Chapter 17
Shear Strength of Siliciclastic Sediments from Passive and Active Margins (0–100 m Below Seafloor): Insights into Seismic Strengthening

Joshua R. DeVore and Derek E. Sawyer

Abstract Submarine geohazards threaten coastal communities and global economies. Submarine debris flows are the largest mass-wasting events observed on the Earth's surface, comprising of up to 50 % of basin fill. Further insight can be gained into these important processes by understanding in-situ preconditioning factors that lead to slope destabilization. We examine two locations from the International Ocean Discovery Program data archive to determine how external effects on sediment properties compare between passive margins and active margins. We select representative passive margin (Amazon Fan) and active margin sites (Nankai Trough), and analyse peak shear strength, void ratio, and composition from the uppermost 100 m below seafloor. This depth corresponds to a depth range in which most submarine mass movements originate. However, it is not appropriate to directly compare shear strength and void ratio of samples from different settings due to differing stress histories, sedimentary composition, and consolidation properties. We focus on ideal locations on both margin types that have solely undergone one-dimensional burial, no diagenesis/cementation, and no unroofing. We find that active margin sediments exhibit an increase in shear strength when compared to their passive margin counterparts, while void ratio tends to be higher on active margins. We are currently conducting a focused lab program to better understand compositional effects and determine the intrinsic properties of each site to more definitively normalize the in-situ sediment profiles. Our results suggest a potential link between shear strength and margin seismicity.

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17.1 Background and Significance

Earthquakes can be an effective triggering mechanism of underwater landslides and slide-generated tsunami because they impose large and sudden horizontal and vertical loads on the slope that induce excess pore pressure, reducing shear strength. When a submarine landslide occurs, it disrupts the overlying water column and can generate a slide-induced tsunami. Submarine debris flows are the largest mass-wasting events observed on the Earth's surface, yet we know little about in-situ preconditioning factors that lead to slope destabilization in the submarine environment. Our ability to model and predict landslides and tsunami is greatly affected by an insufficient understanding of the physical properties of seafloor sediments and how they evolve with depth, time, and location.

Most (~80 %) of submarine mass movements fail within 100 m below the seafloor (mbsf) (Hampton 1996; McAdoo et al. 2000, 2004; Moscardelli 2007). Not all earthquakes generate submarine landslides; however, all earthquakes impart seismic energy to slope sediments as a shear stress. When a shear stress is applied to saturated, fine-grained sediment during an earthquake, an instantaneous increase in pore pressure is induced. This pore pressure increase weakens the sediment, reducing its shear strength temporarily. If this temporary weakening does not cause failure, pore pressure will slowly diffuse over time allowing the soil to compact into an overconsolidated state. Thus, an earthquake that does not induce a submarine landslide could have a strengthening effect on the slope, increasing its resistance to future failure. This process has been termed 'seismic strengthening' (Locat et al. 2002; Lee et al. 2004) and is proposed to be a fundamental process that controls shear strength evolution on continental margins.

Boulanger (1999), Locat et al. (2002), and Lee et al. (2004) performed small-scale geotechnical tests on reconstituted marine sediments. These studies exposed samples to high-frequency simulated earthquakes and measured the reduction of pore water with subsequent periods of drainage, correlating void ratio reduction to an increase in shear strength (Fig. 17.1). Bench-top experiments are performed under different timescales and conditions than natural field-scale settings. In order to compliment these successful pilot studies, we analyse shear strength of margin sediments from the International Ocean Discovery Program (IODP) archive. We aim to explore the rationale that, if seismic strengthening is a fundamental process, near-surface sediment on active margins will exhibit higher shear strength values versus passive margins.

