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Estimation of compressive strength of cement-treated marine clays with different initial water contents

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Abstract

A formula to estimate unconfined compressive strength of cement-treated marine clays is proposed. The formula has a form similar to the gel–space ratio theory. In the proposed formula, the strength of cement-treated soil is given by volumetric solid content, strength increase coefficient due to cement, exponential parameter *N* representing the effect of the void structure of soil and cement content in respect to the solid material of soil. The formula was adapted to the results of laboratory strength tests of cement-treated soils made of six dredged marine clays with different levels of initial water content. The strengths estimated by the proposed formula agreed with the measured strengths fairly well, using the parameter $N=3.5$–4.6. The formula was applied to the strength estimate of foam- and bead-treated soils made from dredged marine clay, using the parameter $N=2.1$–2.5. The applicability of the proposed formula was examined with the results of strength tests carried out for the design of cement-treated soil for the construction of D runway at Tokyo's Haneda Airport. Seven samples collected in the construction sites were mixed with different amounts of cement and the different levels of initial water content. On fitting the proposed formula to the results of all the data, the proposed formula estimates the measured strength well. On comparing the estimates with those using a conventional formula based on the water–cement ratio, the proposed formula generated better-fit estimates.

Keywords: Cement-treated soil; Marine clay; Unconfined compressive strength; Dredged soil; Port and harbor

1. Introduction

With rapid development and growing industrial and human settlement in coastal areas, there is rising demand for raw materials for coastal development projects. These materials are increasingly difficult to supply. At the same time, there is a need to re-use or dispose of large quantities of dredged soils that are generated in port and navigation dredging works (Port and Bureau, 2006). One treatment process that has been widely used to improve soft clayey soils is the cement mixing method. In 2001–2002, 7 million m^3 of cement-treated soil, made by mixing clay dredged in Nagoya Port with cement slurry, was used as filling material for the Central Japan International Airport (Satoh, 2003). In the expansion of Haneda Airport, completed in 2010, some 49 million m^3 of dredged soils from the navigation channel of Tokyo port were used as filling material, after being mixed with cement slurry by pneumatic mixing (Iba et al., 2009; Watanabe et al., 2009). In addition, nearly 8 million m^3 of dredged clay was mixed with cement and air-foam to create a foamed lightweight soil (Watabe and Noguchi, 2011). Dredged soft clay is also used as an

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intermediate protection layer for cut-off sheets in offshore disposal structures (Watabe et al., 2000, 2001), suggesting that there are potential benefits of using cement-treated dredged soils. Kasama et al. (2006, 2007) conducted a series of high-pressure dewatering experiments on cement-treated soils and reported that dewatered soils may show large compressive strengths nearly equivalent to that of concrete. This means that cement-treated soils are not limited to geomaterial uses but could also be used as tiles or bricks. Udaka et al. (2013) and Tsuchida et al. (2014) reported that after proper preconsolidation, dredged clay with a small amount of added cement shows compressibility behavior similarly to undisturbed natural clay, which has bonding structure formed during long years of sedimentation. Although cement treatment techniques are used for many purposes, in general, knowledge of strength-developing mechanisms is not extensive, and the cement industry has not seen major progress in the design of mixtures for cement-treated soil for nearly 40 years (Japan Cement Association, 2012).

In practical engineering, it is desirable to know the amount of cement required for the improvement of a particular soil before implementing the treatment process. A series of laboratory tests is performed to determine the amount of cement required in a mix in order to achieve the expected strength.

