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Numerical Study of Creep Effects on Settlements and Load Transfer Mechanisms of Soft Soil Improved by Deep Cement Mixed Soil Columns under Embankment Load

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Abstract

Deep cement mixed (DCM) soil columns have been widely utilized to improve soft soil and to form a composite ground to support embankments or seawalls. However, the influence of the time-dependent behavior, such as creep, of the soft soil on the performance of DCM column-supported embankments is not well understood, not yet considered in existing design methods. In this study, the finite element (FE) model was established to investigate the creep effects on settlements and load transfer mechanisms of the soft soil improved by DCM columns under embankment load. Comparisons were conducted for the cases of the soft soil with or without creep. It is found that there is a further unloading process in the stress state of the soft soil caused by the creep. Therefore, stress concentration ratio for the soft soil with creep is higher than that for the soft soil without creep. At the same time, the DCM column is capable to reduce the creep strain rate of the soft soil, thereby it improves the creep behavior of the soft soil. The parametric analysis demonstrated that the area replacement ratio and Young's modulus of the DCM column can largely influence the long-term behaviors of the DCM column-improved composite ground. For the larger value of area replacement ratio (>30%), the influence of the creep effect of the soft soil on loading transfer can be significantly reduced. The numerical results were also compared with the results calculated by German design method (EBGEO) and British design method (BS 8006). Regarding the vertical stress taken by the DCM column, EBGEO method provides a lower limit while BS 8006 method provides an upper limit.

Keywords: Column-supported embankment, deep cement mixed soil column, soft soil, creep, settlements, load transfer

Nomenclature

ARR	Area replacement ratio (%)
a	Equivalent size of the column (m)

c'	Effective cohesion (kPa)
EOP	End of primary consolidation
FE	Finite element
D	Thickness of soft soil (m)
DCM	Deep cement mixed
E'_{50}	Young's modulus (MPa)
H	Embankment height (m)
HKMD	Hong Kong marine deposits
h_g	Arching height (m)
J	Tensile stiffness (kN/m)
k_{column}	Coefficient of permeability of DCM column (m/day)
k_{soil}	Coefficient of permeability of soft soil (m/day)
L	Length of the DCM column (m)
m_v	Coefficient of volume compressibility
n	Stress concentration ratio
p	Loading on the top of the embankment (kN/m^2)
q_{peak}	Peak deviator stress (kPa)
s	Column spacing (m)
S	Settlement (m)

t_e	Equivalent time
ε	Strain
γ	Unit weight (kN/m^3)
κ^*	Modified swelling index
λ^*	Modified compression index
λ_1	Dimensionless parameter
λ_2	Dimensionless parameter
μ^*	Modified creep index
ν	Poisson's ratio
σ_z	Vertical stress (kPa)
σ'_z	Effective vertical stress (kPa)
φ'	Effective friction angle ($^\circ$)
χ	Dimensionless parameter

1. Introduction

In coastal areas, embankments for supporting transportation infrastructures are inevitable to be constructed over soft soils, marine clay in most cases. In order to solve the issues of excessive total and differential settlements or even failure of embankments owing to the high compressibility and low bearing capacity of the underlying soft soil ground, appropriate ground improvement techniques are required (Han and Wayne, 2000; Yapage and Liyanpathirana, 2018). Among various techniques, the combination of pile support and geosynthetic reinforcement becomes one of the most suitable techniques for solving the abovementioned issue because of its economy and effectiveness. Therefore, the geosynthetic-reinforced pile-supported embankments have been widely utilized and studied by numerous engineers and researchers (Han and Arkins, 2002; Han and Gabr, 2002; Gangakhedkar, 2004; Liu *et al*., 2007; Rowe and Taechakumthorn, 2011; Lai *et al*., 2014).

