Chapter 16
A Numerical Investigation of Sediment Destructuring as a Potential Globally Widespread Trigger for Large Submarine Landslides on Low Gradients

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Abstract Submarine landslides on open continental slopes can be far larger than any slope failure on land and occur in locations worldwide on gradients of $<2°$. Significantly elevated pore pressure is necessary to overcome the sediment's shearing resistance on such remarkably low gradients, but the processes causing such overpressure generation are contentious, especially in areas with slow sedimentation rates. Here we propose that the progressive loss of interparticle bonding and fabric could cause such high excess pore pressure. Slow sedimentation may favour the formation of a structural framework in the sediment that is load-bearing until yield stress is reached. The bonds then break down, causing an abrupt porosity decrease and consequently overpressure as pore fluid cannot escape sufficiently rapidly. To test this hypothesis, we implement such a loss of structure into a 2D fully coupled stress-fluid flow Finite Element model of a submerged low angle slope, and simulate consolidation due to slow sedimentation. The results suggest that destructuring could indeed be a critical process for submarine slope stability.

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16.1 Introduction

Submarine landslides are one of the main processes for moving sediment in the ocean, and in some cases there is strong evidence that they have generated far travelled tsunamis (Masson et al. 2006). Submarine landslides can contain >1,000 km^3 of sediment and be two orders of magnitude larger than the biggest terrestrial slides. The largest of these landslides occur on open continental slopes at passive margins, and as the tsunamigenic potential of a submarine landslide scales up with the volume of displaced material, these landslides are of specific socioeconomic interest. In order to enable a thorough evaluation of the geohazard of a particular region, as well as for potential mitigation efforts, there is a need to understand what causes these large landslides. However, the inability to observe submarine landslides directly makes them more difficult to analyse than many other geohazards. Our understanding of what causes these landslides is limited to hypotheses that are difficult to test rigorously and involve large uncertainties.

The largest open continental slope landslides tend to occur on extremely shallow slope angles of 2° or less. They also have similar headwall heights of about 100–250 m (Hühnerbach et al. 2004; Twichell et al. 2009), and occur as translational slab slides along bedding parallel glide planes (Masson et al. 2006). The morphological similarity among these large landslides, albeit being located in very different depositional environments, is striking and suggests a common trigger mechanism.

Mechanically, failure of such shallow slopes can only be explained by pore pressures that greatly exceed hydrostatic pressures, and thereby decrease the sediment's shearing resistance. However, the potential excess hydrostatic pressure sources that are discussed in the literature are often not capable of explaining the observed landslides. The dissociation of gas hydrates for example may act at the upper end of the gas hydrate stability zone (<600 m water depth). However, headwall depths of landslides at low gradient slopes cluster at 1,800–2,500 m water depth, and some headwalls occur down to 3,600 m water depth (Hühnerbach et al. 2004; Twichell et al. 2009). Gas hydrates are stable at these deeper water depths, suggesting that at least some large landslides are not triggered by hydrate dissociation. In the Gulf of Mexico high excess pore pressures (up to 70 % of the vertical effective stress in hydrostatic conditions) could be attributed to the rapid burial of low permeable sediment at deposition rates >30 m/ky (Dugan and Flemings 2000; Flemings et al. 2008). It is, however, difficult to generate such high overpressures, or to drive fluid laterally, in areas of slow sedimentation (<1 m/ky) such as north-west Africa, south-east Australia, or parts of the US east coast (Urlaub et al. 2012). Di Prisco et al. (1995) showed that even minor earthquakes can potentially cause failure of shallow (<20 m) submerged slopes, although some recent very large earthquakes have caused few submarine slope failures (Sumner et al. 2013). Nevertheless, deep-seated failures require significantly stronger ground acceleration due to higher effective stresses at large sediment depths (Di Prisco et al. 1995). It is therefore more likely that the excess pore pressure provided by an earthquake acts as a final trigger on a slope that already is in an overpressured state. But what other general mechanism that is independent of burial rates, and that could be global rather than local, could cause excess pore pressure at depths corresponding to those of failure planes of large volume landslides?