Unconfined compressive strength q_u of cement-treated soil is easily related with water content w of the original soft soil and cement content C in volumetric expression. Some approaches can be quoted as below (Miyazaki, 2003; Miyazaki et al., 2003).

$$q_u = a\,w + b \tag{1}$$

$$q_u = a/\left(W/C\right)^x + b \tag{2}$$

$$q_u = a\,C/w^x + b \tag{3}$$

Eq. (1) is a linear relationship between unconfined compressive strength and water content. Whenever cement content is changed, the parameters a and b involved in Eq. (1) have to be amended. Such a correlation is regarded as of no practical use. Eq. (2) is based on the idea of estimating compressive strength by means of the water–cement ratio, (W/C). Eq. (3) expresses that unconfined compressive strength increases with cement content and decreases with water content in an exponential form. Kida et al. (1977) introduced a modified water–cement ratio $(W/C)'$ where the waster was defined as that being subtracted under the pF-value of less than 3 from the treated soil. In Eqs. (2) and (3), water content and cement content are regarded as two factors governing unconfined compressive strength, but the amount of soil particles is not reflected explicitly. Lee et al. (2005) studied the strength and modulus of marine clay–cement mixture with high cement content and concluded that water–cement ratio alone cannot account for the variation in the strength and the influence of the soil–cement ratio must be also included. Recently, the mechanical properties of cement-treated clays with high water content have been extensively investigated by Horpibulsuk (2001) and Horpibulsuk et al. (2003, 2004, 2011) with the approach using the water–cement ratio as shown in Eq. (2). Sasanian and Newson (2014) carried out the extensive parametric study on the behavior of cement-treated clay and showed that the higher the activity number, the higher the strength of the clay at a given cement–water ratio.

Based on many laboratory tests of saturated dredged clays obtained from various ports around Japan, Tang et al. (2001), Miyazaki (2003) and Miyazaki et al. (2003) proposed an empirical prediction of unconfined compressive strength with cement content and specific volume v of dredged clay, where v is defined as $v = G_s w/100 + 1$, i.e., the ratio of total volume of soil to the volume of soil particles. Eq. (4) expresses the correlation among unconfined compressive strength q_u, cement content C, and specific volume v.

$$q_u = \frac{K(C - C_0)}{v^2} = \frac{K(C - C_0)}{(G_s w/100 + 1)^2} \tag{4}$$

where v is specific volume of clay, G_s is specific gravity of soil particles, w is initial water content after cement is mixed (%), C is cement content per 1 m^3 of cement-treated soil (kg/m^3), C_0 is threshold of cement content for strength gain of treated soil (kg/m^3) and K is coefficient of strength gain (kN/kg m).

Eq. (4) reflects that the greater the cement content and the lower the water content, the higher the strength of a treated soil. Fig. 1 shows application examples of Eq. (4) to clayey soils. By properly assigning parameters of strength coefficient K and threshold C_0, unconfined compressive strength q_u can be predicted with fair precision with respect to different curing periods. The correlation coefficient R between predicted unconfined compressive strength q_u^* and measured strength is evaluated ranging from 0.911 to 0.992. There is an interesting tendency for the threshold C_0 not to change with curing periods as the same cement-treated soil. This fact supports the validation of Eq. (4).

The important variable C is given by cement content per 1 m^3. Whenever water content changes, the ratios of both cement to soil particles and cement to pore water are implicated in that change. This means that the expression of cement content C is harder to give an explicit definition.

Referring to the opinion of gel–space ratio theory for cement paste in concrete engineering, the authors modified Eq. (4) to arrive at a new strength prediction based on the ratio of cement weight to soil particles c and the volumetric solid content Y of treated soil. Here, the volumetric solid content Y is equivalent to the inverse of specific volume v, the volume ratio of solidity particles to whole volume of cement-treated soil. In this paper, it is shown that unconfined compressive strength can be predicted with coefficient of strength k_c by the characteristics of individual soil, effective cement adding ratio $(c - c_0)$, and volumetric solid content Y in exponent form as Y^N.

2. Prediction of unconfined compressive strength in terms of volmetric soild content for cement-treated soils

As expressed in Eq. (4) by Miyazaki et al. (2003), the variables of cement content C and C_0 are presented in a unit of kilograms per m^3 (kg/m^3) of cement-treated soil. The factor of coefficient of strength gain K is presented in a unit of kN/kg m.