

Viscous Behaviour of Soft Clay and Inducing Factors

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Abstract As a result of the scarcity of land for construction, a number of projects to construct man-made islands or to expand lands over soft grounds keeps increasing. Creep behaviour of soft ground has been considered as a challenging issue for engineers and researchers for many years. A number of studies have focused on the method to predict the creep deformation of the ground under a construction site. However, there is no unified theory to clearly explain the mechanism of soil creep deformation of soils. Results of the critical review in this paper indicate that the causes of soil creep can be categorised into five main groups, namely (a) the breakdown of the inter-particle bonds, (b) sliding between the soil particles, (c) water flow from micro-pores to macro-pores (d) the deformation due to the structural viscosity and (e) the deformation due to the jumping of bonds. This paper presents these mechanisms in details with an effort to

recommend an enhanced explanation for the creep compression mechanisms of clays.

Keywords Creep · Soft soils · Structural viscosity · Adsorbed water · Clay mineralogy

1 Introduction

As the social and economical development of the world keep advancing along with the increase in population, the availability of appropriate sites with proper soil for construction becomes increasingly meager. Soft soils are more predominant around coastal areas or river sides, where the demand for construction is usually higher. Various projects in Australia have been constructed on unsuitable ground such as the Ballina Bypass, Port of Brisbane Expansion, and Port Botany Expansion. The Ballina Bypass project has been undertaken to upgrade a 12 km four lane road between Newcastle and the Queensland border. Most of the road is on coastal soil including soft clays of various thickness. Two trial embankments were constructed in 1998 to investigate the soil behaviour in that area, and it is reported that soft soils exhibit large creep deformation (Huang et al. 2006).

In the Port of Brisbane Expansion project, the land expansion of 235 ha of a sub-tidal area is a reclaimed site underlaid by 9 m of soft dredge materials overlying 30 m deep soft to firm seabed clays (Ameratunga

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et al. 2010). Due to the deep soft soil deposit (30 m), long term settlement and the secondary consolidation component are critical factors to be dealt with. Ground improvement techniques such as surcharge with wick drains and vacuum preloading were adopted in this project to reduce the post construction settlement as the clay deposit becomes overconsolidated after improvement. As discussed by Ameratunga et al. (2010), the amount of over-consolidation to be targeted in the design was a difficult question for the designer because of uncertainties in the secondary consolidation behaviour.

Port Botany Expansion is an important infrastructure development in New South Wales, Australia. This project to extend the existing port at Botany Bay reclaimed an area of 63 ha for developing a new container terminal. The major structure of the project is a 1,850 m long quay wall for the berth, which comprises more than 200 precast counterfort units of 20 m height with the weight of 640 tonnes per unit. The geological study of this area shows that the site rests on about 15 m layer of dense sand over a deep layer of marine clays (McIlquham 2010).

In Melbourne, creep settlement is the challenging issue for several projects carried out on the areas resting over Coode Island Silt. The soil is classified as soft silty clay with high compressibility and low permeability (Ervin 1992). The soil produces excessive settlement, even though the applied pressure was in overconsolidation range. Therefore, settlement predictions for Coode Island Silt were unreliable and still present a challenge for geotechnical design and construction (Bouazza et al. 2004).

These projects are just a small number of existing developments carried out on inappropriate ground for construction in Australia. These emphasise the importance of advanced study on soft soil engineering, particularly soil deformation. Soft soils consist of clay and silt with remarkable amount of pore water, and they may undergo extraordinary settlements under the effect of the surcharge loads. Therefore, knowledge of how to identify soft soil and its engineering properties and characteristics is critical. This will assist geotechnical engineers to identify if ground improvement is viable, and which methods would be most appropriate for the site. The prediction of consolidation and creep compression are vital in soft soils and the long term deformation must be emphasised in engineering design and practice. It should be noted that the soil

creep mechanism is the foundation to develop constitutive models for soft soil behaviour, particularly for long term settlement.

Time dependent behaviour of soils has been a contentious topic for many researchers for several decades. Since Terzaghi's classical theory of one-dimensional consolidation has provided reasonable estimation of the settlement induced by the hydrodynamic effects, the true settlement is believed to continue in a long period after the end of pore water pressure dissipation period. The term "creep" or "secondary compression" has been adopted to describe the settlement, or so-called volume change, under a constant effective stress (Bjerrum 1967). In general, the real behaviour of soils depends on various factors such as the soil composition, the clay mineralogy, the moisture content, and the stress–strain relationship (Feda 1992). However, interactions of various factors influencing the behaviour of soils, especially the consolidation process remain unclear. It is important to understand profoundly the mechanism of the soil deformation because further numerical modellings are constructed based on the assumptions associated with the nature of the soil deformation. Different mechanisms can lead to different solutions for predicting the soil behaviour. The conventional or simplified methods may not be appropriate to answer the complicated questions regarding soil behaviour such as the relationship between stress–strain–strain rate, and the effect of temperature, even though they can provide reasonable estimation of soil settlement in some simple conditions. In this study, after a brief review of clay mineralogy, various mechanisms proposed by geotechnical investigators to describe soil creep phenomenon are explained in details. Then discussion of the proposed mechanisms in regard to soil macroscopic and microscopic properties is presented.

2 Clay Mineralogy

The presence of clay particles in soils is one of the main reasons for soil creep deformation. Therefore, it is essential to review basic knowledge of clay mineralogy, which has significant impact on the engineering properties of clay soils. The clay particles have different shapes such as bards, plates and sheets and are composed of complex silicates of aluminium,

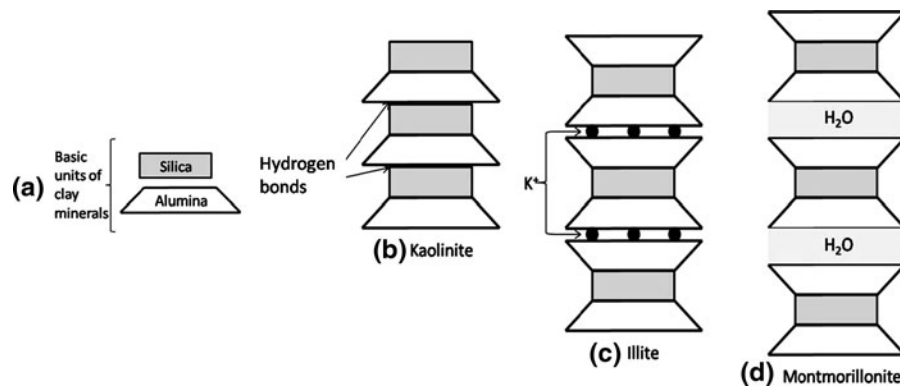


Fig. 1 **a** Basic units of clay minerals, **b** Kaolinite, **c** Illite, and **d** Montmorillonite (after Das 2008)

magnesium, and ion. According to Das (2008), the two basic units of clay minerals are silica tetrahedron and alumina octahedron, forming respectively silica and alumina sheets, as schematically represented in Fig. 1a. Different structures of the stacked combinations of the basic sheet structures with different types of bonding between the sheets result in different types of clay minerals. The three main clay minerals are kaolinite, illite and montmorillonite as illustrated in Fig. 1b–d.

