e.g., Casas et al., 2004; Sultan et al., 2000) and samples with no continental sediments contributions (e.g., Yenes et al., 2012). These results imply that the phenomenon occurs in sediments of various compositions; however, all the samples in which it has been described contain a certain proportion of clays (Le, 2008).

Due to the wide distribution of AOC across continental margins and sedimentary basins, the phenomenon is of great interest for both basic and applied science (e.g., offshore geotechnical engineering). Nonetheless, its origin is still debated, and its effects on the seabed are most likely underestimated. The aim of this work is, therefore, to investigate the origin and
effect of AOC on the most superficial seabed sediments; in particular, an experimental approach based on standardized oedometer tests has been designed to characterize the occurrence and evolution of AOC at depth. On the other hand, it is well known that the stability of marine sediments is closely related to their consolidation state (e.g., Baltzer et al., 1994; Dan et al., 2007; Ladd and Foott, 1974; Lafuerza et al., 2012; Sultan et al., 2000; Wiemer et al., 2015, 2017). In this sense, the increased strength and density of the sediment that occurs in the layer with AOC may facilitate the development of translational slides. For this reason, understanding and determining its origin and possible development should allow areas with a potential landslide risk to be identified.

2 Apparent overconsolidation (AOC)

Although few studies have investigated the AOC, Silva and Jordan (1984) performed 180 one-dimensional consolidation tests on samples obtained from 52 surveys of the NW Atlantic and Central Pacific and found AOC in the first 2-4 m of sediment in all cases, whereas at greater depths the sediments already appeared normally consolidated or even underconsolidated. In all cases, the authors attributed the phenomenon to high levels of interparticle bonding and some cementation effects, although this was not observed.

Sultan et al. (2000), attempting to determine the origin of AOC, reported the results of a study conducted on sediments from the Gulf of Guinea (GoG) in which they confirmed that superficial overconsolidation does not have a mechanical origin (MOC). These authors proposed an osmotic consolidation mechanism generated by ionic changes between the free interstitial water and the water adsorbed by the surface of the clays. The increase in the ionic concentration causes expulsion of the water located in the spaces between the clay particles, thus generating a
denser sediment with the same tensional state. Subsequently, Le (2008) studied the same region and concluded that the peak strength in the uppermost sediment layers of the GoG could also be due to modification of the superficial structure by biological activity (bioturbation), which would facilitate drainage of the sediment and thereby cause an increase in the density and strength of the material.

The possible causes of AOC in marine sediments have been narrowed to the following three factors:

1. **Inorganic cementation by agents such as silicates, carbonates, iron oxides or aluminum oxide** (interparticle bonding through chemical cementation) (Anandarajah and Lavoie, 2002; Brandes et al., 1996; Bryant and Bennet, 1988; Eng, 2004; Hamilton, 1964; Keller and Bennett, 1973; Lafuerza et al., 2012; Richards and Hamilton, 1967; Silva and Jordan, 1984; Veyera et al., 2001). This explanation has been used most often in the scientific literature, since it effectively explains the AOC observed in some areas and specific samples. However, as noted by Bryant and Bennet (1988), this process does not sufficiently explain why the phenomenon has only been observed in the first meters of the sedimentary column and not throughout the entire sampled column, because, if this cementation process is generated in the first few meters of the sedimentary column, the cementing agent should also be observed in the deepest samples. On the other hand, this process would explain the phenomenon when the cementing agent is actually detected; however, AOC has been observed in samples where there is no cementing agent.

2. **Bioturbation and organic cementation** (bonding of sediment particles by organic sustances) (Baltzer et al., 1994; Baraza et al., 1990, 1992; Briggs et al., 1985; Busch and Keller, 1982; Cochonat et al., 1992; Ehlers et al., 2005; Kuo and Bolton, 2013; Le, 2008;
MacKillop et al., 1995; Perret et al., 1995; Richardson et al., 1985). These processes could explain the phenomenon in some areas and certain samples; however, the results of a study by Perret et al. (1995) indicated that this process would hardly reach depths greater than 15 cm. As with chemical cementation, the existence of these processes in only surface sediments would be fortuitous, and it would be odd if it had not occurred in sediments that are now located at greater depths (Busch and Keller, 1982); in this sense, Baltzer et al. (1994) suggested that the loss of labile organic compounds during the first diagenesis may be responsible for the loss of AOC at depth. Additionally, in the work of Kuo and Bolton (2013) in the GoG, the resistant crust was found to be due to an accumulation of invertebrate faecal pellets, and that their degradation at depth diminished the effect. Therefore, in some cases, it seems the accumulation of organic matter and bioturbation causes a hardening of the upper sedimentary layer, although this effect can be lost at depth. However, as with chemical cementation, this does not explain the existence of AOC in areas and samples where there is no evidence of the existence of organic matter and bioturbation.