16.1.1 Destructuring of Cemented Hemipelagic Clay as a Source of Overpressure

Sediment cores from passive continental slopes often contain hemipelagic clay intervals with 70–85 % calcium carbonate content. Visual observations, for example from the north-west African continental slope, show that the calcareous hemipelagic clay is often very stiff and has a comparatively high porosity at 5–6 m below seafloor (Masson, personal communication). This same stiff clay layer is remarkably uniform over hundreds of kilometres and a large range of water depths, and it is conceivable that those layers could form regionally extensive failure planes.

The stiffness of hemipelagic sediment is likely a result of early cementation that takes place during deposition and before the skeleton has the opportunity to readjust to the new, leaving a particularly open structure and high porosity. Post-depositional processes such as bioturbation, interaction of organic matter, electrostatic bonding or creep may also contribute to the formation and preservation of such an open structure (Locat et al. 2003). There is, however, a critical depth at which the vertical stress would be equal to the resistance of the bonding strength generated by cementation (Skempton and Northey 1952). If loaded further the bonds are liable to break leading to a progressive degradation of the open structure ('destructuring'). This comparatively rapid collapse of pore space, along with corresponding reduction in permeability causes overpressure as the excess pore fluid cannot dissipate.

The structural resistance provided by the cement is highly variable and depends strongly on the physical and chemical conditions applied during its formation, as well as the sediment's composition (Locat et al. 2003). In laboratory measurements the onset of structure degradation often occurs for overburden of $\sim$100–500 kPa (e.g. Liu and Carter 1999; Tanaka and Locat 1999). This pressure range equals depths of $\sim$20–100 m below seafloor (using a submerged unit of weight of 5 kN/m^3), which corresponds to the depths of failure planes for large volume landslides. Destructuring is stress-controlled, and thus independent of sedimentation rates. Considering that structure is a general property of marine clays, excess pore pressure generation as a result of destructuring could therefore be a rather general process, hence explaining the global distribution of major landslides.

16.1.2 Aims and Approach

In this paper we explore whether the progressive loss of structure during burial and shearing could cause sufficient excess pore pressure to cause failure of a low gradient continental slope. This contribution is novel because previous submarine slope stability analyses have not addressed destructuring effects.

We use a Finite Element model to simulate consolidation and burial of a cemented hemipelagic clay layer in a typical continental slope with a gradient of 2°. Consolidation occurs as a result of self weight and a continuous, spatially varying load. The cemented hemipelagic layer is initially stiff and load-bearing, but as it reaches critical pressures gradually looses its strength and stiffness.

16.2 Methodology

The Finite Element model uses fully coupled transient 2D plane strain pore fluid diffusion and stress analysis. The fluid is governed by Darcy's law while the mechanical part is based on the effective stress principle. The sediment is assumed homogeneous and fully saturated with a single incompressible pore fluid (sea water).

16.2.1 Material Model

The modelled material represents fine grained hemipelagic sediments. The elasto-plastic, isotropic hardening Modified Cam Clay model accounts for compaction, and is adjusted slightly to include destructuring effects. Permeability is nonlinear, anisotropic and changes as a function of porosity (Table 16.1). We choose the porosity-permeability relationship for hemipelagic clays of Binh et al. (2009), as it is one of the few to include samples from depth >10 m below seafloor. The physical-mechanical properties are average values for hemipelagic clays based on published data (Table 16.1), except for the slope of the consolidation curve (λ), which is explained in the following paragraph.

The consolidation path of structured sediment subjected to loading is shown in Fig. 16.1. In the following, the slope of the curve in the volume-pressure plot, λ, is referred to as compressibility. At low pressures, the structured (undisturbed) sediment is comparatively stiff (A to B in Fig. 16.1b), and structure allows the sediment to maintain high porosity. As pressure increases and exceeds the resistance provided by the structure, the sediment progressively looses its cement, and the structure-permitted porosity decreases rapidly (B-C). This destructuring phase is characterised by a steep slope of the consolidation curve. As loading and the loss of structure continues, the compression curve appears asymptotic to the equilibrium curve for structureless sediment (C-D). Kinematic hardening models have been developed that include the effect of destructuring, which require an extensive set

Table 16.1 Material model parameters representing hemipelagic clay. Refer to Fig. 16.1c for explanations of λ_c, λ_d and λ_{sl}.