According to Das (2008), clay particles have a net negative charge on the surface, and they present both negative and positive charges on the edge. As a result of balancing the negative charge, the positive charged ions or cations in the pore water are attracted to the surface of the particles. These ions are defined as the exchangeable ions such as Al^{3+} , Ca^{2+} , Mg^{2+} , NH_4^+ , K^+ and Na^+ . Due to the attractive and repulsive forces between ions and clay surface charge, the ion concentration of cations is inversely proportional to the distance from the surface of the particles, while the ion concentration of anions increases with the distance. A water molecule is known as a dipole with positive and negative charges at its two ends, and water molecules can be electrically attracted to the clay particles in three ways (1) the positive ends of dipoles are attracted to the negative charged surface of clay particles, (2) the negative charged ends of dipoles are attracted to cations around the clay surfaces, and these cations are attracted to the surfaces of clay particles, and (3) hydrogen bonding is formed between the oxygen atoms in water molecules and oxygen atoms on clay surfaces by sharing the hydrogen atoms of water molecules. The illustration of attraction patterns of water molecules on clay particles is shown

in Fig. 2. The layer of floating cations and anions on clay particle surface is termed as double layer (Mitchell 1976). Double layer affects the range of interaction forces including repulsive and attractive forces between clay particles, and is affected mainly by the concentration and valence of cations (Craig 2004). Adsorbed water is the innermost part of the double layer which is strongly held on the clay particle surface. In addition, adsorbed water molecules are believed to be able to move freely parallel to the clay particle surface, but their movement is restricted on the perpendicular direction to the surface.

Interparticle forces between the clay particles are also important for elucidation of clay mineralogy. The net force among particles is determined based on the difference between two opposite forces (repulsive and attractive forces) with respect to the distance of particles. According to Mitchell (1956), the interparticle forces between clay particles affect the arrangement of clay particles, particle orientation or the relative position between adjacent particles, all of which are defined as the fabric of clay. The fabric of clay has significant impact on the engineering properties of that clay (Mitchell 1956; Mesri and Olson 1971; Rao and Matthew 1995). Table 1 summarises the characteristics of two distinct clay fabric arrangements which are flocculation and dispersion. Moreover, for a given mass at any compression pressure, clay in dispersed state has a smaller volume than clay in flocculated state, because the parallel arrangement of particles in dispersed state is more oriented than the random arrangement in flocculated state. At the same preconsolidation pressure, under the effect of a same increment of stress, there is more relative movement

Fig. 2 **a** Water molecule and **b** attraction of water molecules on the surface of clay particle (modified after Ranjan and Rao 2007)

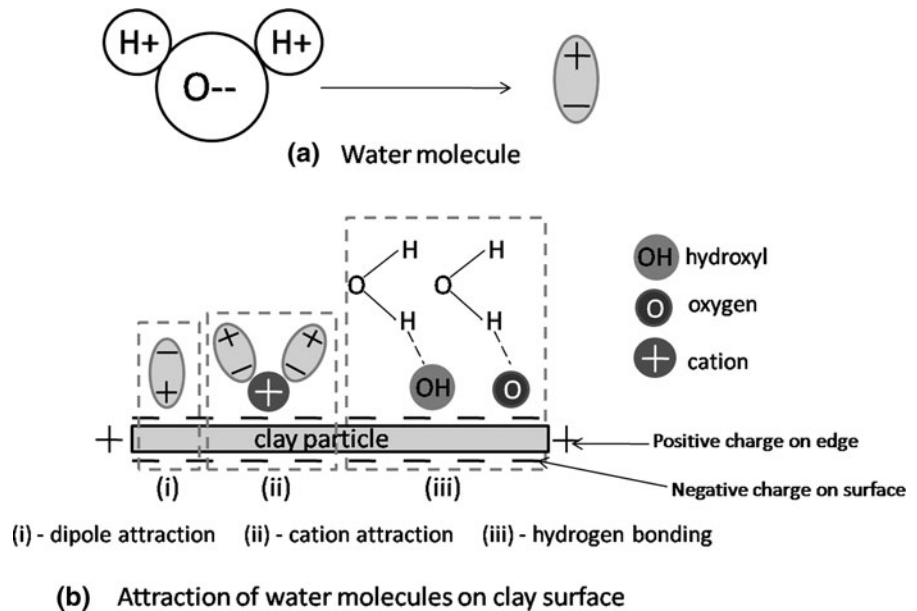


Table 1 Flocculation and dispersion of clays (after Mitchell 1956)

Flocculation	Dispersion
Net force between clay particles is attraction	Net force between clay particles is repulsion
Flocculation caused by the attraction between the positive charged edge of a particle to the negative charged surface of its adjacent particle	Dispersion caused by the repulsion between the negative charged surfaces of adjacent particles
The system of clay particles in random arrangement	The system of clay particles in parallel arrangement

between clay particles in flocculated state than in dispersed state. The movement of clay particles tends to change the particle arrangement from random to parallel orientation.

Based on the experiments on the fabrics of 14 undisturbed and remoulded clays, Mitchell (1956) investigated the effects of the clay fabric on secondary compression or creep. Undisturbed clay has more random particle arrangement than remoulded clay. Therefore, the orientation change happens more in undisturbed clay than in remoulded clay, while remoulded clay has more packed state, leading to less relative movement (shifting) between clay particles. As a result, the secondary compression ratio of undisturbed clay is higher than that of remoulded clay. In brief, clay mineralogy including mineral composition, clay water system and electrostatic forces within clay system altogether results in the distinctive properties of clay in comparison to other soils, and these effects of clay mineralogy on creep behaviour of clay are significant.