3. Strong physical-chemical bonds between particles and ionic exchanges that can cause strong attractions between particles (either ionic or Van der Waals forces) (Anandarajah and Lavoie, 2002; Baraza et al., 1990, 1992; Brandes et al., 1996; Brausse, 2001; Bryant and Bennet, 1988; Eng, 2004; Le, 2008; Sultan et al., 2000; Wetzel, 1990). One of the first studies in which this mechanism was discussed in detail was that of Sultan et al. (2000), who proposed, as already mentioned, osmotic consolidation induced in the diffuse double layer (DDL) of clays according to the Gouy-Chapman theory (Chapman, 1913; Gouy, 1910). Ikari and Kopf (2011) proposed that this process is caused by hydrogen bonds between water molecules within the double layer. Prior to this study, Mathew and Rao (1997) had already
shown that the oedometric compressibility of a marine clay could be modified by cationic exchanges. This process generally occurs when there is slow sedimentation (e.g., Bryant and Bennet, 1988; Busch and Keller, 1982; Cochonat et al., 1992; Colliat et al., 2011; Hamilton, 1964; Leonards and Ramiah, 1960; Richards and Hamilton, 1967). However, it has also been postulated that the process may be favored by currents and wave action (e.g., Cochonat et al., 1992; Kayen et al., 1989; Roberts and Cramp, 1996; Schwab, 1986; Sultan et al., 2000), or small seismic shocks (e.g., Sultan et al., 2000; Wiemer et al., 2017).

These processes have generally been encompassed within what is known as secondary consolidation and aging. The secondary consolidation causes a progressive settlement of the sediment once the pore pressure excess has been completely dissipated, and as a result, the sediment is subjected to a constant effective stress for a long period of time (Bjerrum, 1967). However, in some cases (Eng, 2004; Leroueil et al., 1996; Perret et al., 1995), it has been observed that, under these conditions, there is greater settlement than can be attributed to the secondary consolidation according to the concept of Bjerrum (1967); in these cases, sediment aging is proposed (Fig. 1). Schmertmann (1991) hypothesized that this behaviour could be attributed to the thixotropy of the clay components in the sediment. Thixotropy is a reversible process that causes an increase in clays strength as a consequence of particle reorientation of and ionic exchanges (Mitchell, 1960). Thus, this thixotropic effect would occur during the initial accumulation of sediments at the bottom of the sea, under undrained conditions and subjected to small effective stresses (Schmertmann, 1991). Likewise, this same author postulated that when the stress caused by the sedimentary column exceeds a certain value (approximately 20 kPa), the thixotropic effect disappears, and mechanical consolidation becomes dominant.
These two mechanisms (secondary consolidation and aging) cause the formation of a structured soil (Leroueil and Vaughan, 1990), which involves a combination of soil particles arrangement, i.e., the fabric of the soil, and inter-particle bonds, i.e., the forces between particles that are not purely frictional in origin (Lambe and Whitman, 1969; Mitchell, 1993).

In a one-dimensional consolidation test (oedometer test), the pre-consolidation pressure ($\sigma'_p$), in other words, the maximum effective pressure that the sediment has supported, can be determined considering the pressure at which the compression curve yields.

Nevertheless, this mechanical behavior is not only related with the overburden load, and it has been observed that sometimes the yield point indicates a higher pressure than that from the sedimentary load. After testing and considering reconstituted and natural
samples from different geological conditions, it was stated that post-sedimentary processes were behind this effect (Leroueil and Vaughan, 1990; Burland, 1990). Two different explanations for the same mechanical situation guided Burland (1990) to introduce the yield stress ratio (YSR), defined as the ratio between yield stress ($\sigma'_y$) and the effective overburden pressure or in situ lithostatic pressure ($\sigma'_o$). This index is equal to the overconsolidation ratio (OCR) -the ratio between $\sigma'_p$ and $\sigma'_o$- when only loads from sedimentation have affect the samples ($\sigma'_y = \sigma'_p$), and higher when post-sedimentary processes exists (Cotecchia and Chandler, 2000); therefore, it is useful for detecting, interpreting and also measuring the mechanical effects on the unidimensional compression of the samples tested.

3 Method

In this work, standardized tests were used to study the physical, compositional and mechanical properties of surface sediments obtained from the continental slope of the Gulf of Cádiz (Table 1), collected in a context of contouritic drift and, consequently, where the recovered sediment should be normally consolidated (OCR = 1) (García et al., 2016; Hernández-Molina et al., 2008a, 2008b).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Prof.</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW14-BC-23</td>
<td>35º 46.3200’N</td>
<td>6º 46.9400’W</td>
<td>667 m</td>
<td>37 cm</td>
</tr>
<tr>
<td>MW14-BC-07</td>
<td>35º 55.4486’N</td>
<td>6º 55.9010’W</td>
<td>814 m</td>
<td>16 cm</td>
</tr>
</tbody>
</table>

Table 1. Samples used in this study. Each box corer was sampled with two 90 mm-diameter PVC tubes, which provided two sub-samples (A and B) for each box corer.
The samples were obtained via a box corer (Table 1) during the MOWER oceanographic surveys aboard the B.O. Sarmiento de Gamboa. The box corer system provides surficial and practically non-deformed samples, which are useful for performing tests that require the internal structure of the sediment to be preserved.