17.2 Global Shear Strength Trends

We acquired datasets from IODP, including peak shear strength (measured with an automated vane shear device), moisture and density, and compositional characteristics. We only selected sites from active and passive margins in siliciclastic

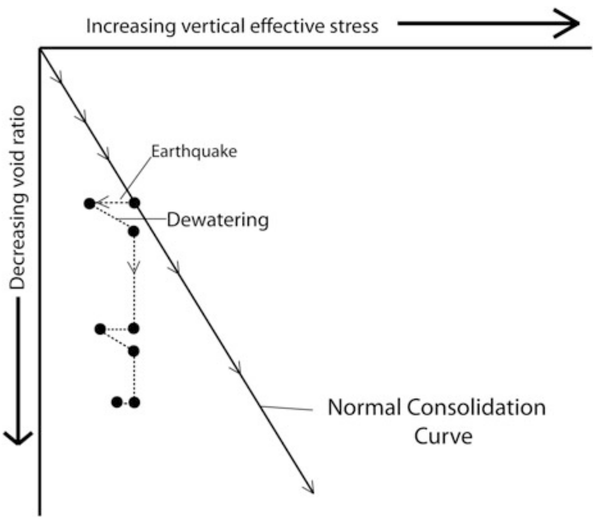

Fig. 17.1 Example of "seismic strengthening" produced with direct shear tests on reconstituted sediment (Adapted from Lee et al. 2004). Through four seismic cycles, the sample becomes progressively overconsolidated. Vertical effective stress is reduced as pore pressure increases and returns to its natural hydrostatic state following drainage of excess pore fluid

sediments. Active margins used in this study are from the Cascadian subduction zone, the Nankai Trough, the Japan Trench, the Lapulapu Ridge; and east Taiwan. Passive margin sites are West Africa, Amazon Fan, the eastern United States, and the Gulf of Mexico.

A preliminary survey of shear strength from active and passive margins shows a tantalizing result with a simple plot of shear strength for the upper 100 mbsf (Fig. 17.2). Higher shear strength on active margins is clearly observed both with depth and frequency of shear strength values. Global shear strength data suggests that there is an apparent strengthening signal exhibited on active margins (Fig. 17.2).

It is not appropriate to directly compare shear strength and void ratio of samples from different settings due to the fact that each setting will have different sedimentary composition and consolidation properties. These data must first be normalized. The challenge is to find ideal type locations on both margin types that have undergone exclusively one-dimensional burial, no diagenesis/cementation, and no unroofing of overburden.

17.3 Ideal Type Sites

We have identified one passive margin site and one active margin site from the global database that have hydrostatic pore pressure conditions, continuous burial histories, and are both composed of fine-grained siliciclastics,: Amazon Fan (Site 942) and South Japan (Site C0001E) (Fig. 17.3). South Japan site C0001E from IODP bleg 315 is representative of siliciclastic sedimentation on an active margin that is composed dominantly of silty clays and clayey silts with rare interbedded ash