3 Mechanisms of Creep Deformation

After Terzaghi's outstanding theory of one dimensional consolidation of soils in 1923 that explains the rate of excess pore water pressure dissipation, it has been observed from laboratory results and field observations that settlement continues even after complete dissipation of pore water pressures. In order to distinguish the two components of the compression, the term 'primary consolidation' is used to describe the time dependent process due to the change in volume induced by the expulsion of water from the voids, and transferring loads from the pore water to the soil particles. On the other hand, creep or so-called secondary compression is generally defined as the deformation under a constant effective stress (Taylor and Merchant 1940; Bjerrum 1967). It is necessary to exclude creep phenomenon from the deformation under constant load because the effective stresses can be variable under a constant load. Research on the long-term settlement of soils has become important and been developed for many

decades. However, there has been no unified approval to explain the mechanism of creep deformation resulting in different schools of thought and consequently various methods to predict soil settlement. This section attempts to make a comprehensive explanation for the mechanism of creep for clayey soils based on various existing relevant studies such as Taylor and Merchant (1940), Murayama and Shibata (1961), Mitchell et al. (1968), Barden (1969), Navarro and Alonso (2001), Mitchell and Soga (2005) and others. Although some of the explained mechanisms can be used to describe the creep behaviour of silt and granular soils, this study focuses on the creep behaviour of soft clays and the primary factors.

3.1 Creep Due to the Breakdown of Interparticle Bonds

Soil is considered as a complex structure because of its heterogeneous compositions when compared to other materials such as metal or glass. In the macroscopic point of view, an element of clayey soils, as shown in Fig. 3, contains clay particles, coarse grain particles and water. Water in the macroscopic view is defined as free water which flows due to the hydraulic gradient. According to Taylor and Merchant (1940) and Terzaghi (1941), the compression processes including both primary and secondary (or creep) settlement are explained based on the transfer of stress and the rearrangement of soil particles. Under the effect of the applied stress, free water flows out of the soil element, resulting in the rearrangement of the soil structure. It may lead to an increase in the solid-to-solid contacts in the soil. The flow of free water may take a period of time to be over, and is controlled by the soil permeability; therefore, the primary consolidation is a time dependent process. The primary consolidation increases the contact between soil particles, and also decreases the voids between particles. Since the spacing between the particles reduces, soil particles transform to more packed state. The contacts between particles gradually increase, causing the increase in the effective stress with time as a result of the total stress transferring from pore water to the contacts between particles. At the contacts between particles, particularly between clay particles, different types of bonding, and interparticle forces such as the primary valence bonds between particles, van der Waals forces, hydrogen

bonds, bonds by sorbed cations, attraction forces between particles with different charge, and cementation bonds, occur (Yong et al. 2010).

However, the bonds between particles may be broken or destroyed by the increase in the effective stress. The breakdown of bonds between soil particles may cause further rearrangement of soil particles, consequently further settlement or compression called creep. The breakdown of interparticle bonds is considered as a mechanism of creep deformation proposed by Taylor and Merchant (1940), Terzaghi (1941), and accepted by Gibson and Lo (1961), Mesri (1973, 2003), Mesri and Godlewski (1977), and Crooks et al. (1984).

There are various causes of the breakdown of the interparticle bonds. It can be induced by the relative movements of particles with respect to each other due to the shear displacement or the change in particle spacings induced by the change in the net interparticle forces (Mesri 1973). Bolt (1956) considered the deformation of a natural soil induced by the combinations of both mechanical and chemical factors considering the soil composition including both coarse grained and fine grained particles with different compressibility.

3.2 Creep Due to Jumping of Molecule Bonds

Murayama and Shibata (1961), Christensen and Wu (1964), Mitchell (1964), and Kwok and Bolton (2010) explained the creep mechanism based on the theory of rate process. The creep deformation is caused by the movement of the atoms and molecules to a new equilibrium position under the effect of constant stress. Because the movement of atoms and molecules (called flow unit) relative to each other is resisted by virtual energy barriers, a sufficient activated energy is required to conquer the barriers. Creep in clay is the displacement of oxygen atoms, which is seen as the flow units, within the contact surface between clay mineral particles (Kuhn and Mitchell, 1993). In fact, the flow units do not remain static, but dynamically vibrate with a certain frequency. Considering that creep is defined as a rate process, Mitchell et al. (1968) suggested that the activation energy, E_{act} , not only depends on the deviatoric stress but also depends on elapsed time of creep.

The concept of activation energy is explained in detail by Low (1962) as he examined the influence of the absorbed water on the exchangeable ion

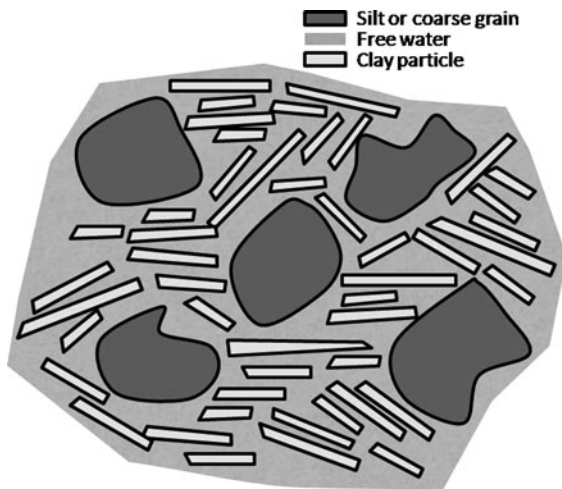


Fig. 3 An element of soil in macroscopic view

movement. In Fig. 4, there is the schematic illustration for the concept of activate energy which includes a close packed arrangement of an ion (gray filled circle) surrounded by water molecules (white filled circles). If the ion moves from one position to another (such as from a to b), it must break the bonds with all adjacent molecules with the charge on the clay surface and push back the molecules in front of it to replace to that space. The whole process of ion movement from a to b requires a sum of different energies for different bonds, which is named the activation energy, E_a .

According to Mitchell et al. (1968), the deformation of soils is evaluated based on the activation energy and the number of inter-particle bonds per unit area using Eqs. 1 and 2. The inter-particle bonding is referred to solid-to-solid bonds (such as between soil particles),

or mineral-to-mineral, or mineral to mineral through the interlayer adsorbed layer, which is temperature dependent. Equations 1 and 2 can be considered as a general stress strain relationship, because they show the dependence of strain rate on deviator stress and temperature.

$$\dot{\epsilon} = A \left(\frac{t_1}{t} \right)^m \exp(\alpha D) \quad (1)$$

$$\alpha = \frac{\lambda}{4SkT} \quad (2)$$

where A is the strain rate at unit time t_1 and $D = 0$; D is the deviator stress ($\sigma_1 - \sigma_3$), t_1 is a reference time, t is time, m is the negative slope of the relationship between logarithm of strain rate and logarithm of time, S is the number of flow units, k is a constant equal to 1.38×10^{-16} (erg/°K), λ is the distance between equilibrium positions of flow units, and T is the absolute temperature (°K). These parameters, A , α and m can be obtained by two creep tests. The value of m can be firstly determined by the plot of logarithmic of strain rate versus logarithmic of time. A and α are respectively the intercept at unit time and the slope of the plot of logarithmic of strain rate as a function of stress for different time values.