During the survey, an ARGUS ROV was used to obtain samples of seawater from near the bottom. These samples were used to study the influence of salinity (seawater vs distilled) of water used on the different deformability tests.

The properties of the sediments sampled were characterized through granulometric tests (screening and sedimentation) and by determining of the Atterberg limits (AENOR, 1999). The mineralogical composition was determined via X-ray diffraction (XRD); the diffractograms were produced in step/scan mode with a θ/2θ configuration on a Bruker D8 Advance diffractometer equipped with a Cu tube, primary monochromator (λ = 1.54056Å), and scintillation detector. The quantification of phyllosilicates it was done by XRD of the < 2μm fraction by oriented aggregates. Finally, the chemical composition of the seawater near the sampling area was analyzed using a plasma spectrometer (ICP-OES).

The deformability tests were performed on undisturbed samples with a one-dimensional oedometer consolidation test according to the general standards (AENOR, 1999) (Table 2), and additional modifications involving load gradients and step durations. Even though some differences exist between drainage under real conditions -where the water flows basically upwards when dissipation of pore pressures takes place- and those on the oedometer test -which favours two drainage paths: upwards and downwards-, they only affect the duration of the
consolidation process and, therefore, the test can be considered an acceptable simulation for studying the AOC.

<table>
<thead>
<tr>
<th>E</th>
<th>REFERENCE</th>
<th>S</th>
<th>DEPTH (cm)</th>
<th>WATER</th>
<th>TIME (hours)</th>
<th>REL.</th>
<th>LOADING STEPS</th>
<th>σ'\textsubscript{max} (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>MW14-BC23-15-B-MAR</td>
<td>B</td>
<td>14.5</td>
<td>Seawater</td>
<td>24</td>
<td>No</td>
<td>13</td>
<td>490.5</td>
</tr>
<tr>
<td>3</td>
<td>MW14-BC23-19-A-DEST</td>
<td>A</td>
<td>18.5</td>
<td>Distilled</td>
<td>24</td>
<td>No</td>
<td>13</td>
<td>490.5</td>
</tr>
<tr>
<td>4</td>
<td>MW14-BC23-19-B-MAR</td>
<td>B</td>
<td>18.5</td>
<td>Seawater</td>
<td>24</td>
<td>No</td>
<td>13</td>
<td>490.5</td>
</tr>
<tr>
<td>5</td>
<td>MW14-BC23-21-B-DEST</td>
<td>B</td>
<td>21</td>
<td>Distilled</td>
<td>24</td>
<td>No</td>
<td>13</td>
<td>490.5</td>
</tr>
<tr>
<td>6</td>
<td>MW14-BC23-24-B-MAR</td>
<td>B</td>
<td>24</td>
<td>Seawater</td>
<td>24</td>
<td>No</td>
<td>13</td>
<td>490.5</td>
</tr>
<tr>
<td>7</td>
<td>MW14-BC23-27-B-DEST</td>
<td>B</td>
<td>27</td>
<td>Distilled</td>
<td>24</td>
<td>Yes</td>
<td>29</td>
<td>982.5</td>
</tr>
<tr>
<td>8</td>
<td>MW14-BC23-30-B-MAR</td>
<td>B</td>
<td>30</td>
<td>Seawater</td>
<td>24</td>
<td>Yes</td>
<td>29</td>
<td>982.5</td>
</tr>
<tr>
<td>12</td>
<td>MW14-BC07-15-A-DEST</td>
<td>A</td>
<td>14.5</td>
<td>Distilled</td>
<td>&gt; 168</td>
<td>No</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>MW14-BC07-15-B-DEST</td>
<td>B</td>
<td>14.5</td>
<td>Distilled</td>
<td>&gt; 168</td>
<td>No</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.** Deformability tests. E: test number; S: sample; DEPTH: depth in cm from the seafloor; WATER: type of water used in the test; TIME: duration of each load step; REL: Reloading test; and L. STEPS: number of loading steps. σ'\textsubscript{max} (kPa): maximum effective vertical pressure during the test. The following loads were applied: (Test 1, 2, 3, 4, 5, 6): 2.5, 4.9, 7.4, 12.3, 24.5, 49, 98, 245.3, 490.5, 98, 24.5, 7.4, 2.5 kPa; (Test 7, 8, 9, 10): 1.5, 3.9, 6.4, 8.8, 11.3, 13.7, 18.7, 26, 50.5, 75, 26, 11.3, 3.9, 6.4, 13.7, 26, 50.5, 62.8, 75, 87.3, 124.1, 246.7, 492, 982.5, 246.7, 75, 13.7, 3.9, 1.5 kPa; (Test 12 and 13): 1.5, 3.9, 6.4, 11.3, 16.2, 26.0, 50.5, 75.0 kPa

Tests 1 to 6 were performed to determine the effect of the water type utilized (distilled or seawater); in all tests, thirteen steps of 24 h each were made. For tests 7 and 8, the samples were loaded to the equivalent pressure of 10 m depth, unloaded and then reloaded; this involved a total of twenty-nine steps, 24-hours steps. In tests 9 and 10 the same steps were applied but each load was maintained for a week (168 hours), to study the secondary consolidation. Test 11 involved
twenty-nine, 24-hours steps, but for greater accuracy, steps of 25 gr weights were used up to 27.22 kPa (step 22). Finally, in tests 12 and 13, there were eight steps, each longer than a week (up to 100 days in the 11.3 kPa step) to activate the possible aging of the sediment.