Recently, the long-term performance of the geosynthetic-reinforced column-supported embankments has been paid attention. Yapage *et al*. (2013) simulated column-supported embankments considering the strain-softening behavior of DCM columns. The long-term viscous behavior of geosynthetic reinforcements was investigated by Liu and Rowe (2015). Although, the consolidation of subsoils was considered for simulating the long-term performance of DCM column-supported embankments (Huang and Han, 2010). The time-dependent stress-strain behavior, such as creep, of soft soils, was neglected when studying the effect of DCM columns on controlling settlements. The post-construction settlements owing to creep might influence the load transfer and consolidation behavior of the composite ground treated by DCM columns under embankment load. This influence was not well studied and properly considered in the current researches and design methods. On the other hand, Sexton *et al*. (2017) found that the creep behavior of soft soils can be reduced by installing stone columns. The stone columns might be unsuitable for improving very soft marine clays since no enough confined pressure can be provided by those kinds of soils (Sexton *et al*., 2017). DCM columns normally function similarly to the stone columns in the soil improvement, so the creep behavior of soft soils should also be influenced by installing DCM columns. However, there are very limited studies on the effects of DCM columns on controlling settlement, reducing creep behavior of soft soils, and transferring load.

Nowadays, the third runway of Hong Kong International Airport (HKIA) is under construction over an area of contaminated soft marine clay. In order to control settlements and minimize the side-effects on the marine environment, DCM technique has been designed to improve the marine clay (Airport Authority Hong Kong, 2012). In load transfer platform (LTP) areas, the typical columns are 2.3 m in diameter and 4.8 m in spacing, corresponding to an area replacement ratio of 23%. Outside the LTP area, DCM columns form walls with different area replacement ratios in a range from 30% to 40%. The length of the DCM columns is normally from 6 m to 25 m depending on the profile of marine soil. Relying on this background of the DCM technique application, a finite element (FE) modelling is carried out for a DCM column-treated soft soil ground under embankment load. The objective of this study is to compare the responses of the composite ground (the soft ground improved by DCM column)considering creep and those ignoring creep, instead of simulating and assessing the real project of the airport runway in Hong Kong. Furthermore, this study also aims to investigate the influence of different design parameters of DCM columns on controlling settlements and transferring load with considering creep of the soft soil, which will provide a valuable reference in the design of column- or pile-supported embankment.

2. Description of finite element model and design methods

2.1 Finite element model

In this study, PLAXIS 2D (2015 version) was adopted to simulate a geosynthetic-reinforced embankment over a soft ground improved by a DCM column under axisymmetric condition. The embankment is 3 m in height and 10 m thick soft soil is under the embankment load, as shown in Figure 1. The soft soil involved in this study is the Hong Kong marine deposits (HKMD), which is regarded as weak soils for reclamation projects owing to its low shear strength, high compressibility, and obvious time-dependent behavior (Yin and Zhu, 1999). The embankment is supported by an end-bearing DCM column with a diameter of 2.3 m. The area replacement ratio of the composite ground of the DCM column-improved soft soil is 23%. Ground water table was set on the surface of the composite ground. The distance between the geosynthetic reinforcement layer and the bottom of the embankment is 0.3 m. The construction period was set as 30 days corresponding to a construction rate of 0.1 m/day in this study.

The finite element model was meshed into 480 15-noded elements with the relative element size of 0.5. The soft soil was simulated by Soft Soil Creep model. Both the fill materials of the embankment and the DCM column were simulated by Mohr-Coulomb model (Huang and Han, 2009; Voottipruex et al., 2011; Mun et al., 2012; Horpibulsuk et al., 2012; Jiang et al., 2014; Jamsawang et al., 2015a, b and 2016; Yapage and Liyanapathirana, 2018). The geosynthetic reinforcement was modeled by geogrid elements. Details of the models can be referred to Brinkgreve *et al.* (2015).