Notation		Value	Remarks	References
κ	Swelling index	0.028		Powrie (2002)
ν	Poisson ratio	0.3		Powrie (2002)
λ_c	Slope of normal consolidation line (Fig. 16.1c)	0.10	Undisturbed: $p' < 100$ kPa	Hattab and Favre (2010)
λ_d		1.20	Destructuring: 100 kPa $< p' <$ 300 kPa	
λ_{sl}		0.48	Remoulded: $p' > 300$ kPa	
φ_{crit}'	Friction angle	30°		
M	Slope of critical state line	0.87	$M = \dfrac{\sin\phi_{crit}' \cdot 6 \cdot \sqrt{1-b+b^2}}{3+\sin\phi_{crit}' \cdot 2b - \sin\phi_{crit}'}, b = 0.5$	Powrie (2002)
k_y [ms]	Vert. permeability	$10^{-15}e^{18.93n}$	n = porosity	Binh et al. (2009)
k_x [ms]	Horiz. permeability	$10^{*}k_y$		

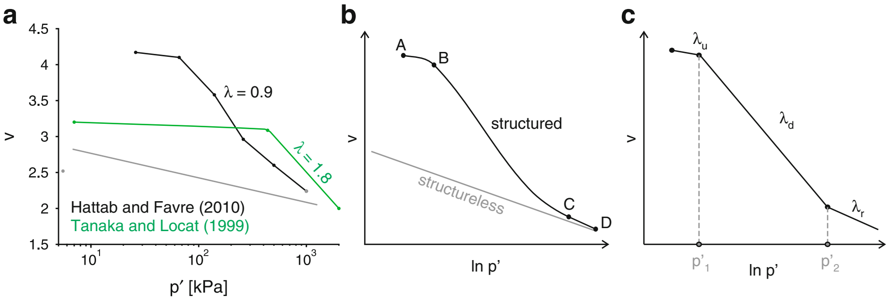

Fig. 16.1 Destructuring during compression in plots of specific volume, v, against mean effective pressure, p′: (**a**) Oedometric paths of two deep sea sediment samples with slope λ. The *grey line* represents the oedometric path of a structureless sample. The *black line* represents cemented hemipelagic (Hattab and Favre 2010) and the *green line* microfossil rich clay (Tanaka and Locat 1999). (**b**) Schematic representation of a typical consolidation path of structured sediment, and its structureless counterpart (*grey line*). (**c**) Definitions of material parameters for the implementation of destructuring in the material model

of parameters. We deliberately refrain from using such constitutive models as these specific parameters are hardly known for deep sea sediments. To account for destructuring effects instead, we introduce compressibility as a function of pressure in our elastoplastic material definitions. Three different λ values for different pressure ranges represent three stages of the material: cemented (λ_c, $p' < 100$ kPa), destructuring (λ_d, 100 kPa $< p' <$ 300 kPa) and structureless (λ_{sl}, $p' > 100$ kPa, Fig. 16.1c).

We use the λ and critical pressure values reported by Hattab and Favre (2010). The authors conducted consolidation tests on cemented hemipelagic clay samples from the deep sea Gulf of Guinea, where sedimentation rates are about 0.3 m/ky For stresses below 90 kPa the sediment is stiff without a significant porosity decrease ($\lambda_c < 0.10$). Between 100 and 300 kPa cementation degrades progressively and the volume loss is significant ($\lambda_d = 0.90$). We choose a slightly higher λ_d. This is because it is likely that the true compressibility during destructuring is underestimated, as a considerable part of the structure has been lost due sampling and recovery (Locat and Lee 2002). For higher stresses λ_{sl} decreases to 0.48.