This approach allows for the following to be determined: (1) the tensional history of the sediment; (2) the influence of the water used (distilled or seawater) on the test results; (3) how the intensity of the load, its gradient and duration affect the sediment, influencing the results; and finally, (4) the influence of AOC on the potential development of sedimentary instabilities.

4 Results

The semi-quantitative analysis of the mineralogical composition determined by XRD indicates that the samples tested were composed mainly of calcite (23-25%), quartz (19-24%) and phyllosilicates (51-58%), among which clay minerals, mainly kaolinite (21-14%) illite (16-13%) and chlorite (12-5%), predominate. The geotechnical characterization tests (granulometry and Atterberg limits) show that they are clay-silts (13-15% sand, 40% silt, 45-47% clay) with low plasticity (plasticity index between 13.7 and 14.6), classifying the samples as ML (low plasticity silt) according to the Unified Soil Classification System (USCS).

The seawater used in the oedometer tests had a conductivity of 50200 μS/cm, with the following main cations: Na (12454 ppm), Mg (1398 ppm), K (511 ppm), and Ca (410 ppm).

The results from the oedometer tests (Table 3) in all cases showed the existence of overconsolidation (OCR > 6), which has been considered to be AOC as it cannot be related to an MOC process. This finding indicates that the sediment is structured and, consequently, the so-called pre-consolidation pressure ($\sigma'_p$) is more accurately designated as yield stress ($\sigma'_y$) and the OCR can be replaced by the YSR ($\sigma'_y/\sigma'_v$).
Table 3. Results of the oedometer tests. DEPTH: depth in cm from the seafloor; ρ: density (gr/cm³); w: moisture content (%); e₀: initial void ratio; σ'₀y: yield stress (kPa); Cc: compression Index; and YSR: yield stress ratio.

<table>
<thead>
<tr>
<th>TEST / SAMPLE</th>
<th>DEPTH</th>
<th>ρ</th>
<th>w</th>
<th>e₀</th>
<th>σ'₀y</th>
<th>Cc</th>
<th>YSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 / NW 14_BC23_15_A_DEST</td>
<td>14.5</td>
<td>1.67</td>
<td>63</td>
<td>1.5510</td>
<td>-</td>
<td>0.3710</td>
<td>-</td>
</tr>
<tr>
<td>3 / NW 14_BC23_19_A_DEST</td>
<td>18.5</td>
<td>1.73</td>
<td>61</td>
<td>1.6270</td>
<td>9.00</td>
<td>0.3670</td>
<td>6.63</td>
</tr>
<tr>
<td>5 / NW 14_BC23_21_B_DEST</td>
<td>21</td>
<td>1.76</td>
<td>58</td>
<td>1.5450</td>
<td>12.50</td>
<td>0.3540</td>
<td>8.11</td>
</tr>
<tr>
<td>7 / NW 14_BC23_27_B_DEST</td>
<td>27</td>
<td>1.78</td>
<td>51</td>
<td>1.4100</td>
<td>17.00</td>
<td>0.3230</td>
<td>8.58</td>
</tr>
<tr>
<td>9 / NW 14_BC23_24_A_DEST</td>
<td>24</td>
<td>1.76</td>
<td>56</td>
<td>1.4609</td>
<td>16.00</td>
<td>0.3121</td>
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<tr>
<td>11 / NW 14_BC23_30_A_DEST</td>
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<td>15.00</td>
<td>0.3300</td>
<td>6.81</td>
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<td>12 / MW14-BC07-15-A-DEST</td>
<td>14.5</td>
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<td>0.871</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
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</tr>
<tr>
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<td>1.3410</td>
<td>18.00</td>
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</tr>
<tr>
<td>8 / NW 14_BC23_30_B_MAR</td>
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<td>1.4030</td>
<td>18.00</td>
<td>0.3530</td>
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<tr>
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<td>47</td>
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<td>15.00</td>
<td>0.2713</td>
<td>7.57</td>
</tr>
</tbody>
</table>

### 4.1 Influence of test-water salinity

High YSR values were obtained in the tests using both distilled water and seawater (Table 3). When comparing the oedometric curves from two samples from the same depth (Fig. 2) but tested with different water (distilled water: blue curve; seawater: red curve), the plot showed that the compressibility was almost identical and, therefore, it is not salinity-dependent. A slight collapse was only observed in the sample tested with distilled water when the vertical effective pressure reached approximately 15 kPa (Figs. 2 and 4); this collapse may have been related to the circulation of distilled water, and this phenomenon has also been observed in other
similar studies (Dan et al., 2007). Once this threshold had been exceeded, the compression index was again similar to that of the sample tested with seawater.