From the results of several triaxial creep tests with different temperature conditions and shear stress levels, Mitchell et al. (1968) concluded that soil creep is a thermally activated process, as the logarithm of creep strain rate divided by the absolute temperature T , $\log\left(\frac{\dot{\epsilon}}{T}\right)$, is inversely proportional to the reciprocal of the absolute temperature T ($1/T$). In general, the increase in the temperature may induce the increase in

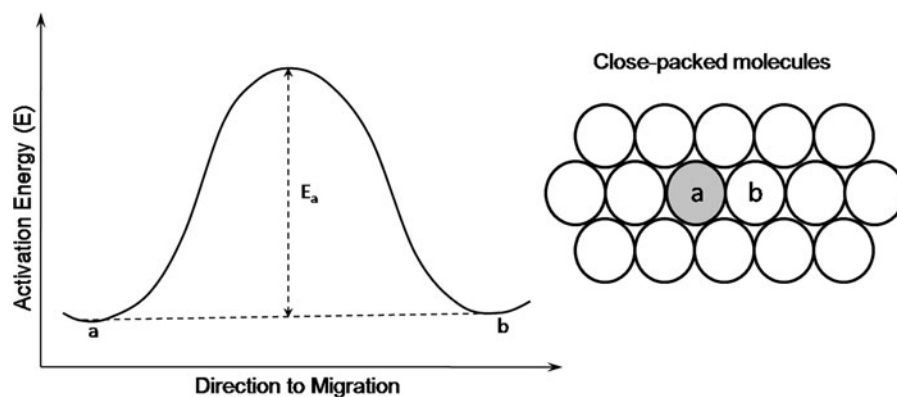


Fig. 4 Schematic representation of an ion surrounded by water molecules, and the enegy barrier which it must surmount in moving between equilibrium positions (after Low 1962)

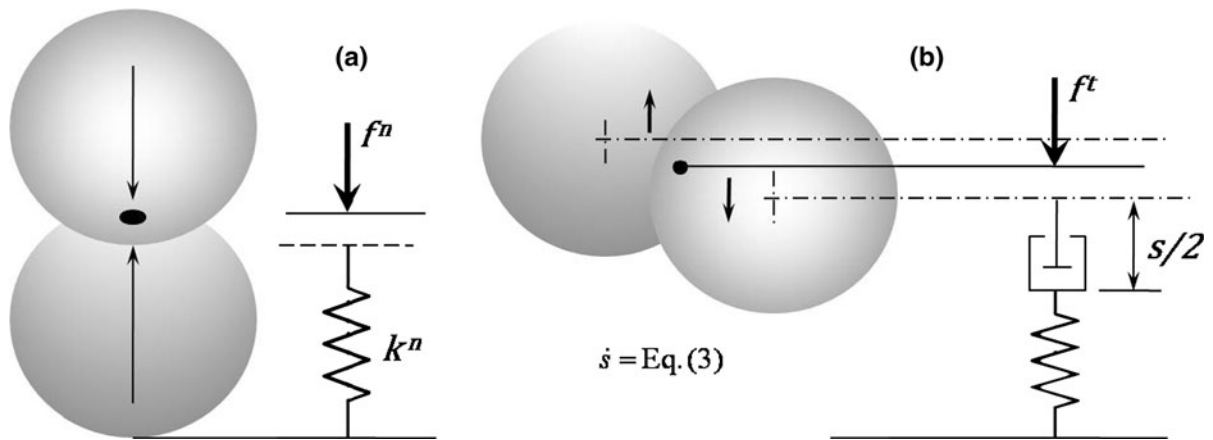


Fig. 5 Contact mechanism used for individual particles in numerical model: **a** Normal force mechanism, and **b** tangential force mechanism (after Kuhn and Mitchell 1993)

the creep rate. However, Mesri (1973) suggested that the effect of temperature on the creep rate is insignificant compared to the influence of other factors such as the precompression and the sustained loading. In terms of the effects of shear stress on creep, Mitchell et al. (1968) observed the linear relationship between the logarithm of creep strain rate and the deviatoric stress obtained from several undrained creep tests. In addition, based on shear creep tests, creep behaviour is shown to depend on the applied shear stress (Singh and Mitchell 1968; Yin and Graham 1999). As reported by Vermeer and Neher (2000), there are three typical types of creep behaviour under a constant shear stress. For deviatoric stresses about 30 % of the shear strength, creep strain is small, and creep strain rate decreases and approaches zero after a period of time. For higher deviatoric stresses up to 70 % of the shear strength, creep strain develops with a constant strain rate. For deviatoric stresses greater than 70 % of the shear strength, the creep strain rate is accelerated, and may cause soil failure.

3.3 Creep Due to Sliding Among Particles

Grim (1962) explained creep as the reduction in volume mainly due to slipping between soil grains, while primary consolidation is caused by squeezing out water with insignificant slippage between grains. When water content reduces during primary consolidation, the bonding forces between the particles increase with the decrease in the spacing between

particles. The increase in bonding forces causes the increase in the frictional resistance of particles against slipping relative to each other. Hence, the reduction in the volume during creep takes place slowly. Gupta (1964) explained that creep is caused by the relative sliding movement of clay particles under an external load. However, the relative movement between the clay particles is delayed by the bonds of water molecules existing in adsorbed water layer, and can gradually cause the change in the orientation of soil particles.

Kuhn and Mitchell (1993) proposed a new concept for creep compression which is due to a sliding movement between the particles. This concept is similar to the mechanism of the deformation of interparticle bonds as discussed in Sect. 3.1. All types of soils including wet and dry materials appear to have interparticle bonds between solid–solid contacts, at which the resistance to shearing deformation exists when the soil is subject to an application of pressure. This proposed mechanism was expected to describe soil creep generally under the effects of shear stress and temperature. As a result of the nature of viscous friction, the sliding movement is caused by the tangential component of the contact forces between soil particles, f_t . The deformation is proposed by the relationship between the sliding velocity (\dot{s}), the sliding force and the friction ratio between the tangential force and the normal force (f_t/f_n). The mechanism is derived by the principle of rate process theory of Mitchell et al. (1968) as discussed in Sect.