2.2 Selection of parameters

The main parameters of the Soft Soil Creep model are the modified compression index λ^*, modified swelling index κ^*, and modified creep index μ^*. The values of those indices, which are consistent with those of Feng and Yin (2017) used in their FE modelling, were chosen in this study. According to Sexton *et al*. (2017), numerical difficulties occur in PLAXIS, when using $\mu^* = 0$ to analyze the case of soft soil without creep. Therefore, a very low value of μ^* was used (1% of the value of μ^* used in the case of soil with creep). Figure 2 shows that this method can minimize the creep contribution very well.

Yin and Lai (1998) and Yin (2001) investigated the stress-strain-strength behavior of cement-treated HKMD with different water contents and cement contents by conducting a series of unconfined compression (UC) tests and consolidated undrained (CU) triaxial tests. For the case of cement-treated HKMD with 20% in cement/soil ratio and 100% in initial water content, the effective cohesion of the cement-treated soil is 87 kPa and the effective friction angle is 46°. These parameters were assigned to the DCM column in this numerical simulation. And the peak deviator stress q_{peak} of cement-treated soil under the abovementioned dosage is 455 kPa. The fitting result from Yin (2001) showed that the average Young's modulus E'_{50} equals 89 times the peak deviator stress q_{peak}. Therefore, the Young's modulus of the DCM columns of 40.50 MPa was used in this study.

Yin and Fang (2006) observed a rapid consolidation of a composite ground improved by a DCM column and regarded that the DCM column has a similar function of a vertical drain.

Chai *et al*. (2006) and Horpibulsuk *et al*. (2012) had a different view that the consolidation was accelerated because of the higher coefficient of consolidation caused by high stiffness of DCM column instead of the permeability. Regarding the permeability of cement treated-soils, some scholars, such as Chew *et al*. (2004) found that it can be higher than the untreated soil, while the converse results were also reported by Kitazume and Terashi (2013). In this study, the permeability of the DCM columns was assumed to equal the permeability of the surrounding soil.

High strength PET geogrids are selected as the geosynthetic reinforcements and simulated by geogrids elements with a stiffness of 5000 kN/m in this study. The interfacial friction between the geosynthetic and surround filling material was simulated by creating interface elements, as the red lines attached to the geosynthetic shown in Figure 1. van Santvoort (1995) suggested that a reduction factor, whose value may vary from 0.7 to 0.9 for different types of reinforcement, can be utilized to consider the interfacial friction angle between the filling material and geosynthetic. Following the assumption of Yapage and Liyanapathirana (2018) and Abusharar *et al*. (2009), the reduction factor was selected as 0.8 in this study. The values of the parameters in FE simulations are listed in Table 1.

2.3 Design methods

Embankments are normally supported by prefabricated concrete piles or soil columns (Ariyarathe and Liyanapathirana, 2015). Among different types of pile- or column-supported embankments, load transfer is a crucial and common concern. It is usually related to soil arching phenomenon, which was first studied by a famous trap door experiment conducted by Terzaghi (1943). Subsequently, plenty of experimental and numerical studies were carried out to deeply understand the soil arching and the load transfer mechanism in pile- or column-supported embankments without and with geosynthetic reinforcements (Low *et al*., 1994; Deb and Basudbar, 2007; Chen *et al*., 2008; van Eekelen *et al*., 2012a, 2012b, 2013; Wu *et al*., 2019; Zhao *et al*., 2019). Many design methods, *e.g.* EBGEO (Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements) method and BS 8006 (British standard) method, were proposed to consider load transfer in embankments and to calculate tensile strains in geosynthetic reinforcements (Guido *et al*., 1987; Abusharar *et* al., 2009; EBGEO, 2010; BS 8006, 2010). However, those design methods normally neglected the time-dependent stress-strain behavior of subsoils. It is widely accepted that behavior of soft soils is time-dependent (Gragam *et al*., 1983; Augustesen *et al*., 2004; Yin *et al*., 2011). And the time-dependent behavior could also affect the load transfer mechanism thereby influence the overall performance of pile- or column-supported embankments.

In this study, the simulation results are compared with the results calculated by BS 8006 and EBGEO (2010).