16.2.2 Model Description

Although slope failure is expected in the upper 250 m, large overall model depths are necessary to avoid boundary effects. Hence, the model is 5,500 m deep in z-direction at the shelf, and 2,000 m at the abyssal plain. The entire model is 120 km long in x-direction with a slope angle of 2°. The shelf and abyssal plain are each 10 km long. Water depth is 200 m at the shelf break and 3,700 m the abyssal plain.

The lateral boundaries of the model are fixed in the horizontal direction, but are free to move vertically. The base of the model is fixed in both vertical and horizontal directions. The upper boundary is free to move in either vertical or horizontal direction. The landward boundary of the model is impermeable, but pore fluid is allowed to flow through the abyssal plain boundary. No flow takes place through the basal boundary as sediments at this depth are highly lithified and virtually impermeable.

The water column is not modelled as such but represented by a pressure load corresponding to the hydrostatic pore pressure at the seafloor. The newly added sediment is simulated by an equivalent vertical vector load on the seafloor that increases linearly over time. The maximum loading rate along the shelf corresponds to 0.15 m/ky and decreases linearly downslope to 0.01 m/ky at the right side boundary.

Before loading by sediment deposition begins, all stresses are in equilibrium with the gravitational load ($g = 9.81\ \mathrm{m/s^2}$), and pore pressures are hydrostatic throughout the model. As only slow deposition is considered in this study, the sediment in the model is initially normally consolidated. The initial porosity corresponds to a depth-porosity relationship for deep sea clays (Kominz et al. 2011). A detailed description of the model can be found in Urlaub (2012).

16.2.3 Assumptions and Limitations

Newly deposited sediment only provides a surface load in the models. Compaction and pore fluid generation and the build up or degradation of structure within the newly deposited sediment would occur in nature, but are not simulated here. Consequently, the model is not capable of simulating failure within this interval of newly deposited sediment. However, as the failure surface for the landslides considered here is typically at depths of 100–250 m below seafloor, this limitation is only critical if the thickness of deposited sediment exceeds 100 m. This is only the case when significantly longer time scales or higher deposition rates than the ones considered here (800 ky for 0.15 m/ky) are modelled.

The model is a first attempt of testing the effect of a cemented layer whose resistance has been exceeded on the stability of a submarine slope. The mechanical model is a highly simplified representation of a cemented sediment. Destructuring as implemented here neglects the effect of shearing and kinematic hardening, as well as the loss of strength. More complex material models are available that can be used to model structured clays. However, these constitutive models require a large number of parameters. Such parameter sets do not exist for marine sediments, mainly due to sample disturbance during recovery. The model thus predicts excess pore pressure generation, but may not truly represent failure mechanisms.

16.3 Results

The model is run for 800 ky. To evaluate excess pore pressure generation and slope stability during the analysis we show the temporal evolution of overpressure ratio u* (the ratio of excess pore pressure to vertical effective stress in hydrostatic conditions), porosity n, vertical effective stress σ'_v, and total shear strain γ, at six nodes of different depths at the upper slope (Fig. 16.2a–d). The upper two nodes are located at 0 and 19 m below the model surface and they are not affected by destructuring. Changes in porosity are comparatively small and u* is always <0.05. Effective stress increases continuously and shear strains do not exceed 3 %. The node at 28 m below the model surface begins at the upper boundary of the destructuring pressure range. Hence, it compacts rapidly but upwards drainage of pore fluid is possible as the overlying sediment is intact and maintains its high porosity and permeability. Consequently, u* is small and σ'_v increases as loading goes on. Shear strains increase at a constant rate to about 0.145. The three deeper nodes (36–63 m below model surface) are actively destructuring from the start of the model run, as indicated by a rapid porosity decrease. No drainage paths exist due to rapid collapse of pore spaces in the material above and below, so that u* rapidly increases to 0.6. If the model would run for longer, u* is expected to reach even higher values as it is continuously rising with time. The load is increasingly carried by the pore fluid and σ'_v remains constant. Shear strains reach up to 15 % with a decrease in the rate at which γ increases towards later stages of loading.

