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RHEOMETRIC CHARACTERIZATION OF THE FLUID MUD FORMING POTENTIAL OF A BAY MUD

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ABSTRACT: When a cohesive mud bed in a wide estuary or bay yields due to wave action, measurable damping of wave height occurs as energy is absorbed by the highly viscous sediment. In order to assess the fluid mud generating potential of an estuarine mud, controlled oscillatory shear stress tests were carried out in a rheometer on naturally consolidated mud from Suisun Bay in California. Since only one sample was available for testing, three cohesive clays of known compositions and different concentrations were also subjected to oscillatory rheometry. The aim of these tests was to draw conclusions from the rheological behavior of these clays on the yield behavior of the bay mud at a lower than its natural concentration at which this mud is in the liquefied state. Tests on the clays revealed that the so-called flow-point stress characterizing bed yield could be described reasonably well by a simple exponential function dependent on the concentration. This observation permitted the selection of a similar exponential equation for the bay mud as well as delineation of the shallow parts in Grizzly Bay, a sub-embayment, where a potential exists for fluid mud generation and wave damping.

Keywords: Cation exchange capacity, flow-point stress, fluid mud, mud density, liquefaction, mud rheology, yield stress

INTRODUCTION

Depending on its consistency, fluid mud in tidal bays can damp waves and influence patterns of refraction, diffraction and breaking. Fluid mud can be generated when the wave-induced oscillatory stress causes it to yield and liquefy. If bank levees protecting nearby lowlands are to be constructed, it is necessary to determine the extent to which fluid mud may reduce the wave height required for setting the design maximum water level.

In this study the stress at which mud liquefaction would occur was measured in shear rheometry for the shallow submerged flats of Suisun Bay in California, where existing levees are expected to be retrofitted as part of a major wetland restoration effort.

MUD RHEOLOGY

Controlled shear stress rheometry of viscoelastic materials such as an estuarine mud involves the application of a harmonically varying stress

$$\tau(t) = \tau_0 \sin \omega t \qquad (1)$$

where τ_0 is the shear stress amplitude and ω is the angular frequency. The resulting complex shear modulus (G^*) and the complex viscosity (η^*) are defined as

$$G^* = G' - iG'' \qquad (2)$$

$$\eta^* = \eta' + i\eta'' \qquad (3)$$

where the elastic response of mud to stress is represented in terms of G' and η'', and the viscous response in terms of G'' and η' (Metzger 2006).

Referring to Fig. 1, the results of the test are given in terms of the variation of G' and G'' with increasing stress amplitude τ_0 (alternatively the results can be presented in terms η' and η''). For a given τ_0, if $G' > G''$ the sample tends to be gel-like, otherwise it is a liquid. At low values of τ_0 both G' and G'' are practically independent of the amplitude in the linear viscoelastic range (LVR). The upper limit of LVR is defined as the yield stress τ_y. A second important stress is the flow-point stress τ_f at the point of crossover where $G' = G''$, beyond which the material flows (in the liquid range, LR). The zone between τ_y and τ_f is referred to as the yield zone (YZ).

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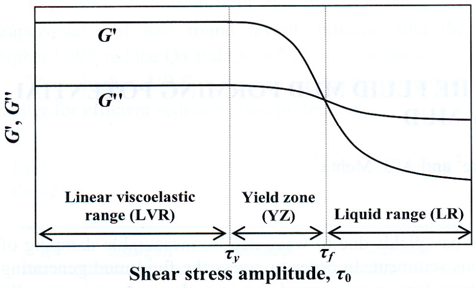

Fig. 1 Definitions of the yield stress and the flow-point stress in oscillatory controlled shear stress testing

EQUIPMENT AND MATERIAL

The rheometer used in the experiments was TA Instruments AR2000ex at the Food Science and Human Nutrition Department of the University of Florida. In the present study a concentric cylinder with vane geometry was used (Table 1) as the measuring system and the temperature was maintained at 20°C. Since the air-bearing design of the torque motor driving the vane results in a large torque to inertia ratio, inertial effects of the mechanical components were required to be calibrated for each dynamic test setting.