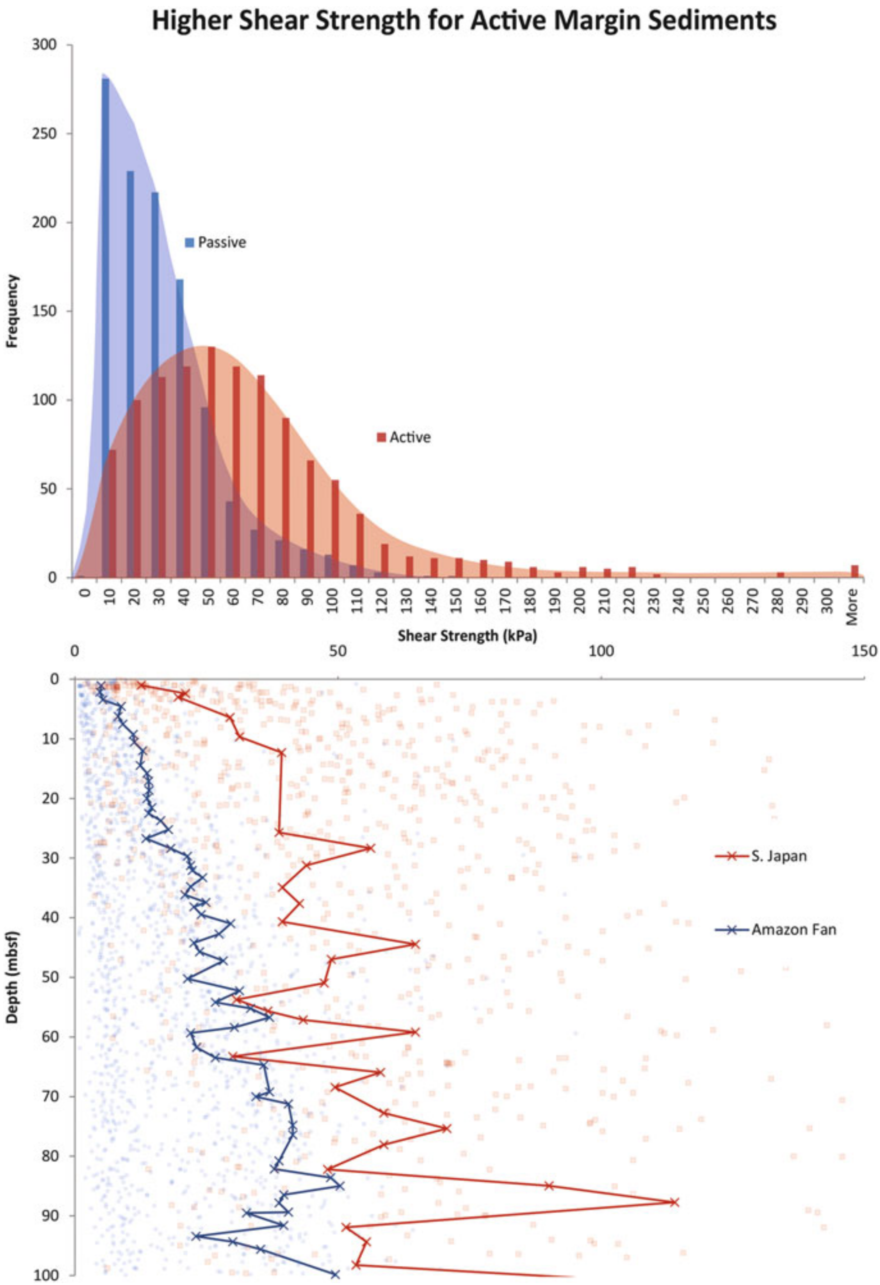

Fig. 17.2 Active margin sediments exhibit higher shear strength than passive margin sediments. (**a**) Frequency and distribution of shear strength of 83 sites from siliciclastic margins. All data points (>10,000) are measured by the automatic vane shear system from the IODP data archive. (**b**) Shear strength plotted versus depth. The *blue* and *red* translucent background data are the entire dataset that is shown in 1A. It is observed that active margins (*red*) generally have higher shear strength values with depth. Given that shear strength is a function of many variables, we have identified one 'pristine' site on each margin. 'Pristine sites" are those that have no evidence for

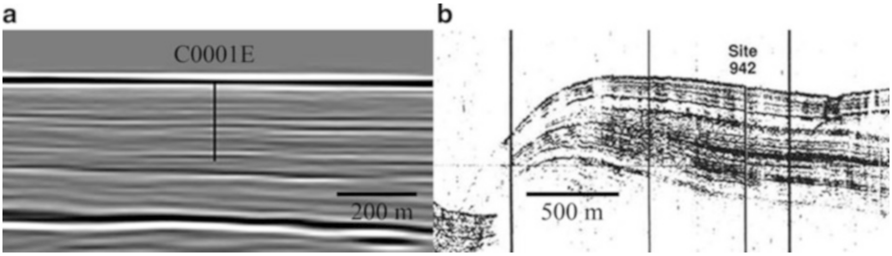

Fig. 17.3 Seismic surveys of South Japan site C0001E (**a**) and Amazon Fan site 942 (**b**). These sites represent pristine depositional conditions displaying horizontal sediment layers in the upper 100 mbsf and are free from any noticeable deformation. Note that the transparent layer at site 942 may be a debris flow, however, this layer is well below 100 mbsf and does not affect our layer of interest. The *black vertical bar* represents the core locations

deposits, and has experienced relatively low sedimentation rates (~0.1 mm/year) over the Quaternary. Amazon Fan site 942 from leg 155 of the Ocean Drilling Program (ODP) was chosen as a paleoceanographic site to provide an expanded hemiplegic sedimentation record for the Holocene.