3.2, and is simulated by a discrete element numerical model of more than 1,000 circular disks. The mechanisms of normal force and tangential force at the contact of two individual particles are shown in Fig. 5. The creep deformation is described by a system including a linear string which is represented for the normal force in Fig. 5a and a combination of linear string and a dashpot in series which is represented for the tangential force illustrated by the dashpot in Fig. 5b. As the model displays similarity to the creep behaviour of soils, it is suggested that the sliding mechanism can be applied for all soils. As reported by Kuhn and Mitchell (1993), the sliding velocity can be calculated as follows:

$$\dot{s} = \lambda v' = \lambda \frac{2kT}{h} \exp\left(\frac{-\Delta F}{RT}\right) \sinh\left(\frac{1}{2kT} \frac{\lambda f_t}{n_1 f_n}\right) \quad (3)$$

where λ is the distance between neighbouring equilibrium positions, suggested to have the order of 2.8×10^{-10} m (2.8 Å), T is the absolute temperature, k is Boltzmann's constant of 1.38×10^{-16} erg/K, h is Planck's constant of 6.626×10^{-27} erg/s, R is the universal gas constant (8.31 J/(mol K)), n_1 is the number of bonds per unit of normal contact force, and ΔF is free energy of activation in range of 84–190 kJ/mol. ΔF represents the bonding strength, as ΔF is the total energy required to break down all the energy barriers to allow the displacement of the flow units to a new position without applied potentials.

3.4 Creep Due to Water Flows in a Double Pore System (The Double Porosity)

Creep, on the other hand, is suggested to result from the transfer of pore water from micropores to macropores. This mechanism is explained based on the assumption of double levels of soil structure, microstructure and macrostructure, which was originally proposed by Dejong and Verruijt (1965) and pursued by many researchers including Berry and Poskitt (1972), Zeevaart (1986), Navarro and Alonso (2001), Mitchell and Soga (2005) and Wang and Xu (2006). As described in Sect. 2, single particles consist of stacked layers of structural sheets of clay minerals. The microstructure unit of clay consists of several single particles packed together by interparticle forces and bonds. The arrangement of single particles in a microstructure unit produces amount of pores which is

called micropores. The microstructure units are also known by terms as flocs, clusters or peds. The macrostructure of clay is formed by the aggregation of several microstructure units, and the pores between microstructure units are called macropores (Yong et al. 2010).

Meanwhile, Zeevaart (1986) described two structures differently. The primary structure consists of a continuous skeleton formed by coarse grains and large pores of gravitational water, while the secondary structure is formed by clay clusters aggregated around the primary structures. Micropores are the pores existing within clay clusters, and water inside micropores which is formed by double layer water has different viscosity from water in pores within the primary structure. Figure 6 shows the illustration of two structures of Zeevaart (1986).

Under the application of pressure, water inside the micropores of the clay clusters will be expelled out of the clay clusters moving to the larger pore (or macropores). The water flow may cause the deformation inside the clay clusters such as the reduction in spacing between clay minerals or the relative movement between the particles inside the clusters. Creep compression is explained as the reduction in micropore water and the relative reduction in pores in the microstructure. Navarro and Alonso (2001) explained the transfer of water from micropores to macropores induced by the difference of chemical potentials of water between microstructural and macrostructural water which causes the mass transfer in order to reach the equilibrium state. According to the quantitative analysis of exchangeable cations in pore fluid, Akagi (1994) concluded that the mechanism of the consolidation is based on the drainage of pore fluids and the deformation of pores. The primary consolidation is due to the drainage of pore fluid in the macropores between the grains of clay particles (called “peds”), and creep (or “secondary consolidation” adopted by Akagi 1994) is the result of the delayed deformation of micropores within the clay particles induced by the viscous flow of pore fluid existing in the micropores. The definition of peds and pores is provided in Table 2. Moreover, according to Akagi (1994), the compression of soft clay during the constant rate of strain loading is explained as the deformation of macropores between macropeds.

Fig. 6 Schematic concept of clay structure (modified after Zeevaert 1986)

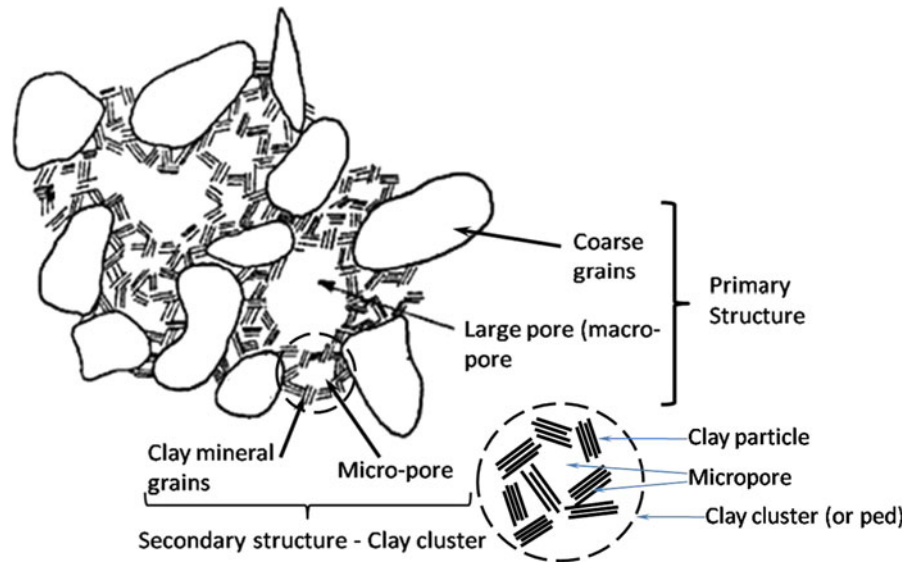


Table 2 Types of peds and pores (after Matsuo and Kamon 1977)

Type of ped	Type of pore	Recognition
Macroped (> 50 μm)	Macropore (>10 μm)	By naked eye and spy glass
Mesoped (2–50 μm)	Mesopore (1–10 μm)	By optical microscope
Microped (0.1–2 μm)	Micropore (0.01–1 μm)	By scanning electron micropore
Submicroped (<0.1 μm)	Submicropore (<100Å)	By transmission electron microscope