In BS 8006, the support of the subsoil is ignored so that all the embankment loading is taken by columns and reinforcements. The vertical stress on columns (or piles) can be calculated by Marston's formula (Marston and Anderson, 1913) or Hewlett and Randolph's method (Hewlett and Randolph, 1988). In this study, Hewlett and Randolph method is used to calculate the vertical stress on the DCM column. The critical location where the arcing fails is assumed to occur on the top of the column (or pile cap), expressed as:

$$\sigma'_{z,column} = \frac{\gamma H s^2 \beta}{a^2 (1+\beta)} \tag{1}$$

$$\beta = \frac{2K_p}{(K_p+1)(1+a/s)}\left[(1-a/s)^{-K_p} - (1+K_p a/s)\right] \quad (2)$$

where $K_p = \frac{1+\sin(\varphi')}{1-\sin(\varphi')}$, s is the column spacing, γ is unit weight of the embankment fill, H is the height of the embankment, a is the equivalent size of the column, φ' is the friction angle of the embankment fill.

In EBGEO (2010), the subsoil support is considered. The vertical stress acting on the soft soil is calculated as

$$\sigma'_{z,soil} = \lambda_1^{\chi}(\gamma + p/h)\left\{h(\lambda_1 + h_g^2\lambda_2)^{-\chi} + h_g\left[(\lambda_1 + h_g^2\lambda_2/4)^{-\chi} - (\lambda_1 + h_g^2\lambda_2)^{-\chi}\right]\right\} \quad (3)$$

where $h_g = s/2$ for $H \geq s/2$; and $h_g = H$ for $H < s/2$; $\chi = \frac{a(K_{crit}-1)}{\lambda_2 s}$; $K_{crit} = \tan^2(45° + \frac{\varphi'}{2})$; $\lambda_1 = \frac{(s-a)^2}{8}$; $\lambda_2 = \frac{s^2 + 2a(s-a)^2}{8}$; p is the loading on the top of the embankment which is zero in this study. The vertical stress taken by the column is calculated as

$$\sigma'_{z,column} = [(\gamma H + p) - \sigma'_{z,soil}]\frac{A_E}{A_P} + \sigma'_{z,soil} \quad (4)$$

where A_E is the unit cell area, A_P is the cross-sectional area of the column.

3. Finite element results analysis

The results of the FE simulation focus on different responses of settlements and load transfer in the composite ground with and without creep.

3.1 Creep effects on settlements

The maximum settlements of the soft soil with and without creep are plotted in Figure 2. As expected, the maximum settlement of the composite ground with creep is larger than that without creep. Casagrande's method (1936) (termed as the logarithm of time fitting method in BS 1377) is used to determine the time of end of primary (*EOP*) consolidation. This method was also adopted by Sexton (2014). For the case of soft soil without creep, primary consolidation takes approximately 500 days. While primary consolidation takes approximately 800 days when considering creep. However, it should be noted that the *EOP* is utilized to reflect the consolidation rate of the soft soil instead of determining when creep happens in this study.

In order to examine the effect of the DCM column on controlling settlements, the settlements of the untreated soft soil are also plotted in Figure 2. For both cases of soft soil with and without creep, the maximum settlements are reduced significantly when the DCM column is involved in. The consolidation process of the soft soil can be significantly accelerated by DCM column. The difference between the maximum settlement with creep and that without creep in the DCM column-treated case is less than the difference between the maximum settlements with and without considering creep in the untreated case. This reveals that creep behavior of the soft soil can be reduced by the DCM column.

Figure 3 illustrates the relationship between ε and $\log(\sigma_z')$ of point *a* at different situations. Adopting the concept of "equivalent time" proposed by Yin and Graham (1989), the untreated soft soil creeps to point 1, corresponding to the equivalent time t_{e1}. For the DCM column-treated soft soil, the combination of creep and unloading process makes the state of clay reach point 2, corresponding to the equivalent time t_{e2}. Since t_{e2} is larger than t_{e1}, smaller creep strain rate of the clay treated by DCM column resulting in a reduction in creep behavior of the soft soil.