Suisun Bay (Fig. 2) is part of a large and shallow estuarine system which includes San Francisco Bay and receives freshwater and sediment discharge from the Sacramento and San Joaquin Rivers. Grizzly Bay and Honker Bay are the two main sub-embayments of Suisun Bay (Fig. 2), where the spring tidal range is about 2 m. Bed sediment in the shallow flats of Grizzly and Honker Bays contain a silty clay with little spatial variability (Hampton et al. 2003). The mud sample was collected in 5.1 m deep water close to Honker Bay. It was in the consolidated natural state with water content of 63%. Prior experience with mud from this area indicates that liquefaction of this mud occurs at a water content of 300% (Krone 1962). Unfortunately, native water was not readily available for dilution of this mud. As a result three commercial clays of known composition were additionally tested with the intent to extend the results for mud to higher than its natural water content (or lower concentration) by analogy with the rheological response of the clays at high water contents (low concentrations).

Table 1 Concentric cylinder with vane geometry dimensions

Rotor type	Rotor radius (mm)	Stator radius (mm)	Immersed height (mm)	Gap (μm)
Vane	14	15	42	4000

Table 2 Particle size and CEC values of sediments tested

Quantity	Bay mud	K	KB	KBA
Nominal size (μm)	2-4	1	1	1
CEC (mEq. $100g^{-1}$)	56.5	6.8	11.7	12.6

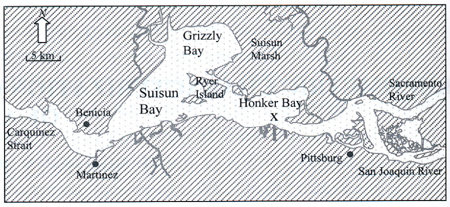

Fig. 2 Suisun Bay, California. Muds sample location is X (water depth 5.1m NAVD88 datum)

The cation exchange capacity (CEC in milliequivalents per 100 grams of sample) of the mud sample was 56.5 (Table 2), which indicates that it was highly cohesive. The clays were a kaolinite (K), a bentonite (B) and an attapulgite (A). Their particle sizes and cation exchange capacities are given in Table 2. From these CEC values we note that among the three K was the least cohesive and B had the highest degree of cohesion. The clays were mixed with each other and tap water as necessary to prepare samples for testing with the desired variation in the CEC (hence cohesion) and consistency. The mixtures actually tested were: (1) K, (2) KB consisting of 95% (by weight) K and 5% B, and (3) KBA consisting of 90% K, 5% B and 5% A. K, KB and KBA were prepared at different water contents *W*, nominally 110, 120, 130, 140, and 150%.

RHEOMETRIC DATA

All tests were carried out at a typically representative wave frequency $\omega = 10$ rad s^{-1}. For the mud sample (SM), Fig. 3 shows the experimentally obtained storage modulus G' and the loss modulus G'' as functions of the stress amplitude τ_0. From this plot the estimated stresses are: yield stress $\tau_y = 2.03$ Pa (end of LVR and start of YZ) and flow-point stress $\tau_f = 55.7$ Pa (end of YZ and start of LR). The difference between the two quantities highlights the importance of using the correct definition relevant to the problem being considered. For all sediments Table 3 lists the sample water content *W*, the concentration *C* (dry weight per unit volume of sample),

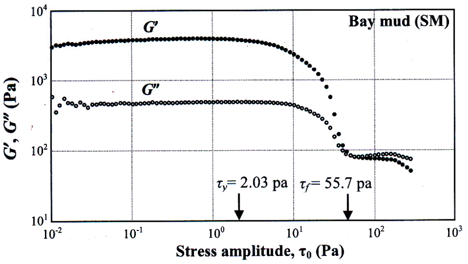

Fig. 3 Variation of storage modulus G' and the loss modulus G'' with amplitude τ_0 of the applied oscillatory stress (ω = 10 rad s^{-1})

the wet bulk density ρ, τ_y and τ_f. The flow-point stress τ_f has a precise definition and can be conveniently taken as the characteristic stress at which fluid mud plays a role as the absorber of wave energy in the bay.