Thus, based on these results, it can be deduced that the AOC is not an artefact generated in the laboratory caused by the salinity of water. Nevertheless, it is also interesting to notice that, when comparing samples from the same depth, YSR values from seawater tests are usually higher than those using distilled water.
Fig. 2. Oedometric curves: blue test curve generated with distilled water (1/NW 14_BC23_15_A_DEST); and red test curve generated with seawater (2/NW 14_BC23_15_B_MAR). In the sample analyzed with distilled water, when the effective vertical pressure reaches 15 kPa, a slight collapse occurs.

4.2 Influence of secondary consolidation

The test results showed differentiated oedometric behaviour as a function of how the load increases (Fig. 3).
Fig. 3. Consolidation behavior in response to steps with small load increments (blue lines) and steps with geometrically progressing loads (red lines). The representation was generated considering a value of 100% settlement over 24 hours.

Thus, when the loading steps of the oedometer tests progress geometrically (red curves in Fig. 3), in accordance with the standard test (AENOR, 1999), simulating sedimentation from large and instantaneous sedimentary contributions to the basin, typical consolidation curves are obtained, showing a clear difference between primary consolidation (settlement controlled by the dissipation of excess pore pressures) and secondary consolidation (settlement controlled by soil viscosity). In these cases, most of the settlement occurs in the first post-load increase, as shown by the steep slope of initial curves, whereas the secondary consolidation is characterized by very homogeneous, gentle slopes (secondary compression index, $C_\alpha$).

However, when the test involve small loading steps increments, simulating the consolidation generated by small sedimentary contributions to the basin (blue curves in Fig. 3), the behaviour is totally different since, in these cases, most of the settlement has not occurred by the time primary consolidation supposedly taking place, evidenced by the lack of initial slopes. Nevertheless, secondary consolidation is characterized by a steeper slope, with higher secondary compression indexes ($C_\alpha$) than those from the test involving geometrically progressing loading steps.

4.3 Influence of sediment aging

The influence of the length of time that each load step is applied for has been determined (Fig. 4); thus, if we compare the oedometric curves obtained when the steps are maintained for
24 hours according to the AENOR (1999) standard (red curve in Fig. 4) with those obtained when the steps are maintained for 168 hours (blue curve in Fig. 4), we can see that in both cases, the results are similar (Table 3) since both present similar AOC (YSR = 6.81 and 9.08, respectively) and compression indexes (Cc = 0.3300 and 0.3121, respectively). In this sense, it should be noted that, according to various authors, sediment aging begins after several days of the sediments being loaded, from approximately 14 days (e.g., Hueckel et al., 2001) to more than 45 days (e.g., Eng, 2004). It is, therefore, possible that in tests where the sediments was under a load for a week, the aging process had not started.

![Void ratio vs Effective stress graph](image-url)
**Fig. 4.** Oedometric curves (void ratio vs. effective stress). Blue: 9/NW14_BC23_24_A_DEST (Duration of steps: 168 hours); and red: 11/NW 14_BC23_030_A_DEST (Duration of steps: 24 hours).

To effectively generate sediment aging, we designed tests 12 and 13 (Table 3), where some of the loading steps were maintained for more than 100 days. The results of these tests show that aging occurred only at the beginning of the consolidation process and, specifically, in the second loading stage (3.9 kPa); in this step, the settlement generated by aging can be observed after 8 days of constant load, when the curve reaches very high values (Fig. 5).

**Fig. 5.** Consolidation curves obtained for the 3.9 kPa stage. Red curve 12/MW14-BC07-15-A-DEST; and blue curve 13/MW14-BC07-15-B-DEST.
5 Discussion

The analytical approach has allowed us to look in detail at the presence of AOC in surface sediments and its disappearance at depth. In all cases, the results obtained show in all cases the existence of AOC as a consequence of sediment structuring. Analyses of the tested samples ruled out the presence of organic matter or inorganic cementitious agents that could explain this structuring.

The salinity of the water used in the tests has also been excluded as a cause of an empirical artefact, since AOC was observed in samples tested with both seawater and distilled water. However, Sultan et al. (2000) noted that the AOC and peak strength detected in the most superficial samples obtained in the GoG could be explained by an osmotic effect due to an ion concentration gradient in the interstitial water, meaning water in that case did influence on the magnitude of the process. Later analyses with samples, also from the GoG (De Gennaro et al., 2005; Le, 2008), demonstrated that changing the salinity of the test water has a minimal effect on the oedometric behaviour of the samples. Consequently, although the salinity of the water used in the oedometer tests does not lead to AOC, as show in both this work and previous studies (e.g., De Gennaro et al., 2005; Le, 2008; Rajasekaran and Rao, 2002), in some cases, during the sedimentary process, salinity may contribute to the structuring of the sediment (Sultan et al. 2000). Some of our results, involving samples from the same depth but tested using different water types, point to the same conclusion, as the YSR value was higher when seawater was used.