3.2 Creep effects on lateral deformations of DCM column

The lateral deformations of the DCM column with and without considering the creep effect of the surrounding soil are plotted in Figure 4. The location of the observed lateral deformations of the columns are laid on and along the interface between the column and surrounding soil (x= 1.15 m, z= 0.2m ~9.6 m).

For both cases with and without considering creep of the surrounding soil, the largest lateral deformation appears at the top of the DCM column. Near the top part of the column (say z <1 m), the lateral deformation decreases with depth. As the depth goes deeper, the lateral deformation decreases after a slight increase (see 1 m <z< 2 m). When considering the creep of the surrounding soil, there is more lateral deformation of the column compared with the case ignoring the creep of the surrounding soil.

3.3 Creep effects on load transfer

The effect of the DCM column on controlling settlements can be interpreted by load transfer mechanism. Due to the difference in stiffness between the column and the surrounding soft soil, the majority of applied load concentrates on the DCM column resulting in a nonuniform stress distribution over the DCM column and the surrounding clay. With the development of the differential settlements between the column and the surrounding clay, shear stress is mobilized in the embankment to contribute transferring load. With respect to the clay, this process is similar to unloading (Madhav *et* al., 2010). Owing to the unloading, the soft soil tends to be over-consolidated. When considering creep of the soft soil surrounding the DCM column, a further load transfer owing to the creep settlements reduces the load taken by the soft soil resulting in a further unloading, as illustrated in Figure 3.

The vertical stresses over the DCM column and surrounding soft soil are shown in the distribution profile in Figure 5. During construction of the embankment (within 30 days), there is no difference between the stress distribution with creep and that without creep. For both cases with and without creep, the maximum vertical stress appears on the edge of the DCM column. As the surrounding soft soil consolidates, the vertical stresses taken by the surrounding soft soil decrease and the vertical stresses taken by the DCM column increase correspondingly. When considering creep, the vertical stress on the DCM column increases significantly at $t_{Long-term}$, and the maximum vertical stress tends to move toward the center of the column. The creep influences on transferring process of the vertical stress can be found in Figure 5.

Stress concentration ratio (*n*), which is calculated as the ratio of the average vertical stress taken by the DCM column to the average vertical stress taken by the surrounding soft soil, is an important factor which has been generally accepted to reflect the load transfer mechanism (Han and Gabr, 2002; Liu *et al*., 2007; Chen *et al*., 2008; Abusharar *et al*., 2009). Figure 6 shows the values of *n* with and without creep of the soft soil on the location of $z = 0$. If the creep behavior of the soft soil is ignored, then no more apparent differential settlement occurs between the DCM column and surrounding soft soil after primary consolidation. Hence, no more load is transferred from the soft soil to the column due to which the value of *n* is limited to approximately 10.5 in this study. In contrast, the creep settlement of the soft soil would induce a further load transfer from the soft soil toward the column. Theoretically, if the vertical stress is not large enough to yield the column, the value of *n* will keep increasing.

Figure 7 shows the stress paths of different points in the soft soil at different depths. The locations of point *a*, *b*, *c*, and *d* are shown in Figure 1. For the point *a*, which is located near the top of the soft soil, the stress path develops along the critical state line and following by an unloading process. When considering creep, the final stress state is lower than that of the case without creep. For the points located at deeper positions, the soft soil undergoes an unloading process owing to the load transfer when the DCM column is involved in. Therefore, the stress paths are shortened and flattened. When considering creep, the stress paths for both cases with and without DCM column treatment tend to move to the left side. This is mainly because creep of the soft soil induces more excess pore water pressure and resulting in less effective stresses taken by the soil particles. If DCM column is involved in, the unloading process owing to load transfer decreases both deviator and mean effective stresses. The effects of both increased excess pore water pressure and load transfer make the stress paths hook-shaped.

