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Dynamic properties of fine-grained soils engineered with a controlled organic phase

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ABSTRACT

Soils with high organic content are frequently encountered beneath earthquake sensitive infrastructure, such as bridges or levees. Historically, the dynamic properties of these organically rich soils have been difficult to predict due to the heterogeneity of the natural organic matter that is found in natural soils, even though their response to dynamic loading remains critical to assessing the ongoing stability of the infrastructure. In this study, an experimental investigation was performed on a montmorillonite soil that was modified with a controlled organic phase. Quaternary ammonium cations were exchanged onto the soil particle surfaces through cation exchange with the clay's naturally occurring cations (e.g., Na^+, Ca^{2+}). Quaternary ammonium cations with a variable structure were chosen, which allowed control on the cation's size and length of alkyl chain, as well as a control on the density of organic loading on the clay surface. The dynamic properties of organoclays were then quantified experimentally using resonant column and bender element tests. This study demonstrated that the increase in the total organic carbon content of the soil increased the shear wave velocity and stiffness of the soil (G_{max}) due to a reduction in the void ratio of the organically rich soil. Cation structure did have a measureable impact on the soil stiffness, with organic cations with carbon concentrated primarily in a single tail demonstrating higher stiffness than those soils engineered with a branched cation structure. When compared to inorganic soils, the presence of the organic cations in the soil increased the range of linear elastic behavior of that soil, with the organoclays having a threshold strain of 0.024% or higher. The soil samples with the largest percentage of total organic carbon and the lowest void ratio demonstrated the largest damping ratio (ratio between dissipated and stored energy) during cyclic loading at small strain. Regression analysis of the dynamic test results demonstrated that the total organic content and the void ratio were the most dominant factors in determining G_{max} for the high organic content clays.

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1. Introduction

Soils with high organic content are frequently encountered beneath earthquake sensitive infrastructure, such as bridges or levees. Historically, the dynamic properties of these organically rich soils have been difficult to predict due to the heterogeneity of the natural organic matter that is found in natural soils, even though their response to dynamic loading remains critical to assessing the ongoing stability of the infrastructure. In part, the systematic study of soils with high organic content is difficult due to the extreme variability in the nature of the organic matter found in a soil system, which can exist in states that range from low molecular weight dissolved compounds to large fibrous peaty particulates. Additionally complicating the issue is the fact that organic matter can be geochemically reactive with particle surfaces and pore fluid, and can alter the water retention characteristics of a soil.

While many studies have quantified the dynamic properties of fine grain soils (e.g., [8,10,17,32,47,56]), and either peat or high organic content soils [5,18,19,20,21,23,24,45,50,61], relatively few studies have tested the effect of organic content in soils with low organic carbon contents (total organic carbon content $< 15\%$). Tests on peat sampled beneath a levee in the Sacramento-San Joaquin Delta in California demonstrated that modulus reduction and damping ratio relationships were similar to those observed for high plasticity clays and reported that shear wave velocities were between approximately 20 and 130 m/s [5,61]. Of additional significance for high organic content soil is the fact that previous studies have shown that normalized secant shear modulus values increase and equivalent damping ratios decrease with increasing

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consolidation stress and increasing organic content [21,24,61]. By examining earthquake motions recorded at Union Bay in Seattle, Seed and Idriss [45] estimated that damping ratios of peat were approximately three times larger than those of the clays at the site, and were also more nonlinear than those clays. Resonant column experiments on the peat specimens from the Queensboro Bridge found that, for the tested range of cyclic shear strain (up to approximately 1%, at confining pressures ranging from 7 to 303 kPa), the peat exhibited essentially linear behavior with low damping ratio [50]. Resonant column tests on the Mercer Slough peat presented significant nonlinearity at low consolidation stresses, which decreased as the confining pressure increased [24]. Cyclic triaxial tests on a peat from the Sherman Island levee demonstrated that the normalized secant shear modulus and equivalent damping ratio versus cyclic shear strain amplitude relations were a function of the consolidation stress up to a critical value, exhibiting increasing linearity up to approximately 40 kPa [5,61].

While significant advances have been made in the understanding of the dynamic behavior of organic/peat soils, mechanistic understanding of their behavior under dynamic load remains complicated by the fact that natural organic matter is composed of such a complex structure. In this study, an experimental investigation was performed on a montmorillonite soil that was modified with a controlled organic phase. Quaternary ammonium cations were exchanged onto the soil particle surfaces through cation exchange with the clay's naturally occurring cations (e.g., Na^+, Ca^{2+}). Quaternary ammonium cations with a variable structure were chosen, which allowed control on the cation's size and length of alkyl chain, as well as a control on the density of organic loading on the clay surface. The dynamic properties of organoclays were then quantified experimentally using resonant column and bender element tests. The results from this study were evaluated in terms of the effect of shear strain, total organic content, void ratio, plasticity index, and cation structure on the modulus and damping ratio of the organoclays.