Once we had ruled out the fact that the AOC was due to cementing agents or calculation/testing artefacts, we studied how secondary consolidation influences the process, since it is well known that a consequence of this consolidation is sediment structuring (e.g.,
Bjerrum, 1967; Eng, 2004; Tavenas and Leroueil, 1977). The results of our tests showed that the magnitude and duration of the secondary consolidation were related to the load gradient applied in the oedometer test, simulating different sedimentary processes: geometrically progressing loading steps simulated sedimentation by means of large and instantaneous sedimentary contributions; whereas loading steps with small, linear increments simulated the consolidation generated by slow sedimentation via smaller contributions.

The results of our tests show that when sedimentation is slow, most settlement in the samples is not produced by oedometric consolidation, but rather is generated during secondary consolidation. This is non-reversible settlement and therefore involves the development of sediment structuring that is unrelated to the effective stresses supported by the sediment and, consequently, would be partly responsible for the observed AOC.

Different studies have shown that the AOC develops more strongly when sedimentation rates are low (e.g., Bryant and Bennet, 1988; Busch and Keller, 1982; Cochonat et al., 1992; Colliat et al., 2011; Hamilton, 1964; Leonards and Ramiah, 1960; Richards and Hamilton, 1967). However, Perret et al. (1995) observed AOC phenomena in both in turbidites (with high deposition rates) and slowly deposited sediments; although they observed that the turbidites presented less overconsolidation, they did not find conclusive evidence that this aspect directly influenced the overconsolidation, but rather that it indirectly influenced other factors, such as bioturbation and other physical properties, which in turn influenced the development of AOC.

Our results are consistent with AOC originated via secondary consolidation. However, in some cases, it has been shown that the structuring observed in superficial marine sediments cannot be attributed solely to secondary consolidation (Eng, 2004; Leroueil et al., 1996; Perret et al., 1995); in these cases, the structuring mechanism is aging, generated by inter-particle bonds
produced by forces that are not purely frictional in origin (Lambe and Whitman, 1969; Mitchell, 1993).

The aging of the sediments depends on the type and percentage of the clays present, although this has also been observed in sands, sandstones, and clayey sands (De Waal, 1986; Mesri et al., 1990; Schmertmann, 1991). According to Eng (2004), the phenomenon seems to be influenced by the environment and age of the sediment, since aging mainly occurs in reconstituted samples and not in undisturbed samples. However, our results show that sediment aging can also occur in undisturbed samples. In our samples, we have observed that aging only occurs in the initial loading stages and that, in the later stages, settlement is related only to oedometric and secondary consolidation, and there is no sediment aging. In this sense, Hueckel et al. (2001) noted that sediments seem to retain a memory of previous aging episodes. In short, in reconstituted samples, or very shallow undisturbed samples (which have undergone little lithostatic stress), aging can be activated in an oedometer test in the initial loading steps, whereas in samples that have already undergone a higher lithostatic pressure, aging has already occurred in situ and is not reactivated in the laboratory.

Our results also support the hypothesis of Schmertmann (1991), which suggested that aging, generated by a thixotropic effect, would occur in sediments with high void ratios, subjected to low effective stresses in undrained conditions, during the first stages of the sediment accumulation on the seabed. This process causes the structuring of the surface sediment and is partly responsible for the high YSR values detected in the most superficial samples.

The loss of sediment structuring as during continuous burial is also a widely described phenomenon. Sediment structuring due to secondary consolidation is irreversible, while that caused by aging (thixotropy) can be lost during the sedimentary process, when the effective
pressure increases. Leroueil and Hight (2002) noted the possibility of sediment destructuring due to rupturing of the bonds between particles or between aggregates, and to the modification of the arrangement of metastable particles, generating a general weakening of the material. On the other hand, when the lithostatic load increases, the effective stress to which the sediment is subjected also increases; when this exceeds a certain threshold (20 kPa according to Schmertmann, 1991), mechanical consolidation becomes the dominant effect and masks the initial AOC. When very shallow samples that have undergone in situ aging process are tested, sediment structure can be detected in the laboratory (Fig. 6A). However, when testing deeper sediments that have undergone an aging process at the initiation of sedimentation, laboratory tests does not detect the structure as it is masked by subsequent mechanical consolidation (Fig. 6B).
Fig. 6. A: Synthetic consolidation curve of a shallow sample with AOC detectable in laboratory tests. B: Synthetic consolidation curve of a deeper sample with AOC masked by subsequent mechanical consolidation.

5.1 Implications for submarine landslides

In general, the most superficial seabed sediments of the seabed that exhibit AOC also present a significantly increased shear strength (e.g., Cochonat et al., 1990; Le, 2008; Yenes et al., 2012). Any of the processes that generate AOC can also produce a density increase in the
sediment. Thus, the density increases regardless of whether the AOC is due to an inorganic cementation by silicates, carbonates, iron oxides, or other cementing agents (e.g., Veyera et al., 2001), or the bonding of sediment particles has an organic origin (Pusch, 1973). In the latter case, generating an AOC layer may also be associated with bioturbation processes, thus facilitating sediment drainage and consequently increasing the density and strength (e.g., Ehlers et al., 2005; Le, 2008; Perret et al., 1995). Finally, if the AOC is related to the aging phenomena generated by the physical-chemical bonds between particles caused by osmotic consolidation in the clay sediments, then, in all cases, this process will generate denser sediments without modifications in the stress to which they are subjected (Sultan et al., 2000).

