Engineering Geology 154 (2013) 1–5

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Technical Note

The viscosity of fine-grained sediments: A comparison of low- to medium-activity and high-activity clays

Sueng Won Jeong *

Korea Institute of Geoscience and Mineral Resources, 124, Gwahang-no, Yuseong-gu, Daejeon, 305-350, Republic of Korea

ARTICLE INFO

Article history:
Received 5 March 2012
Received in revised form 14 December 2012
Accepted 16 December 2012
Available online 4 January 2013

Keywords:
Viscosity
Landslide
Fine-grained sediments
Modified Bingham model
Liquidity index

ABSTRACT

Viscosity is generally recognized as an indicator of landslide mobilization. Viscous behavior at relatively low (high) shear rates is an important predictor of the motion of slow- (fast)-moving landslides. The viscosity in a modified Bingham model at low and high shear rates was examined. The viscous characteristics are primarily dependent on the physico-chemical properties of the materials in question (e.g., grain size, mineralogy, salinity). In this context, the viscous characteristics of low- to medium-activity and high-activity clays (bentonite with different salinities) were compared. Empirical relationships exist between the liquidity index and the plastic viscosity regardless of the mineralogical composition. This study also demonstrated a positive relationship between the liquidity index and the viscosity in a modified Bingham model with $n=1$. The results showed that low- to medium-activity and high-activity clays fall into a similar range for fine-grained sediments mixed with salt water (30 g/L). However, an effect of salinity was evident when using high-activity clays mixed with fresh water. Modified Bingham model is a useful and powerful tool for describing pre- and post-yield viscosity in engineering practice. By correlating the geotechnical and rheological properties of fine-grained sediments, index properties can help to estimate the appropriate values for the rheological parameters of these soils.

1. Introduction

Rheology has many applications in engineering and material sciences. For example, rheology plays an important role in the viscous characteristics of mass movements (e.g., debris flows) that relate to the front velocity and final deposition of failed materials in post-failure dynamics (Major and Pierson, 1992; Malet et al., 2003; Locat et al., 2004; Remaître et al., 2005). In particular, the viscosity of sediments before and after apparent yield stress may also be related to the motion of very slow-moving and fast-moving landslides. The viscoplastic behaviors of fine-grained sediment are commonly described by the Bingham plastic and Herschel–Bulkley rheological models (Coussot and Piau, 1994; Coussot, 2007; Sosio and Crosta, 2009). Eq. (1) represents the Herschel–Bulkley model; it becomes the Bingham model for $n=1$. The applicability of a modified Bingham model to suspensions composed of clay-sized particles has been outlined (Locat, 1997; Jeong et al., 2009). The modified Bingham rheological law (Eq. (2)) is a powerful tool for describing the viscous behavior of debris flows (Imran et al., 2001). To explain flow behavior, classical flow curves can be plotted as the shear stress (τ) against the shear rate ($\dot{\gamma}$). In this context, the behavior of yield stress fluids with regard to shear is generally described as follows:

$$\tau = \tau_y + \eta_h \dot{\gamma}^n \tag{1}$$

$$\tau = \tau_{ya} + \eta_h \cdot \dot{\gamma}^n + \left(\frac{\tau_{ya} \cdot \dot{\gamma}_o}{\dot{\gamma}} + \dot{\gamma}_o \right), \tag{2a}$$

where

$$\dot{\gamma}_o = \frac{\tau_{ya}}{\eta_l - \eta_h} \tag{2b}$$

where τ is the shear stress (Pa), τ_y is the yield stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), n is the flow behavior index (dimensionless), τ_{ya} is the apparent yield stress (Pa), and $\dot{\gamma}_o$ is the shear rate at the transition from a high viscosity regime to low viscosity regime in a modified Bingham model. The model uses two viscosities η_l and η_h. They are the viscosities at very low and high strain rates, respectively. At very low shear rates, the flow behaves as a Newtonian fluid with a high viscosity; however, at sufficiently high shear rates, the flow behaves as a Bingham fluid with a low viscosity. A determination of apparent yield stress (τ_{ya}) and two viscosities are represented schematically in Fig. 1. The Bingham yield stress is denoted by τ_y, whereas the apparent yield stress is determined with the modified Bingham rheological

* Tel.: +82 42 868 3911; fax: +82 42 868 3414.
E-mail address: suengwon@hotmail.com.

0013-7952/$ – see front matter
http://dx.doi.org/10.1016/j.enggeo.2012.12.006

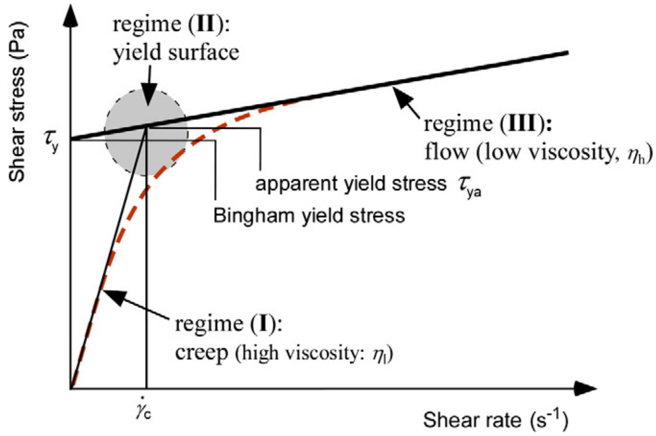

Fig. 1. A schematic view of a modified Bingham model with steady-state rheology. Solid straight line: Bingham fluid with yield stress and viscosity. Dashed line: the flow curve obtained from fine-grained sediments. $\dot{\gamma}_c$ = critical shear rate (s^{-1}).

law. For fine-grained sediments, these two values are very similar (Jeong et al., 2010); thus, $\tau_y = \tau_{ya}$ hereafter.