This site has experienced slower sedimentation rates, ~0.7 mm/year over the Holocene due to its distal location from the main sediment source for the region. This site is an example of a siliciclastic system on a passive margin and is characterized by beds of clayey silt with interbedded laminae to thin beds of silts, with rare laminae of fine silty sands and nannofossil-foraminifer rich clays. These sites represent the most pristine sedimentation with no evidence of soft sediment deformation, slumping or landsliding, and have undergone relatively low rates of sedimentation (0.1–0.7 mm/year). Selecting sites with similar grain distribution, stress histories, and low sedimentation rates will help to normalize any differences that may exist between the sites, having undergone only uniform one-dimensional vertical compression. After selection of these ideal sites, the active margin site still has higher shear strength than the passive margin site margins at equivalent depths (Fig. 17.2).

Fig. 17.2 (continued) diagenesis, soft sediment deformation, landsliding, or gas hydrate presence. S. Japan (C0001E) (*red*) and Amazon (Site 942) (*blue*) are these sites. Following this screening process, the active margin profile is stronger than the passive margin and appears to trend toward a convergence with depth

17.4 Hydrostatic Pore Pressure Conditions at Type Sites

Shear strength is directly impacted by the vertical effective stress that the sediment experiences and an increase in pore pressure can drive slope failure. We estimate in-situ pore pressure to determine if it could be responsible for the observed shear strength differences.

Skempton (1970) demonstrates that clays undergoing sedimentation rates of less than 2 mm/year are at least 95 % consolidated and considered to be normally pressured to depths of 50 m. To further constrain that the type sites are at or near vertical effective stresses corresponding to hydrostatic pore pressures to depths of 100 mbsf, we apply a Gibson time factor equation to each of our sites. Gibson (1958) presents the theoretical solutions for pore pressure during one-dimensional consolidation of clay (Eq. 17.1).

$$u = \gamma' mt - \gamma' (\pi C_v t)^{-1/2} \exp\left(\frac{-x^2}{4C_v t}\right) \int_0^\infty \xi \tanh \frac{m\xi}{2C_v} \cosh \frac{x\xi}{2C_v t} \exp - \frac{\xi^2}{4C_v t} d\xi \quad (17.1)$$

Where u is pore pressure in excess of hydrostatic pressure, γ' is the bulk density of the sediment, m is the sedimentation rate, C_v is the coefficient of consolidation, t is time, and ξ is the depth of interest within the sediment column divided by the total sediment column height as a function of time $\left(\frac{x}{h(t)}\right)$. When the curves of $\frac{u}{\gamma' h}$ are plotted against $\frac{x}{h}$ one develops curves that represent the time factor (T), where:

$$T = \frac{m^2 t}{C_v} \quad (17.2)$$

Variables m and t are assessed from biostratigraphic analyses and regional correlations developed by the scientific party onboard each IODP leg and C_v values are taken from similar sediments in the region. Using these parameters, Table 17.1 represents the calculated T for each site.