2. Materials and methods

Organoclay specimens were prepared using a 1-D slurry consolidation method, as described in Ref. [3]. A brief summary of the preparation method follows. Organoclays were prepared using five quaternary ammonium organic cations: tetramethylammonium (TMA, denoted: $4C_1$) chloride [$(CH_3)_4NCl$], tetraethylammonium (TEA, denoted: $4C_2$) bromide [$(CH_2CH_3)_4NBr$], tetrabutylammonium (TBA, denoted: $4C_4$) bromide [$((CH_2)_3(CH_3))_4NBr$], decyltrimethylammonium (DTMA, denoted: $1C_{10}$) bromide [$(CH_3)_3NC_{10}H_{21}Br$], and hexadecyltrimethylammonium (HDTMA, denoted: $1C_{16}$) bromide [$(CH_3)_3NC_{16}H_{33}Br$]. All cation salts were obtained from Fisher Scientific, and were used as received. The water used in all experimentation was deionized (Barnstead E-pure).

Cations were chosen that would vary the size and the structure of the organic phase that was exchanged on the clay surface, with the experimental matrix designed to distinguish the effect between uniformly distributing carbon around the molecule center (i.e., TMA→TEA→TBA or $4C_1 \rightarrow 4C_2 \rightarrow 4C_4$) versus distributing the carbon in one long branch (i.e., TMA→DTMA→HDTMA or $4C_1 \rightarrow 1C_{10} \rightarrow 1C_{16}$) (Fig. 1). Additionally, HDTMA-exchanged clays were prepared at 30, 60, and 100% of cation exchange capacity to test the effect of density of surface coverage, while TMA, TEA, TBA, and DTMA-exchanged clays were prepared at 100% of cation exchange capacity, to compare the effects of cation structure and size.

After the organic cations were exchanged onto the clay surfaces through ion exchange, the chosen clay slurry was incrementally loaded in a consolidation cell of 10.2 cm in diameter and 45.7 cm in height. Filter paper (P5, Fisher Scientific) and a geotextile were used to provide drainage from the top and the bottom of the cell, and the vertical load was applied to the slurry using the Load Trac Testing Systems (Geotac). Loading and unloading steps were applied in the following sequence: 3.5, 7, 14, 28, 50, 100, 50, 28, 14, 7, and 3.5 kPa, while deformations were recorded by the accompanying software Sigma-ICON (Geotac). After the end of primary consolidation of each loading step, the next loading step was applied. Six organoclays were prepared for testing with both the resonant column and the bender element: 100TMA, 100TEA, 100TBA, 100DTMA, 60HDTMA, and 100HDTMA. Also, 30HDTMA was tested with the resonant column only. After consolidation was completed, the specimens were extruded, and trimmed to final heights, ranging from 13.2 to 16.5 cm, with a diameter of 7.1 cm for the resonant column test; samples were trimmed to a diameter of 10.3 cm and height of 6.1 cm for the bender element tests.

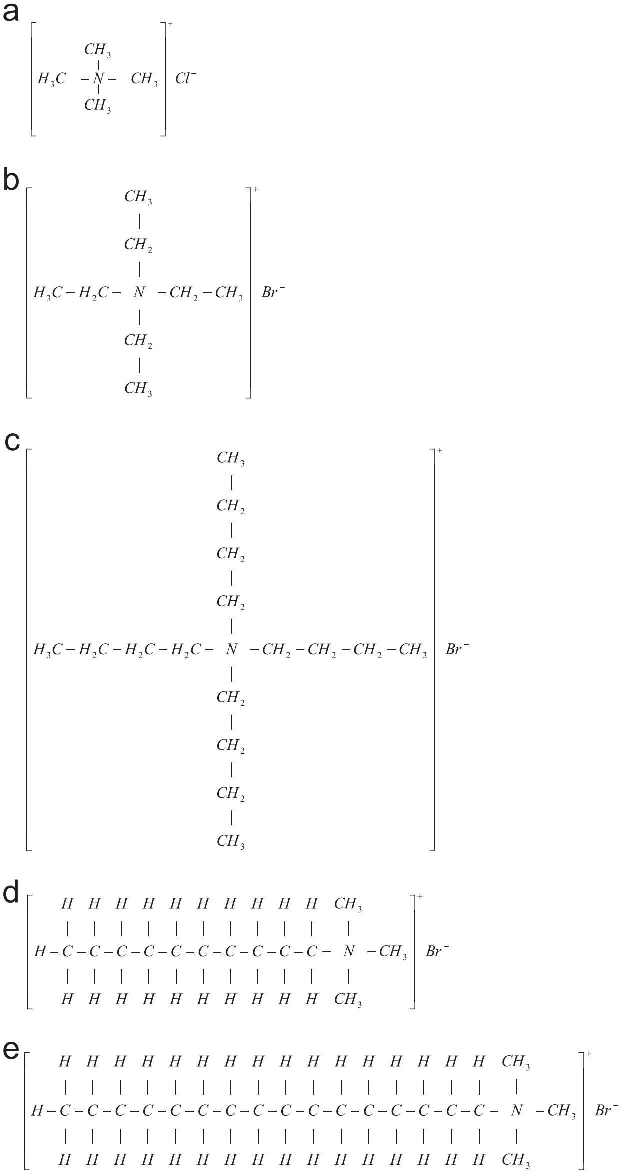

Fig. 1. Chemical formulas of organic cations used to synthesize organoclays. (a) TMA ($4C_1$), (b) TEA ($4C_2$), (c) TBA ($4C_4$), (d) DTMA ($1C_{10}$), (e) HDTMA ($1C_{16}$).

The total organic carbon content (TOC) was measured for each organoclay using an organic carbon analyzer (TOC-V_{CPN}, Shimadzu) and solid sample module (SSM-5000A, Shimadzu).