Chapter 1

INTRODUCTION

1.1. Deformation of Soils and Their Compressibility

There are various types of deformation of soils such as plastic flow, elastic deformation, shear deformation, undrained creep, primary compression, secondary compression, and liquefaction. Most theories of deformation and compression cover deformation of either cohesive or cohesionless soils but there are some theories which cover cohesive and frictional soils. Some types of deformation are stress-dependent and some are time-dependent. Generally, majority of large strain deformations are associated with cohesive compressible soils. In 1923, Terzaghi proposed a time-independent linear-elastic model of compression behavior for a low permeable thin layer of soil. Taylor and Merchant (1940) explained the compression behavior after the primary stage with an elastoviscous model. With these two models, the magnitude and time rate of compression of a soil in the primary and secondary stages can be predicted.

However, studies on compressibility of soils by the early researchers concentrated mainly on naturally sedimented clay deposits, which are either normally consolidated or over-consolidated. On the other hand, some researchers in the chemical engineering field such as Coe and Clevenger (1916), Kynch (1952), Fitch (1966a, b), and Bustos (1987) are among others who studied the sedimentation process. McRoberts and Nixon (1976), Been and Sills (1981), and Tan (1995) applied the sedimentation theory to soil sedimentation.

Tan *et al.* (1988) studied the transition of sedimentation process to consolidation process. Some researchers such as Been and Sills (1981), Lee and Sills (1981), Mikasa (1961), and Toorman (1996) investigated the self-weight consolidation process. Consolidation or compression of slurry-like soil was studied by Carrier III and Beckman (1984), Carrier III and Keshian (1979), and Carrier III *et al.* (1983). Tan *et al.* (1988) has proposed a nonlinear equation for predicting hydraulic conductivity and effective stress from void ratio for stress level of up to 50 kPa. However, the deformation behavior of ultra-soft slurry-like soil upon additional load is not well understood.

Due to the high demand of land in coastal areas, reclamation or remediation of land on ultra-soft soil like recently deposited deltaic or estuarine deposits, waste ponds, and mine tailing ponds became necessary. Such deposits are extremely soft and have very high water content. In addition, these materials are underconsolidated and usually still undergoing self-weight consolidation.

The compression and consolidation behavior of the ultra-soft soil due to additional load is different from that of the normally or overconsolidated soil. The prediction of magnitude and time rate of deformation using Terzaghi's consolidation theory may not be appropriate (Bo *et al.*, 1997a, c and 1999). Terzaghi's consolidation theory leads to an underestimation of the magnitude and an overestimation of degree of consolidation.

Therefore, the settlement prediction during and after reclamation on this type of soil deposit is extremely difficult due to a lack of a deformation model. As such planning and scheduling of soil improvement works become impossible since the duration required for consolidation is not known. Therefore, the development of a compression model which can predict the compression behavior during the viscous stage is important and necessary. Been and Sills (1981) have suggested that a suitable theoretical model for very soft soil is required to be developed.

1.2. Related Previous Research

Past researchers concentrated mainly on the compressibility of normally or overconsolidated soils. Terzaghi's theory was originally developed for a thin layer of compressible soil, and is not easily adaptable for a thick layer of soil involving large strains. Subsequently Gibson and Lo (1961) proposed a model similar to that proposed by Taylor which took into consideration of Large strains by applying a Lagrangian coordinate system.

Since the compression and consolidation of soil is nonlinear, Mikasa (1961) proposed a nonlinear consolidation model using volumetric strain and specific volume rather than settlement and void ratio. Mikasa and Takada (1995) derived a new consolidation theory which accounts for the continuous changes in the consolidation properties with depth. Special consideration for the effect of self-weight of clay and the reduction of thickness were taken into account in addition to the change in soil parameters with respect to space and time.

Since nonlinearity alone is not sufficient to model the compression and consolidation behavior of a soil, viscous effect was taken into consideration by the models of Barden and Berry (1965), Garlanger (1972), Mesri and Rokshar (1974), Leroueil (1994), and Yoshikuni *et al.* (1994).

However, the viscous effect considered in their models is either in the primary consolidation stage or after the primary consolidation stage.

The vertical deformation due to vertical and radial flows has been proposed by Carillo (1942) and Barron (1948). A three-dimensional consolidation model was proposed by Biot (1955) which takes into account the volumetric strain and the all-round flow of pore water from the soil mass.