The flow behavior of a viscous fluid can be characterized by three flow regimes (Figure 1): (1) a creep regime with high viscosity ($\tau < \tau_y$); (2) the transitional region that represents the ultimate shearing resistance of the structure ($\tau = \tau_y$), also termed as the yield point or yield surface (Papanastasiou, 1987; Alexandrou et al., 2003); and (3) a flow regime with low viscosity ($\tau > \tau_y$). Thus, the 'creep' and 'flow' regimes correspond to (1) and (3), respectively. Little is known about the viscous phenomenon before apparent yielding. In the creep regime ($\tau < \tau_y$), the material behaves in a viscous manner. The relationship for $\dot{\gamma} = 0$ resembles that of an ideal plastic fluid (i.e., a fluid that is described by the Bingham law), which, in this case, is viscoplastic. The term viscosity η_l in the modified Bingham model is defined as the first branch of the flow curve in a linear plot. The viscosity at very low shear rates may be a representation of particle resistance in response to microstructural bonding.

The viscous characteristics are primarily dependent on the physico-chemical properties of the materials in question (e.g., grain size, mineralogy, salinity). The grain size and salinity-dependent rheological characteristics are represented schematically in Fig. 2. A significant change in viscosity may be found under the same testing conditions. For materials consisting primarily of clay-sized particles, a viscoplastic description is considered appropriate (Coussot and Piau, 1994; Coussot, 1997). Owing to the nature of materials, the viscous characteristics of low- to medium-activity clays (solid line) and high-activity clays (dashed line, but only in the case of material hydrated with fresh water within a very narrow range of concentrations) differ with respect to the shear stress vs shear rate relation.

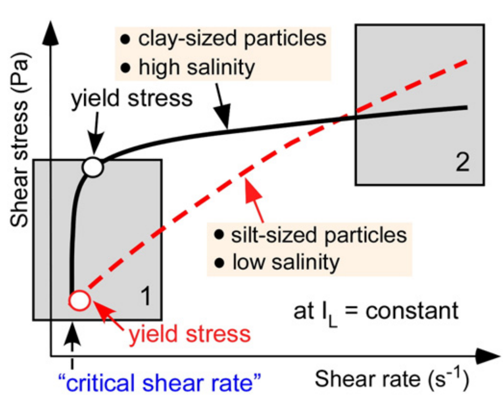

Fig. 2. Flow behavior as a function of grain size and salinity.

At low shear rates (box 1), the Bingham yield stress (τ_y in solid line), or the apparent yield stress, of clays was greater than that of silts. In contrast, for materials composed mostly of silt-sized or coarser particles, the plastic viscosity (the slope of the solid line after τ_y) of clays was smaller than that of silts at high shear rates (box 2).

Although there is an argument about the existence of a true yield stress, we examine the viscosity measured at low and high shear rates based on the modified Bingham model. In this article, we first review general aspects of the flow behavior of fine-grained sediments in the creep (high viscosity) and flow (low viscosity) regimes. Second, the flow curves of geomaterials of different origins and mineralogical compositions are compared. Lastly, we describe some implications of the existence of the viscosity in the creep regime at relatively low shear rates; defining the range of shear rates is difficult but is discussed later.

2. Materials and methods

2.1. Materials

The materials used in this study were fine-grained sediments from the Adriatic Sea. The sediments were collected from the Po Delta in Italy. The Po River is located in Northern Italy and is the most important sediment input to the northern Adriatic Sea. From the Alps near the French border to the Adriatic Sea near Venice, where the Po forms the Po Delta, this river deposits an estimated 20 million tons of sediment annually (Fox et al., 2004). After the 2000 flood event in the northern Adriatic Sea, which introduced large quantities of sediment into the Po delta area, a research program on seabed dynamics in the Adriatic Sea was initiated. In particular, an integration of stratigraphic information and geotechnical investigations was performed to examine the genesis of the seafloor and subsurface undulations on the Adriatic continental shelf (Sultan et al., 2008). Highly bioturbated samples of silty clay sediments collected immediately off the Po Delta in the Adriatic Sea were recovered in 2003 as part of a study to investigate the evolution of the year 2000 sediment layers in a downstream direction. The organic matter content was less than 1.6%. The sediments showed bioturbation and contained fragments of various shells. The primary minerals encountered in Po Delta sediments are quartz, calcite, feldspar, illite, kaolinite, and chlorite. The carbonate content is significant, with calcite concentrations ranging between 1.5 and 13.5% and dolomite concentrations ranging from 1.2 to 12.1% (Levesque, 2005). The fraction of particles smaller than 0.075 mm ranges from 10 to 27%. The materials tested were composed primarily of silty clays and can be considered low-activity clays.

Homogeneous mud was remixed thoroughly and tested using a viscometric system. The geotechnical properties of the soil samples are shown in Table 1. The viscous characteristics of low-activity clays are reviewed here on the basis of data compiled by Jeong (2006) in conjunction with additional rheological data for Wyoming bentonite (montmorillonite-rich material) to allow a comparison in terms of mineralogy.

2.2. Methods

All rheological tests were performed using a rate-controlled Searle-type Rotovisco RV-12 viscometer operated under a steady-state regime.

Table 1
Geotechnical properties of Adriatic Sea soils.

w	w_L	w_p	I_p	S	CF	S.S.	C.E.C.
75.7	65.6	36.1	29.5	30	27	90	12

Note: C.E.C. = cation exchange capacity (meq/100 g); CF (%) = clay fraction; I_p = plasticity index; S.S. = specific area (m^2/g); S = salinity (g/L); w = water content (%); w_L = liquid limit (%); w_p = plastic limit (%).