2D contour plots of the overpressure ratio and incremental shear strains, $\Delta\gamma$, for the entire model area show the final stage of the analysis after loading of the slope for 800 ky (Figs. 16.2e, 16.3). Maximum values of u* reach up to 0.6 within the destructuring layer at about 40–50 m below the model surface at the upper slope (Fig. 16.2e). In addition to such high excess pore pressures, a zone of particularly high incremental shear strains just above the u* maximum appears (Fig. 16.3). This indicates the development of a shear zone that can accommodate a failure plane.

16.4 Discussion

We implemented the gradual loss of structure of hemipelagic clay in a low angle continental slope model. When subjected to 800 ky of continuous and asymmetric sediment deposition at a maximum rate of 0.15 m/ky, high excess pore pressures reaching up to 60 % of the vertical effective stress in hydrostatic conditions develop, along with a zone of locally high shear strains. The excess pore pressures are still increasing when the run was terminated. These patterns indicate that failure may occur along a plane at 100–150 m below seafloor, which is in agreement with the depths of glide planes observed in field data. Similar continental slope models subjected to slow sedimentation without the effect of destructuring do not show any indications of instability (Urlaub et al. 2012). The presence of a pressure-dependent

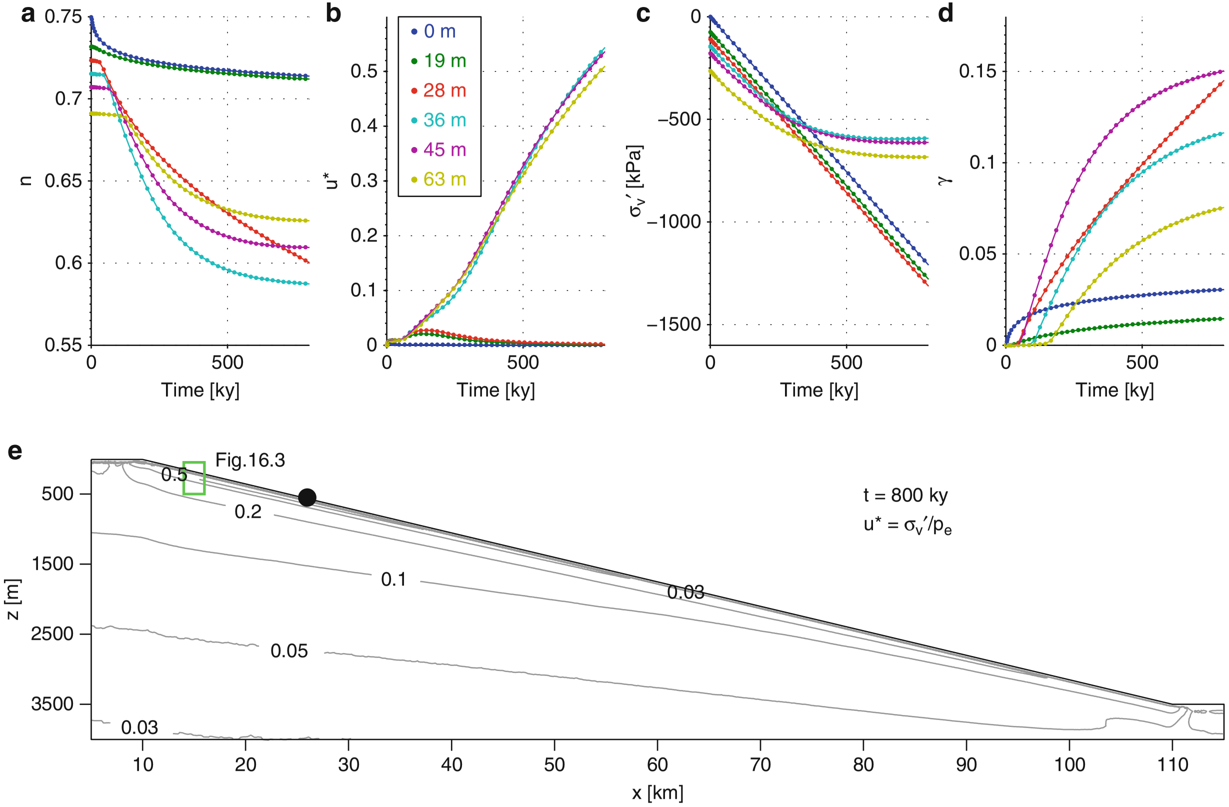

Fig. 16.2 Temporal evolution of (**a**) porosity n, (**b**) overpressure ratio u*, (**c**) vertical effective stress σ'_v and (**d**) shear strain γ at six nodes at different depths. The nodes locate 16 km from the shelf break as indicated by the *black dot* in the *lower panel*, and their initial depths before loading are given in *panel* (**b**). The *bottom panel* (**e**) shows overpressure ratio contours for the entire model domain after 800 ky of continuous loading. The *green square* indicates the close-up section shown in Fig. 16.3

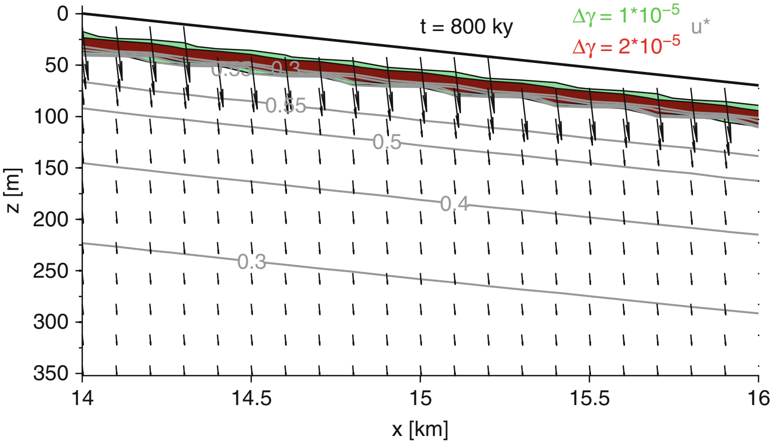

Fig. 16.3 Close-up of a surface-near section showing the overpressure ratio (*grey contour lines*) after 800 ky of constant sediment deposition. *Filled coloured contours* show the incremental shear strain of the last numerical increment. A surface-parallel zone of intense shearing lies just above the maximum overpressure ratio contour line. Taking into account the newly deposited sediment (which is not physically modelled or illustrated), the model surface at this time and distance from the shelf corresponds to a depth of about 115 m below seafloor

