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The enigmatic consolidation of diatomaceous sediment

Gauvain Wiemer [a,*], Ricarda Dziadek [b], Achim Kopf [a]

[a] MARUM-Center for Marine Environmental Sciences, University of Bremen, Germany
[b] AWI - Alfred Wegener Institute Helmholtz-Zentrum für Polar- und Meeresforschung, Germany

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ABSTRACT

Marine diatomaceous sediments are common along the polar belts and equator, but very little is known about their effect on sediment geotechnical properties and slope stability. Consolidation state analysis is frequently applied to derive past maximum overburden stress, to quantify over- or underconsolidation, or to infer excess pore water pressure, all relevant to assess risk of slope failure. Diatoms significantly alter geotechnical and other fundamental engineering properties usually observed in organic or inorganic sediment. The consolidation state of diatomaceous sediments is ambiguously discussed because geological evidence and laboratory data do not always correspond. A literature review revealed a near systematic overconsolidation of shallow diatomaceous sediments (<100 mbsf) and normal or underconsolidation in deeper sediment sequences. One-dimensional compression tests are carried out on material sampled during the R/V POLARSTERN cruise ANT XXIX/4 to a landslide-prone area of the South Sandwich Trench, and on generic clayey-silt - diatomaceous earth sample mixtures. Results indicate that diatoms alter geotechnical properties to an extent that in situ stress conditions may not well be inferred from common consolidation state analysis. Undrained vane shear strength underestimates the in situ undrained shear strength and leads to underestimated normalized undrained shear strength ratios. Enhanced secondary compression with overburden and diatom content leads to a natural curvature of consolidation lines, the latter occasionally falsely interpreted as preconsolidation stress. The observations are furthermore dependent on the predominant diatom order. Moreover, inverse trends of porosity are not necessarily related to excess pore water pressure, but solely to a gradual increase of diatoms with depth.

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1. Introduction

The consolidation state and consolidation behavior of marine sediment is of great importance for both applied and basic studies of the earth. Consolidation behavior is an indispensable engineering entity for foundation works (Terzaghi, 1996) given that the duration and costs of construction projects are majorly affected by the time required for safe loading. In marine geological sciences the consolidation state is of great interest for the inference of the effective overburden stress (σ'_{v0}) and associated evidence for excess pore water pressure. Excess pore water pressure reduces the effective stresses in the sediment and is reflected by underconsolidated sediment (Terzaghi, 1996). Overpressure and underconsolidation of sediment has been associated with many geological processes such as fluid flow (Dugan and Flemings, 2000), rapid sedimentation (Dugan and Germaine, 2008), seismic shaking (Sultan et al., 2009), or to the presence of free gas (Stegmann et al., 2006). Moreover, consolidation state analysis has been applied for the determination of past ice shield thicknesses (Boulton and Dobbie, 1993; Sauer et al., 1993). Since sediment stability and consolidation state are closely linked (Ladd and Foott, 1974), consolidation state analysis is commonly investigated within submarine landslide studies (see e.g. (Baltzer et al., 1994; Dan et al., 2007; Lafuerza et al., 2012; Lee and Baraza, 1999; Sultan et al., 2004; Wiemer et al., 2015).

The consolidation state of marine sediments sampled during ODP (Ocean Drilling Program) or IODP (International Ocean Discovery Program) expeditions is frequently investigated in two ways: A rather approximate method consists in inferring the consolidation state from the normalized undrained shear strength, i.e. the ratio of undrained shear strength (S_u) and effective overburden stress (σ'_{v0}) assuming hydrostatic pore water pressure. The normalized undrained shear strength (S_u/σ'_{v0}) of normally consolidated organic and inorganic soils is in the range of 0.2–0.5 (Karlsson and Viberg, 1967; Ladd and Foott, 1974; Skempton, 1969). Therefore, sediment with an undrained shear strength ratio falling below 0.2 or exceeding 0.5 are considered underconsolidated or overconsolidated, respectively. The undrained shear strength is mostly determined with a regular spacing using a motorized Wykeham Farrance vane-shear device on on-board split sediment cores. The effective overburden stress is calculated from sediment density values and by assuming hydrostatic pore water pressure via $\sigma'_{v0} = \gamma' * z$, with γ' the submerged unit weight, and z the

* Corresponding author.
E-mail addresses: gwiemer@marum.de (G. Wiemer), ricarda.dziadek@awi.de (R. Dziadek), akopf@marum.de (A. Kopf).