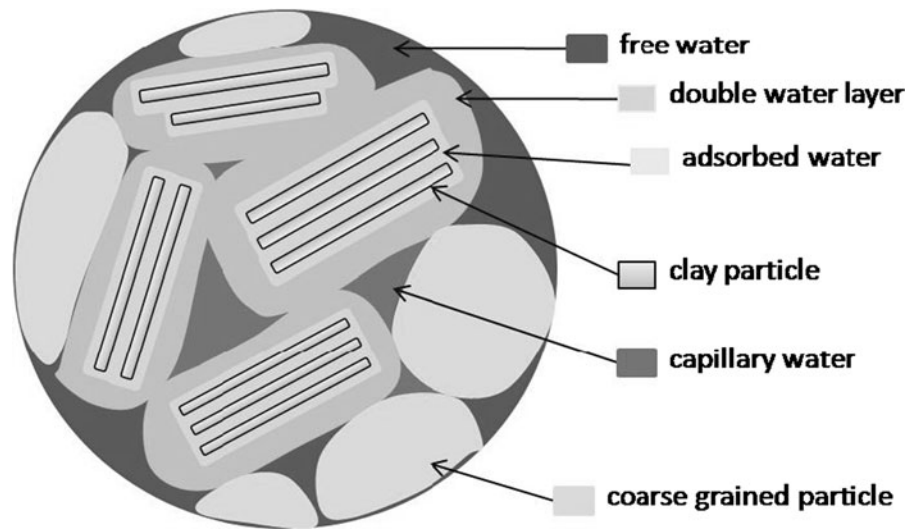
3.5 Creep Due to the Structural Viscosity

In general, viscosity is defined as the resistance of fluid to flow or deform under the applied stress. Fredlund and Rahardjo (1993) defined viscosity as the frictional drag of one plate of fluid sliding over another platelet. Taylor (1942) believed there was plastic structural resistance to compression within clay structure due to double layer surrounding the surface of clay particles, which was termed as structural viscosity. Structural viscosity has significant impact on soil creep. This theory is supported by Terzaghi (1941), Barden (1969), Bjerrum (1967), Garlanger (1972), Christie and Tonks (1985), Graham and Yin (2001) among others. According to several research on clay mineralogy, the viscosity is imposed by the absorbed water layer around particles, and may induce the plastic

resistance against the relative movement between the clay particles. As mentioned in the previous section, the absorbed water layer contains different cations and anions, which makes the water layer exhibit electro-chemical properties far different from the normal water or free flowing water (Grim 1968, Sridharan 2001, Reeves et al. 2006). According to Guven (1993), water system absorbed within microstructure of clay is formed by three types which are (1) the water adsorbed on the internal surfaces of clay mineral, (2) the water layer held between clay minerals (double layer water), and (3) the capillary water held in pores between the clay particles. Figure 7 shows a schematic view of soil water system. Creep compression may be a result of the deformation of clay clusters or microstructure units due to the flow of viscous water. Based on the observation of Winkerkorn (1943), the water layer which is held directly on the clay mineral surfaces can be considered as in a solid state, and the state of the water will be changed with respect to the distance from the clay mineral surface. Moreover, Grim (1968) concluded that the viscosity of double layer water increases with the proximity to the clay surfaces, and the viscosity of double layer water should be higher than that of free water.

Terzaghi (1941) also considered that the viscosity of adsorbed water causes the decrease in speed of the rearrangement of soil structure. Bjerrum (1967) divided the consolidation process of soils into instant and delayed compression instead of primary and

Fig. 7 A schematic view of clay–water system



secondary compression, because he believed it is not possible to separate these two processes. An instant compression occurs simultaneously with the increase of the effective stress, and causes the reduction in void ratio until to reach the new equilibrium state to support the overburden pressure. Besides, delayed compression is the volume change under constant effective stress. According to Bjerrum (1967), delayed compression causes the reduction in water content, resulting in the rearrangement of soil structure which is more stable to resist against the further compression due to the increase in the number of contacts between clay particles. Moreover, the viscosity of pore water was considered as the factor causing the delay in the pore water pressure dissipation. Garlanger (1972), Yin and Graham (1989) are the followers of this concept.

Leonards and Girault (1961) investigated the effect of pore fluid on secondary compression (creep) by comparing compression of the soil with pore fluid of water and carbon tetrachloride (CCl_4). They found that the electrochemical distribution near clay particles due to the orientation of polar molecules within double layer cannot be seen as the influencing factor in any mechanism causing creep deformation. However, the effect of the physico-chemical property of pore fluid was observed to be significant on the rate of secondary compression. Figure 8 shows the reduction in compressibility of the soil with different pore fluids. Although the result shows clearly that different void ratios at the same effective stress for two different pore fluids in the range of normal consolidation, Leonards

and Girault (1961) had no explanation for the reduction, but emphasised that the difference of the preconsolidation pressure between the two curves may be due to the change in interparticle forces resulting from the secondary compressions.

A number of researchers believed that the secondary compression of soils depends on the electrochemical nature of clay minerals. Sridharan and Rao (1973,

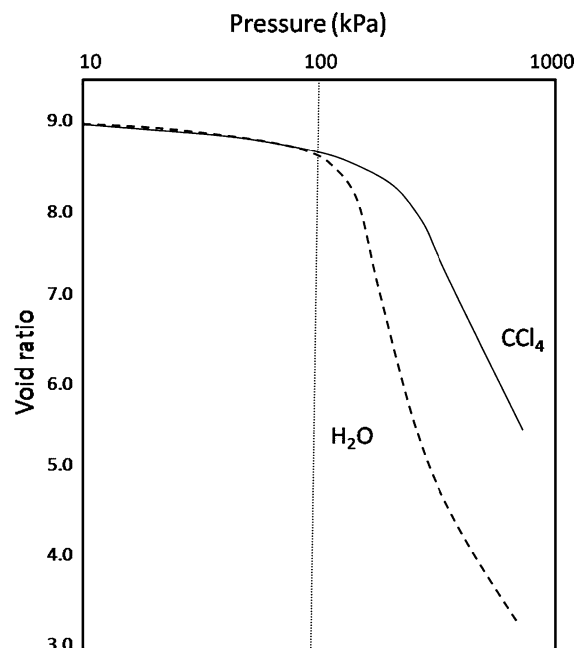


Fig. 8 Effect of pore fluid on compressibility in undisturbed Mexico City Clay (after Leonards and Girault 1961)

1979) concluded that electrical attraction and repulsion forces in the soil structure affect the strength of clay particles, which controls creep compression, while viscosity of pore fluid was suggested to affect only the coefficient of secondary compression. They proposed a modified effective stress in order to account for the contact stress existing in the clay particle level. Equation 4 also includes the effect of pore air pressure in estimating the modified effective stress.

$$\sigma'_c = \sigma' a_m = \sigma - u_w - u_a - R + A \quad (4)$$

where, σ'_c is the effective contact stress as a modified effective stress, σ' is the mineral to mineral contact stress, a_m is the ratio of mineral to mineral contact area to the interparticle area, which is the contact area between clay particles, σ is the externally applied stress, u_w is the effective pore water pressure, u_a is the effective pore air pressure, R is the ratio of total electrical interparticle repulsion force to total interparticle area, and A is the ratio of total electrical interparticle attraction force to total interparticle area.