To quantify the effect of AOC on seafloor stability, we developed a simple model in which the factor of safety (FS) of the slope is determined by the Generalized Limit Equilibrium (GLE) method using the Slide 8.0 program, by Rocscience Inc. (2018). The GLE analyses the forces (or stresses) that act on an assumed failure surface. Failure occurs when the shear stress exceeds the maximum available shear strength. The FS, which is defined as the ratio between the resisting shear strength and the sum of all mobilized shear stress, determines whether a slope is unstable (FS≤1) or stable (FS>1). FS is calculated using the Spencer method (Spencer, 1967), and the failure surface is considered to develop only in undrained conditions (τ = S_u).

To watch effect modifying the shear strength and density of the AOC layer has on seafloor stability, we determined the stability of a usual seabed with an inclination of 10º, a unit weight of 16 kN/m³, and an undrained shear strength gradient of 2 kPa/m. On this seabed, AOC develops in a 1 m-thick layer (Table 4 and Fig. 7). When there is an increase in shear strength in the AOC layer, but the density remains constant (∆γ = 0 in Table 4, blue curve in Fig. 7), the progressive increase in the shear strength of the AOC layer induces an increase in FS (from 1.893 to 2.142),
i.e., this process increases the stability of the seabed. In addition, the failure surfaces generated under these circumstances are deep-seated circular failure surfaces not related to the AOC layer. On the other hand, if the increase in shear strength is associated with increased in density ($\Delta \gamma = 0.5$ in Table 4, red curve in Fig. 7), the FS decreases with respect to the value obtained without changing the density; i.e., the densification process increases the instability. In these cases, when the increase in density is small and the increase in strength is greater, deep-seated circular failure surfaces are produced. However, if the increase in density is greater (other curves in Fig. 7), the break that is generated is more of a flat surface, located immediately below the AOC layer.

If the thickness of the AOC layer increases, the modelling results are similar: in all cases, increased thickness of the AOC layer implies an increase in FS. This suggests that to produce flat failures below the AOC layer, the density increase must be greater to compensate for the increased strength of the AOC layer.

Consequently, when shear strength increases occurs in a layer with AOC, and a certain density threshold is exceeded, an area that acts as a geotechnical weak is generated immediately below the AOC layer. This zone will marks the detachment surface and will favors the development of superficial landslides where the failure plane is parallel to the seafloor, and its depth is much less than its length and width (Fig. 8). Such instabilities are very common in various submarine environments (e.g., Prior et al., 1982; Lee et al., 1991; Edwards et al., 1993; Schwab et al., 1993; Hampton et al., 1995; McAdoo et al., 2000; Tappin et al., 2001; Martel, 2004).

<table>
<thead>
<tr>
<th>$\Delta S_u$</th>
<th>FS ($\Delta \gamma = 0$)</th>
<th>FS ($\Delta \gamma = 0.5$)</th>
<th>FS ($\Delta \gamma = 1$)</th>
<th>FS ($\Delta \gamma = 1.5$)</th>
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<td>1,859</td>
<td>1,738</td>
<td>1,652</td>
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</table>
Table 4. Factors of safety (FS) for a seabed with a 10° inclination, unit weight of 16 kN/m³ and an undrained shear strength gradient of 2 kPa/m. On this seabed, an AOC layer of 1 m thickness is developed with different properties: $\Delta S_u = 1$ (AOC without increase in strength), $\Delta S_u = 2$ (AOC with $S_u = 2$ kPa), $\Delta S_u = 3$ (AOC with $S_u = 3$ kPa), $\Delta S_u = 4$ (AOC with $S_u = 4$ kPa); $\Delta \gamma = 0$ (AOC without increase in unit weight), $\Delta \gamma = 0.5$ (AOC with $\gamma = 16.5$ kN/m³), $\Delta \gamma = 1$ (AOC with $\gamma = 17$ kN/m³), $\Delta \gamma = 1.5$ (AOC with $\gamma = 17.5$ kN/m³), and $\Delta \gamma = 2$ (AOC with $\gamma = 18$ kN/m³). The blue squares correspond to the FS of deep-seated circular failure surfaces, while the yellow squares correspond to the FS of flat failure surfaces located at the base of the AOC layer.

Fig. 7. Graphic representation of the results shown in Table 4.
To study the effect of this type of instability, we modelled a seabed in which an AOC layer develops that can generate flat landslides due to the appropriate combination of increased shear strength and density.
Fig. 8. A: Model illustrating the difference in shear strength–depth profiles for three different situations. B: Modification of the FS by increasing the slope (β) to 15° for the three situations. C: Modification of the FS due to a seismic shake (PGA = 0.05 g).