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depth below sea floor. To quantify the consolidation, the overconsolidation ration (OCR) is estimated from the equation $S_u = \sigma'_{v0} * S * (OCR)^m$, where S is the ratio of shear strength to consolidation stress for normal consolidation (i.e. S = 0.2–0.5), and m is a sediment parameter typically equal to about 0.8 (Ladd and Foott, 1974). Hence, normally consolidated sediment with an inherent OCR of one, presents a liner increase in shear strength which is in the range of 20–50% of the effective overburden stress.

The second, and more accurate method of determining the consolidation state consists in gaining conventional one-dimensional consolidation data (Deutsches Institut für Normung, 2012) in so-called oedometer tests. The data are then most often evaluated according to the Casagrande (1936) or Schmertmann (1953) method in order to infer the preconsolidation pressure (σ'_p) from the analysis of the void ratio (e) to vertical effective stress relationship (Terzaghi, 1996). σ'_p is the largest effective overburden stress a sediment was subjected to. The magnitude of σ'_p is again expressed in terms of overconsolidation ratio (OCR), here, the ratio of σ'_p/σ'_{v0}. Sediments that display values of $\sigma'_p/\sigma'_{v0} = 1$ are called normally consolidated (NC). Sediments that were subjected to effective overburden stresses in excess of the present effective overburden stress are called overconsolidated (OC), and vice versa (Terzaghi, 1996). Overconsolidated sediments that never really experienced the corresponding effective preconsolidation stress are called “apparently overconsolidated”. Apparent overconsolidation typically occurs within the uppermost sediment cover of 0–5 m and may be related to weak interparticle bonds, bioturbation, strengthening by currents and wave action or seismic shaking (Sultan et al., 2000).

Geological and geotechnical studies showed that the occurrence of even minor amounts of diatom microfossils (~10%) in sediment lead to severe deviations of the sediment physical and geotechnical property trends (e.g. γ', S_u, σ'_{v0}) commonly observed in organic or inorganic sediments with burial depth (Bryant et al., 1981; Díaz-Rodríguez and González-Rodríguez, 2013; Hong et al., 2006; Rack and Palmer-Julson, 1992; Tanaka et al., 2003; Volpi et al., 2003). Diatoms constitute a significant proportion of the world's oceans surface sediments. The major belts of silica accumulation are i) the southern belt encompassing the globe almost uninterruptedly in the Southern Hemisphere, ii) the northern belt in the Pacific Ocean, Sea of Okhotsk, Bering and Japan seas, and iii) the near-equatorial belt which is well defined in the Pacific and Indian oceans and less distinct in the Atlantic Ocean. The variety of natural marine diatomaceous sediment deposits range from almost pure diatoms to highly contaminated mixtures of diatom shells with inorganic or organic sediments (Lisitzin, 1971). Diatomaceous earth (DE) is a sediment consisting mainly of accumulated, hollow skeletons left by the unicellular aquatic phytoplankton (diatom). Diatoms grow out from circular (Centric) or elongated (Pennate) center during valve formation. The skeletons or frustules consume the dissolved silica in silica-rich aquatic environments, are symmetric in shape and consist of approximately 90% silica. Diatoms typically have rough surfaces, low density, a high absorptive capacity, a large surface area, and are abrasive (Round et al., 1990). The void space of a single diatom frustule is as high as 60–70% (Losic et al., 2007). Geotechnical properties of diatomaceous sediments are unique: Water content, void ratio, porosity, permeability, compressibility, consistency limits, and undrained shear strength increase with the amount of diatoms, whereby bulk density decreases (Day, 1995; Díaz-Rodríguez et al., 1998; Diaz-Rodríguez, 2011; Shiwakoti et al., 2002; Tanaka et al., 2003).