Following Krone (1963) for the yield stress of cohesive muds measured in a concentric cylinder viscometer, for each clay we will relate τ_f to the concentration C based on the exponential equation

$$\tau_f = \tau_{f0} e^{k_r C} \tag{4}$$

where τ_{f0} (= τ_f at C = 0) has been conveniently selected as 0.1 Pa, a very small value. From the plots in Fig. 4 we conclude that the relationship for SM may also be treated as following Eq. 4. The similarity in the trends for SM and K are likely to be fortuitous.

ESTIMATION OF FLUID MUD THICKNESS

The estimation of maximum water depth at which waves in the shallow areas of Suisun Bay are likely to liquefy mud would permit the identification of the zones in which absorption of wave energy can be expected to be significant. In this bay region the characteristic water content for fluid mud is 300% (Krone 1962).

Since adequate data on fluid mud are not available from this bay, it was necessary to make a rough assessment of the likelihood of its occurrence during wave action. The selected condition for liquefaction is addressed in Fig. 5, in which z' is the downward vertical coordinate and $z' = 0$ represents the bed surface. The thickness z_{fe} of the fluid mud layer is determined by the intersection of two curves, one representing the upward force due to wave-induced vertical movement of mud and the other representing the downward force due to the buoyant weight of soil particles. The equality is expressed as

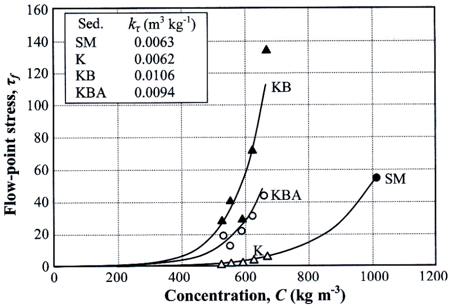

Fig. 4 Variation of flow-point stress with concentration for tested sediments

$$\omega^2 z_{s\max}(z_{fe}) = \alpha_{bc} g'(z_{fe}) \tag{5}$$

where $z_{smax}(z')$ is the amplitude of the vertical displacement of mud, α_{bc} is a coefficient which effectively modifies buoyancy by cohesion, $g'=g(\rho-\rho_w)/\rho_w$ is the reduced gravity and g is the acceleration due to gravity. In general, z_{smax} and therefore $\omega^2 z_{smax}$ also decrease with depth. On the other hand $\alpha_{bc}g'$ increases with depth. The plane where the $\omega^2 z_{smax}$ curve and the $\alpha_{bc}g'$ curve cross defines the boundary between fluid mud and bed. It follows that for the fluid mud thickness z_{fe} to be greater than zero, $\omega^2 z_{smax}(0)$ must be larger than $\alpha_{bc}g'(0)$.

Table 3 Yield stress and flow-point stress measurements

Test	W (%)	C (kg m^{-3})^a	ρ (kg m^{-3})^b	Yield stress, τ_y (Pa)	Flow point stress, τ_f (Pa)
SM	63	1005	1641	2.03	55.7
K-150	153	524	1326	0.36	2.12
K-140	144	551	1343	0.49	2.65
K-130	132	589	1366	0.67	3.46
K-120	123	622	1387	0.78	4.73
K-110	113	664	1414	0.90	7.23
KB-150	153	523	1326	2.27	29.4
KB-140	145	548	1342	2.65	41.0
KB-130	133	587	1366	3.60	30.3
KB-120	124	619	1386	4.89	72.1
KB-110	113	664	1414	7.36	135
KBA-150	151	530	1330	2.65	21.4
KBA-140	145	548	1342	1.23	14.3
KBA-130	134	583	1363	3.09	23.2
KBA-120	125	616	1384	3.60	33.2
KBA-110	115	656	1408	4.20	45.8

[a] $C = \rho_w / [(W/100) + (\rho_w / \rho_s)]$; ρ_s = 2,650 kg m^{-3}, ρ_w = 1,025 kg m^{-3} (mud) and 1,000 kg m^{-3} (clays).