As a result of the experimental tests, Sridharan and Rao (1979) supported the conclusion of Leonards and Girault (1961) that the viscosity of pore fluid has insignificant effect on the secondary compression while the dielectric of pore fluid has notable impacts on the variation of attractive forces and repulsive forces, hence the effective stress and shear strength of the soil. According to Yin (2002), creep mainly results from the combination of two processes including (a) viscous flow of adsorbed water in double layers on clay particles and (b) viscous adjustment of clay structure (plate structure) to reach a new equilibrium to balance with the external effective stresses. Therefore, creep occurs as long as the effective stress exists in the soil, and creep is not related to free pore water whose flow is controlled by the hydraulic gradient.

Feda (1992) explained that as temperature increases, the interparticle bonds between soil particles weaken, causing the increase of deformations within the soil skeleton. Temperature variations can also affect the viscosity of adsorbed water. According to Grim (1968), micropore water and adsorbed water can be completely removed by heating just above room temperature. Temperatures in excess of 100°C can completely remove interlayer water in montmorillonite minerals. By heating over 400°C, the clay

mineral structure can be altered or destroyed. Graham et al. (2001) carried out drained isotropic compression tests on reconstituted illite at 28°C, 65°C and 100°C, and suggested that temperature changes may cause the irreversible volume changes in soils. However, the response of volume changes induced by temperature variations is very much dependent on the soil type.

4 Discussion

The nature of creep compression is still a challenging topic to study even though it has been investigated for many decades. A general definition of creep deformation of soils is accepted to be the deformation or settlement of soils under a constant effective stress. Therefore, there are many proposed theories to elucidate the mechanisms of creep. In the previous sections, five proposed mechanisms by different researchers are critically reviewed as summarised in Table 3. They are (a) the breakdown of interparticle bonds in the soil structure, (b) sliding between particles, (c) water flows in two systems (theory of double porosity), (d) deformation due to the structural viscosity, and (e) deformation due to the jumping of molecule bonds (theory of rate process). Various mechanisms exhibit some similarities. For instance, the creep mechanisms explained by the double pore structures and the structural viscosity focus on the clay mineralogy, and the influencing factors are adsorbed water system, the viscosity and the physico-chemical properties of the clay water system. The combination of these two mechanisms can provide a more comprehensive explanation of creep in microscopic scale. The jumping of molecule bonds can be used to explain the viscous flow of micropore water within the microstructure of soils because double layer water and adsorbed water layer contain complex electro-chemical properties controlled by different types of bonds and forces such as primary valence bonds, van der Waals forces and hydrogen bonds.

Therefore, in spite of the variety of reasons for creep, the mechanism of creep compression can be a combination of various processes, and can be categorised into macroscopic and microscopic aspects. In the macroscopic view, creep deformation is a result of the soil structural rearrangement or adjustment to reach a new equilibrium under an applied stress. The deformation can be induced by the breakdown of the bonds

Table 3 Main creep mechanisms

Mechanism	Main factors/focus	Introduced or supported by
Breakdown of interparticle bonds	Relative movement of particles, soil structure rearrangement	Taylor and Merchant (1940), Terzaghi (1941), and accepted by Gibson and Lo (1961), Mesri (1973, 2003), Mesri and Godlewski (1977), and Crooks et al. (1984)
Jumping of molecule bonds	Activate energy, temperature and deviatoric stress	Murayama and Shibata (1961), Christensen and Wu (1964) and Mitchell (1964), Kwok and Bolton (2010)
Sliding particles	Activate energy, contact forces	Grim (1962), Gupta (1964), Kuhn and Mitchell (1993)
Water flows with two drainage structure (Macro–micro structures)	Two levels of soil structures, water flows in two pore structures and deformation of pores	De Jong and Verruijt (1965), Berry and Poskitt (1972), Zeevaart (1986), Navarro and Alonso (2001), Mitchell and Soga (2005) and Wang and Xu (2006)
Structural viscosity	Different viscosity of absorbed water system, clay mineral–water interaction	Terzaghi (1941), Barden (1969), Bjerrum (1967), Garlanger (1972), Christie and Tonks (1985), Graham and Yin (2001)

between the soil particles and/or the relative movement of particles. In the microscopic level, creep deformation is explained as the deformation of microstructure (clay minerals and absorbed water layer) due to the drainage of pore fluid in micropores, or due to the structural viscosity of pore fluids. In the microscopic level, the interparticle forces between clay particles and the electro-chemical properties of double layer water are the important factors influencing the deformation. The authors believe that the combination of these two structure levels (i.e. macroscopic and microscopic) can be adopted to explain the nature of soil creep, particularly for clay soils. However, in practice or the field scale, the composition of the natural soil is complex and inherently heterogeneous. Therefore, it may be unreliable to explain the behaviour of soils established by the numerical expressions, which are developed based on the micro-elements with assumption of homogenous materials.