The stability analysis was performed for three different situations (Fig. 8A): (1) Seafloor with no AOC: a homogeneous slope consisting of a single, normally consolidated material with undrained shear strength gradients (\(\nabla S_u\)) of 2 kPa/m and a constant unit weight of 16 kN/m\(^3\). (2) Seafloor with AOC: the same slope where AOC affecting the first meter of sediment has developed; this layer has a unit weight of 17.5 kN/m\(^3\) and a constant shear strength (\(S_u = 3\) kPa). At greater depths, the sediment exhibits an undrained shear strength gradient (\(\nabla S_u\)) of 2 kPa/m and a constant unit weight of 16 kN/m\(^3\). (3) Unroofing of a 1-m think landslide: there is a translational slip affecting only the overconsolidated layer first metre; consequently, the material that remains in situ presents real MOC and an undrained shear strength gradient (\(\nabla S_u\)) of 2 kPa/m. In all three cases, the FS modification was determined by increasing the slope (β) to 15° (Fig. 8B). Additionally, we analysed the effect of a seismic shake for the three situations, using pseudostatic analysis, introducing a peak ground acceleration (PGA) of 0.05 g into the model (Fig. 8C).

The results obtained show that if the instability is due only to gravity (Fig. 8B), when we compare the FS of the homogeneous slope with no AOC (blue curve) and the FS of a slope with a 1-m AOC layer (red curve), we can see that there is a decrease of between 2.8% for a 5° slope (β) and 13.8% for a 15° slope (β). Once the AOC layer has slipped, the sediments present slight mechanical overconsolidation, meaning the FS increases considerably (green curve), between 61.5% (β = 5°) and 35.4% (β = 15°). In short, in certain circumstances, the development of AOC
causes a plane of weakness immediately below the overconsolidated sediment; if a surface slip is generated, the seafloor gains stability.

If the instability is generated by a seismic shock (Fig. 8C), PGA = 0.05 g, in all three models, there is a similar drastic reduction of the FS from 56% (β = 5º) to 33% (β = 15º).

Therefore, for an inclination of 10º, a homogeneous slope with no AOC is stable (FS = 1.135), whereas for a slope with AOC, the FS reaches strict equilibrium (FS = 1.056); and for a slope that has already slid, stability is regained (FS = 1.516).

Consequently, in seaboards where there is AOC in the first few metres of the sedimentary column, translational landslides may be generated. Once a slip has occurred in the AOC layer, the sediments that remain in situ present a MOC that causes a stabilizing effect.

This stabilizing effect is similar, although surely on a smaller scale, to that produced in seismically active zones. In this sense, Ikari and Kopf (2015) indicated that in several seismically active zones, the rate of landslide recurrence significantly lower than the rate of earthquake recurrence (Camerlenghi et al., 2010; McAdoo et al., 2004; McAdoo and Watts, 2004; Strasser et al., 2012; Strozyk et al., 2010); furthermore, Andrews et al. (2016) demonstrated that slope stability increases as earthquake frequency increases and sedimentation rates decreases. The explanations for this phenomenon do vary: Strozyk et al. (2010) postulate seismic strengthening, as described in Locat and Lee (2002), where smaller earthquakes that are not of sufficiently high intensity to generate landslides, strengthen the sediment through dynamic compaction.

Therefore, the development of small translational landslides in areas affected by AOC generates a subsequent stabilization of the ocean floor and, consequently, a lower development of large landslides in these areas than would be expected in a sedimentary environment with no AOC.
6 Conclusions

- In this work, we have performed oedometer tests on superficial marine samples obtained using a box-corer in a depositional sedimentary environment dominated by contouritic processes. In all the tests we detected the existence of sediment structuring, which is manifested by overconsolidation (OCR > 6); this structuring is associated with AOC. Performing oedometer tests with both seawater and distilled water ruled out the fact that this effect is a synthetic artefact stemming from the analysis conditions.

- The structuring of the sediment is generated, in part, during secondary consolidation. It has been determined that the magnitude and duration of secondary consolidation are related to the process of increasing loads in the oedometer test, which allows different sedimentary processes to be simulated: when sedimentation occurs due to large and instantaneous sedimentary contributions, most of the sediment settles via oedometric consolidation; whereas in slow sedimentation, most of the sediment settles via secondary consolidation. Therefore, secondary consolidation structuring of the sediment is generated mainly when sedimentation is slow.

- In some cases, it has been shown that the structure observed in superficial marine sediments (AOC) cannot be attributed solely to secondary consolidation; in these cases, the aging process has been postulated as the structuring mechanism. In the tests performed in this work, we observed that sample aging is activated only during the initial loading steps, and that during subsequent steps the settlement is caused only by oedometric and secondary consolidation, with no aging of the sediment. Consequently, in
the marine sedimentation, sediment structuring by aging must occur only in the most superficial samples and would later be masked in deeper samples.

- The most superficial seabed sediments that manifest AOC also present significantly increased shear strength and density, implying that the weakening that develops immediately below the superficial layer due to AOC, facilitates the development of planar superficial slides. If this type of landslide is generated, then the seafloor becomes more stable, and the recurrence of larges landslides in the seabed is less than that expected in a sedimentary environment where AOC does not develop.

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**Declarations of interest**

None

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