Coe and Clevenger (1916), Kynch (1952), and Fitch (1966a, b, 1975 and 1979) are among others who had studied and explained the sedimentation process in their studies of the sedimentation of thickeners. McRoberts and Nixon (1976) and Been and Sills (1981) applied the sedimentation theory to soil sedimentation and carried out laboratory sedimentation experiments together with the measurement of small effective stress gain.

Beyond sedimentation, researchers have been studying self-weight consolidation. Been and Sills (1981), Lee and Sills (1981), Mikasa (1961), Tan *et al.* (1988), and Toorman (1996) were among others who have studied this process. Carrier III and Beckman (1984), Carrier III and Keshian (1979), Carrier III *et al.* (1983), Carrier III and Bromwell (1980) widely studied the compression of slurry-like soil and remediation of slurry waste pond. Determination of consolidation properties of very soft clay was studied by Tan *et al.* (1988) with the measurement of pore pressure and density with Gamma rays. Prediction of consolidation of very soft soil was reported by Cargill (1982a, b) using various time factor charts derived from large strain consolidation theory. The consolidation of soil stratum, including self-weight effects and large strain derived from Gibson *et al.* (1967) was proposed again by Lee and Sills (1981). However, Salem and Krizek (1973) used conventional theory and method to characterize the dredged slurries. The area that is less studied is that of a soil subjected to a surcharge while undergoing self-weight consolidation. In addition to the models and time factor curves required to predict the compression of ultra-soft soil, some test methods such as constant rate of loading, constant rate of strain tests on very soft soil or slurry were carried out by Carrier III and Beckman (1984). A more detail review of their research will be discussed in the relevant subsequent chapters.

1.3. Outline of the Book

This book aims to explain the compression and consolidation behavior of an ultra-soft soil subjected to an applied load. This soil in question was still undergoing self-weight consolidation. The magnitude and rate of settlement during the early stages of compression and consolidation were explained using various experimental tests carried out by an author during the late 1990s. Subsequently, a numerical model is developed by the author for the prediction of magnitude and time rate of deformation of ultra-soft soil during the slurry stage.

The book describes the experimental laboratory and field tests carried out by the author and his coworkers to investigate the compressibility and consolidation of ultra-soft soil. Test results from such comprehensive laboratory tests carried out on samples with various moisture contents and different applied loads were presented and discussed extensively in this book. Results from tests carried out with both small-scale and large-scale consolidometers are widely discussed in Chapters 5 and 6. Both consolidometers used by the author were equipped with pore pressure transducers and settlement monitoring devices. With these tests, the compression and consolidation behavior during the viscous stage were explained. How to determine the transition point from the slurry stage to the soil stages applying these types of tests is described in Chapters 5, 6, and 7. The parameters controlling the magnitude and the rate of deformation are explained and discussed. Consolidation tests carried out with Rowe cell allowed to find out the effect of flow pattern on the deformation behavior. Based on several combinations of Rowe cell tests carried out by the author and his coworkers, a basic equation for the prediction of magnitude of settlement as well as the relationship of various compression indices with the void ratio at liquid limits are proposed. The relationship between void ratio and hydraulic conductivity, time factor curves for prediction of time rate of settlement are also proposed. Several constant rates of loading tests and constant rates of strain tests are also presented to explain the relationship between the void ratio change and effective stress gain. Based on the results from the experimental study extensively carried out by the author, a simplified mathematical model has been adopted. Compression parameters and a large strain coefficient of consolidation parameters are proposed for prediction of the rate and magnitude of compression of ultra-soft soil with this model. The validation of the proposed model is made against the laboratory-controlled measurements. Comparisons between the proposed model and existing models are made and discussed.

In addition to the experimental studies in the laboratory, field tests carried out are also described. The compression and consolidation behavior in the field are monitored by piezometers and settlement gauges throughout the process, and the relationship between the gain in effective stress and deformation is explained. The verification of the improvement of ultra-soft slurry-like soil during and after deformation by various *in situ* testing and laboratory methods is also presented. Finally, the reliability of the proposed model is verified against laboratory results and field data, especially the measured settlements. Validations are made for soil settlement under two conditions: with and without vertical drains.