Pore pressure will range from 0 to 1 (hydrostatic to lithostatic pressure) and indicates the possible overpressure percentage (Gibson 1958). The maximum possible pore pressure at site C0001E is in excess of 1 %, while site 942 possibly has 0.5 % excess pore pressure. We use this analysis to show that the sites are very close to hydrostatically pressured and that we can assume normal vertical effective

Table 17.1 Gibson time factor analysis for target sites

Site	Location	m (m/year)	t (year)	C_v (m^2/year)	T
942	Amazon Fan	0.0007	140,000	13.25	0.0051
C0001E	Japan	0.0001	1,240,000	1.19	0.0104

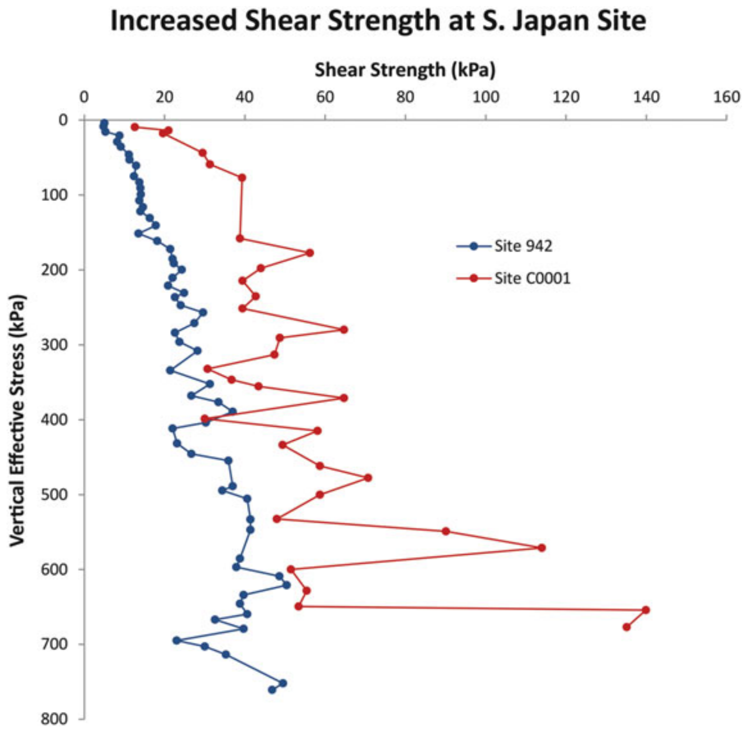

Fig. 17.4 Shear strength with vertical effective stress for isolated 'pristine' sites. Active margin site C0001 still exhibits increased shear strength following the correction for density and pore pressure contrasts between the two sites

stress distributions at our type locations. In this example, shear strengths are greater on active margins than passive margins at the same vertical effective stress (Fig. 17.4).

17.5 Continental Margin Sediment Shear Strength

The coring process can facilitate a reduction in sediment shear strength and is difficult to avoid. If there were no disturbance we might expect shear strength to be approximately 20 % of vertical effective stress (Lambe and Whitman 1969). Standard practices in measuring shear strength are to measure from the interior of the core once it is halved, reducing the likelihood of shear strength alteration. We assume any reduction in shear strength due to coring disturbance to be similar at both sites.

In the preceding discussion, we have analysed sites from south Japan (Site C0001E) and Amazon Fan (Site 942) that exhibit hydrostatic pressure, undisturbed sedimentation, and no evidence for diagenesis or hydrates. Following this screening, the active margin site still exhibits greater shear strength (Fig. 17.4). However, the final step in normalization is to account for potential lithological differences between Japan and Amazon. Seismic strengthening may be a fundamental, margin-wide process affecting shallow (0–100 mbsf) sediment on active margins, increasing resistance to failure and compaction behavior of the continental shelves and slopes. The shear strength trend on active margins appears to move toward a possible convergence with the passive margin trend as vertical effective stress increases. This convergence may be analogous to the boundary between contractive and dilative soil behavior, indicating that only contractive, and therefore shallow sediment, is capable of becoming strengthened by seismicity and requires future work. We are currently conducting a detailed study on the sediment composition and intrinsic physical properties at these sites to assist in isolating the effects of seismicity on shear strength development and void ratio. This study will enhance our understanding of the physical properties of seafloor sediments in response to seismicity.

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