Moreover, the authors believe that the volume of solid in a soil element can have a minimum value if there is no void existing within that soil element. According to Mitchell (1956), for a particular soil, void ratio can reach to a minimum value regardless of the pressure or initial orientation. However, because of the irregular shapes of soil particles, the relatively minute gaps still exist between particles, so that the minimum void ratio cannot be zero. That also means the soil structure cannot deform infinitely. Based on observation of compression of soils, the relationship between the compressions with logarithmic of time was seen to vary not linearly (Bjerrum 1967; Leroueil

et al. 1985). Yin (1999) also believed that there exists a finite creep limit strain which is stress dependent. Thus, there is a finite final strain, meaning that the compression of the soils under a particular applied pressure must cease after a finite period that can be counted in years or decades. The deformation may cease when there is no void and fluid inside the clay particles, or under the final effective stress that the ultimate equilibrium inside the soil structure is reached. The equilibrium state under low level applied stresses may be reached, while pore water is available in the soil. The higher the applied pressures, the lesser water content at the equilibrium state. Under higher stresses, the equilibrium state may be attained, while more double layer water is squeezed out of the soil. The innermost adsorbed water layer, held strongly to the clay mineral surfaces, cannot be removed under the normal ambient temperature and loading conditions, and this layer of water may be treated as solid phase (Grim 1962; Navarro and Alonso 2001). It can be noted that the assumptive upper bound creep strain limit corresponding to the zero void ratio (zero water content) has been considered by a few researchers (e.g. Yin et al. 2002) for simplicity. Figure 9 illustrates a schematic clay water system in two stages (a) free water flows through the voids between soil particles during the compression process, and (b) a system after free water squeezed out completely. As mentioned the creep process may cease after some times; thus, the final soil element when creep ceases, could be similar to the schematic view shown in Fig. 9b. Therefore, it is assumed that when creep deformation reaches its limit, the soil system would involve (1) *no void allowing*

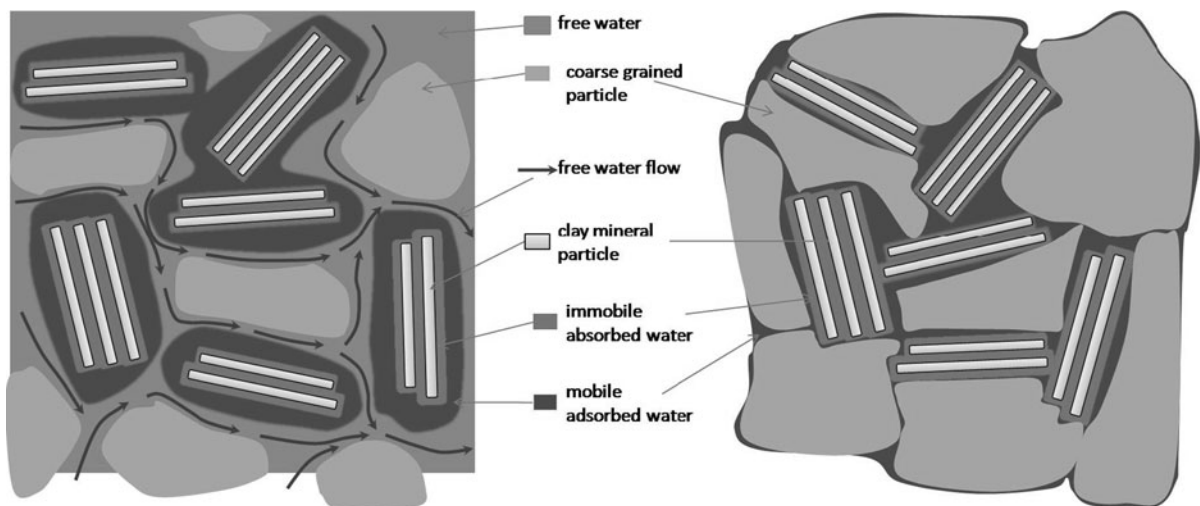


Fig. 9 Schematic clay–water system in **a** free water flows through the pore system from the beginning of the whole compression process, **b** after free water flowed out of the pores

water flow (2) no free water within the soil, and (3) solid particles rearranged and formed a close packed system.

Creep settlement in soft soils remains a notable and challenging issue for geotechnical engineers. In order to improve the ground for future development, various ground improvement techniques such as preloading with vertical drains, vacuum assisted preloading, and deep soil mixing have been applied to consolidate the ground, improve the soil bearing capacity and thus, reduce the risk associated with the long term behaviour of the soft deposit. The combination of vacuum and wick drains applied in the Port Brisbane Expansion project (Ameratunga et al. 2010), vacuum and surcharge preloading in combination with prefabricated vertical drains at Ballina Bypass project (Indraratna 2010), deep soil mixing method considered for Coode Island Silt (Bouazza et al. 2004) are some examples. Reduction in the creep settlement after the ground improvement can be still explained using the above mentioned mechanisms. For instance, preloading method in conjunction with vertical drains, which is one of the most popular techniques applied effectively to improve soft soils, aims to accelerate the consolidation process by excessive applied stress and horizontal and vertical drainages. Water flow through voids inside the soil speeds up by horizontal and vertical drainage paths. In addition, the applied pressure induced by preloading can cause water flow by hydraulic gradient, and later cause the reduction in

voids or pores within soil skeleton. Thus, the soil becomes more compressed, and improved. Therefore, when the preload exceeds the design load, the secondary compression is greatly reduced and consequently the post construction settlement can be minimised (Wong 2006).

5 Summary

The time dependent behaviour of fine grained soils remains a challenging topic for many researchers and engineers even though there have been significant amount of studies carried out to investigate this matter. By and large, creep deformation is considered as the destruction or adjustment of soil structure under the effect of a constant effective stress. Moreover, clay mineralogy plays a significant role as clayey soils have unique electrochemical properties. Based on the existing literature, the mechanisms of creep deformation are explained by different theories such as (1) the breakdown of interparticle bonds, (2) the jumping of bonds of molecule structures, (3) the sliding between particles, (4) water drainage from micropores to macropores, and (5) the structural viscosity. All of these mechanisms have incorporated the role of clay mineralogy more or less. Therefore, the explanation of the mechanism of creep settlement based on the clay mineralogy as well as the deformation of both macro and microstructures of soils can be relevant to employ

for settlement prediction. In the macroscopic view, creep deformation is a result of the soil structural rearrangement or adjustment to reach a new equilibrium under an applied stress. In the microscopic level, creep deformation is explained as the deformation of microstructure (clay minerals and absorbed water layer) due to the drainage of pore fluid in micropores, or due to the structural viscosity of pore fluids. It is also suggested that the creep deformation could cease after a period of time when the whole soil system contains no free flowing water. At this time, the innermost absorbed water layer which is held strongly to the clay mineral surfaces is treated as solid phase.

This paper has provided a comprehensive summary about the mechanisms of soil creep. If the nature of creep can be understood better, a more reliable analysis of soft soil behaviour can be presented. Although further research is required to investigate the relative importance of each creep mechanism contributing to the overall deformation of the soil, this study gives a good insight to researchers and engineers trying to develop analytical or numerical models accounting for soil creep.

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