high compressibility (destructuring) zone seems the only mechanism that could cause failure of a low gradient slope when slow sedimentation acts as the only pressure source. It is therefore possible that destructuring may be important for the stability of continental slopes, and can help to explain failure of low angle slopes at continental margins with little sediment input. It is a process that could operate in many locations worldwide.

It is important to emphasise that the pressure range in which destructuring takes place and compressibility is high ($p'_1 > p' < p'_2$, Fig. 16.1c) directly controls the depth of the failure plane. The rate of porosity reduction during the destructuring phase (λ_d) controls the magnitude of excess pore pressure, and therefore the overall stability. Hence, whether failure occurs, and at which depth the failure plane is located, is prescribed by the mechanical behaviour of the sediment. Further investigations into the role of destructuring on slope stability require a thorough evaluation of these material properties.

Crushing of microfossils during compaction is a process with similar effects on excess pore pressure generation as destructuring of clay. Sediments rich in microfossils do not consolidate to as low porosities as other marine clays owing to microfossil shells acting as a structural component (Tanaka and Locat 1999). However, a “delayed compressibility” that can reach λ values of up to 2.0 is typical for such microfossil rich sediments (e.g. diatomaceous ooze shown in Fig. 16.1a). As a critical pressure is overcome during burial these shells collapse, porosity decreases rapidly and excess pore pressure builds up.

16.5 Conclusion

We investigate whether destructuring of cemented hemipelagic clay can cause sufficient overpressure to cause failure of a low gradient continental slope in an environment with low sedimentation rates. Under the conditions used here for the numerical modelling of the burial of such hemipelagic clay on a 2° slope indicates the development of a bedding parallel failure plane after ∼800 ky. These initial results suggest that the loss of structure has the potential for causing wide spread weak layers that could cause large volume landslides at low gradient slopes globally.

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