Pittenger et al. (1989) and Einsele (1990) suggested diatomaceous sediment to be weak and prone to failure under earthquake loading conditions. Wiemer et al. (2015) investigated the role of diatomaceous sediment within a subaqueous landslide study and showed that in fact diatomaceous sediment may build-up excessive pore water pressure during earthquake loading. Astonishingly, ship board and laboratory based data of normalized undrained shear strength and one-dimensional consolidation reveal that diatomaceous sediments are rarely in a state of normal consolidation to begin with. In reviewing the literature for this study it transpired that marine sediments containing diatom microfossils anywhere in the world are almost systematically associated with a decrease in consolidation state from high overconsolidation within the upper 100 m below seafloor (mbsf) to normal or underconsolidation associated with inherent pore water overpressure further down in the sequence (Fig. 1) (Bryant and Rack, 1990; Ladd et al., 1993; Lee et al., 1990; MacKillop et al., 1995; Pittenger et al., 1989; Rack and Palmer-Julson, 1992; Roberts et al., 1995; Shephard and Bryant, 1980). Fig. 1 shows the OCR and S_u/σ'_{v0} ratio, both as a function of depth and clustered diatom content from several DSDP and ODP legs. In this figure all geological information and possible reasons for the state of consolidation that the authors interpreted are ignored. However, Bryant et al. (1981) draw attention to the fact that geological evidence sometimes contradicts the interpretation of underconsolidation and excess pore water pressure inferred from consolidation state analyses. This raised the assumption of core disturbance as reason for apparent underconsolidation in diatomaceous ooze. Others came to the conclusion that sediments rich in diatoms behave differently in the laboratory than in nature and somehow withstand slowly imparted lithostatic and tectonic forces (Shephard and Bryant, 1980; Volpi et al., 2003). The reason for the discrepancy between laboratory and geological evidence, however, remains unknown.

In a predominantly generic study it is herein intend to advance the understanding and interpretation of consolidation state analysis data obtained from diatomaceous sediments. Mixtures of clayey-silt and diatomite sampled in a shutdown mining site, and a natural diatomaceous ooze from the Circum-Antarctic Opal Belt obtained with a multi-corer during R/V POLARSTERN cruise ANT-XXIX/4 (Bohrmann, 2013) are subjected to standard one-dimensional consolidation tests in order to investigate the reason for discrepancies between geological evidence and laboratory data related to diatomaceous sediments.

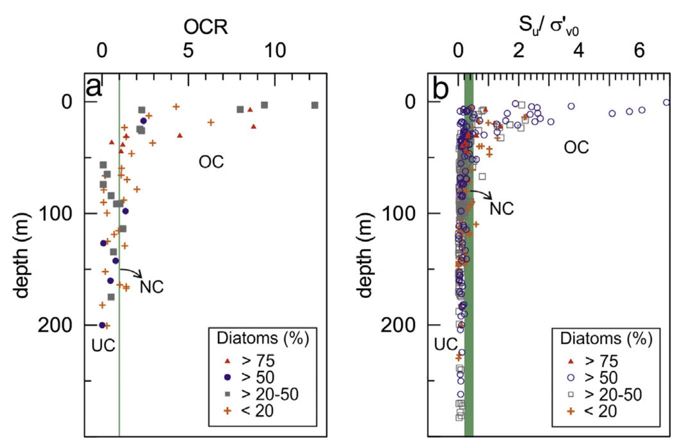

Fig. 1. a) OCR from one-dimensional compression as a function of depth and clustered diatom content from ODP leg 138 sites 844 through 847 (MacKillop et al., 1995), ODP leg 145 site 883 (Roberts et al., 1995), ODP leg 113 site 689, 690, 693, 695, 696, and 697 (Bryant and Rack, 1990), and ODP leg 104, site 642 through 644 (Pittenger et al., 1989). The green vertical line indicates an OCR of one, the state of normal consolidation (NC). b) Normalized undrained vane shear strength (S_u/σ'_{v0}) as a function of depth and clustered diatom content from ODP leg 138 sites 844 through 847 (MacKillop et al., 1995), ODP leg 145 site 883 (Roberts et al., 1995), ODP leg 112 site 679, 680 and 681 (Lee et al., 1990), ODP leg 113 site 698, 690, 693, 695, 696, and 697 (Bryant and Rack, 1990), and ODP leg 104, site 642 through 644 (Pittenger et al., 1989). The green vertical corridor indicates $S_u/\sigma'_{v0} = 0.2$–0.5, the state of normal consolidation (NC). UC stands for underconsolidated and OC for overconsolidated sediment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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