[b] $\rho = [C(\rho_s - \rho_w)/\rho_s] + \rho_w$.

For a given bed the product $\alpha_{bc}g'$ can be assumed to remain independent of time over the duration of wave motion. Wave height, period and water depth which determine $z_{smax}(0)$, and the profile $z_{smax}(z'>0)$ depend on the relevant bed parameters. The bed is assumed to be a viscoelastic material whose dynamics is readily examined in terms of the motion of a harmonic oscillator forced by the water wave. For the solution of the dynamic equation and subsequently z_{fe} from Eq. 5 the reader is referred to the modeling work of Li and Mehta (2001).

The application of the method in terms of the relationship between the water depth and fluid mud thickness is given in Mehta et al. (2012) for Grizzly Bay as an illustration. From the rheometric measurements for the mud and a separate set of tests for the determination of mud viscosity, the following parametric estimates were selected for Grizzly Bay: Water density $\rho_w = 1{,}025$ kg m^{-3}, water viscosity 0.001 Pa.s, wave height (at 2-m isobath) 0.4 m, wave frequency $\omega = 3.18$ rad s^{-1}, particle density $\rho_s = 2{,}650$ kg m^{-3}, thickness of soft mud (from which fluid mud in formed) 0.2 m, mud water content W = 300%, mud viscosity 0.01 Pa.s, mud rigidity (or elastic) modulus 1,000 Pa and cohesion coefficient $\alpha_{bc} = 0.05$.

Model result is plotted in Fig. 6. Note that at depths greater than 2 m no fluid mud is generated. Thus it appears that the expectation would be that fluid mud on the order of 10-20 cm thickness may be found at depths less than about 1-2 m (at low tide).

CONCLUDING OBSERVATIONS

This preliminary study is meant to show how oscillatory testing in the controlled shear stress mode can be used to assess the rheological behavior of mud in a shallow estuary, and from it to determine the fluid mud forming potential in one of the sub-embayments. The rheometric measurements were made in a TA Instruments AR2000ex rheometer. As only one mud sample at low natural water content was available for testing, commercial clays of known composition were additionally tested, and from the similarities in their rheological behavior the approximate properties of mud at higher water contents (lower concentrations) was deduced. These mud properties were then used to run a model meant to calculate the thickness of the (viscoelastic) fluid mud layer formed for a given wave height and frequency in Grizzly Bay, a shallow sub-embayment of Suisun Bay. Model result indicated that at depths greater than 2 m no fluid mud would be generated. Thus the expectation would be that fluid mud on the order of 10-20 cm thickness may occur at depths less than about 1-2 m (at low tide). Verification of these observations is pending the collection of data on the wave field and bottom sediment in the bay.

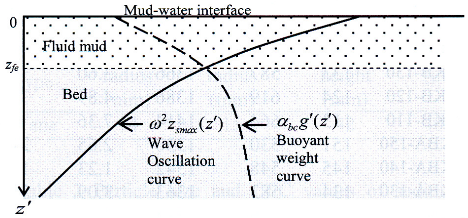

Fig. 5 Equilibrium thickness of fluid mud in a viscoelastic bed

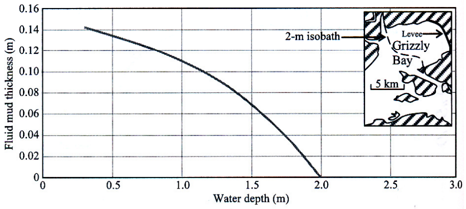

Fig. 6 Fluid mud thickness as a function of water depth in Grizzly Bay. Inset shows 2-meter isobath and levee location in the bay

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