3.4 Creep effects on excess pore pressure

Point *d* in Figure 1 is selected for observing excess pore pressures at different cases. The excess pore pressure responses of the soft soil are plotted in Figure 8 with and without considering creep as well as with and without column improvement. If there is no DCM column in the soft soil, considering the creep of the soft soil will cause a significant increase in excess pore pressure compared with the case ignoring the creep. This increase in excess pore pressure can refer to the explanation given by Yin et al. (1994). If the soft soil is treated by a DCM column, only a slight increase in excess pore pressure is observed when considering the creep of the soft soil. The loading acting on the soft soil is reduced owing to the loading transfer corresponding to an unloading process discussed in Section 3.3. This unloading process takes the soil to an over-consolidated state with a lower creep strain rate, thereby moderating the creep effect on increasing the excess pore pressure.

4. Parametric analysis

In this section, a parametric analysis is conducted to investigate the influences of different parameters of the DCM columns on the settlements and loading transfer on the column-improved soft ground. Area replacement ratio, cohesion, friction angle, Young's modulus, and permeability of the DCM column are varied reasonably. Besides, the influences of the stiffness of the geosynthetic reinforcement is discussed as well. The values of the parameters are listed in Table 2. The FE modelling and procedures are the same as those mentioned above. The simulation results are completed with the results calculated by EBGEO (2010) and BS 8006 (2010). Since there is no specific method to calculate settlements of embankments and underlying soft grounds. In this study, the average settlements on DCM column and surrounding soil are calculated by the following equations.

$$S_{column} = \frac{\sigma'_{z,column}}{E'_{50}} L \tag{5}$$

$$S_{soil} = \sum m_{v,i} \sigma'_{z,soil} D_i \tag{6}$$

where $m_{v,i} = 0.434\lambda^* / \bar{\sigma}'_{v,i}$ for normally consolidated soil (Das, 2010); $\bar{\sigma}'_{v,i}$ is the average value of the vertical normal stress during consolidation on the ***i***-th sublayer of the soft soil; D_i is the thickness of the ***i***-th sublayer of the soft soil; L is the length of the DCM column, as shown in Figure 9.

4.1 Area replacement ratio

Area replacement ratio (*ARR*) of the composite ground underlying the embankment is regarded as a variation to investigate the effect of the DCM column on controlling settlements and transferring load. The *ARR* of the DCM columns or DCM walls used in the third runway project of the Hong Kong International Airport is in the range of 20%~40%. It is recommended that the area replacement ratio should be larger than 10% (Rogbeck *et al*., 1998). Therefore, in this study, the values of the *ARR* are taken as 10%, 23%, 30%, 40%.

Figure 10 shows the influence of area replacement ratio on the stresses acting on the soil and the stresses taken by the DCM column at different times. As the area replacement ratio increases, the stresses on soil decrease. There is no significant difference between the responses of the composite ground under embankment loading at t_{EOP} and the long-term responses when ignoring the creep effect of the soft soil. Therefore, only the long-term responses of the composite ground are represented for the case of no creep. Owing to the unloading process mentioned in Section 3.2, the stress on the soft soil when considering creep effect is smaller than that without creep effect at t_{EOP}. A further reduction of the stress acting on soil occurs when considering long-term loading transfer. The method suggested by EBGEO shows an identical trend with the numerical results, while the BS 8006 is not able to calculate the stress acting on the soft soil. However, the EBGEO method overestimates the stress acting on the soft soil.

As the area replacement ratio increases, the stresses taken by the column decrease. Both BS 8006 and EBGEO can present the identical trend. The creep effect of the soft soil on the stress taken by the column decreases with increasing the area replacement ratio. When the area replacement ratio exceeds 30%, there is no significant difference among the stress at t_{EOP}, the long-term stress, and the stress without considering the creep effect of the soft soil. The BS 8006 method overestimates the stress taken by the column since the subsoil support is ignored. The EBGEO results are in close agreement with the numerical ones when the area replacement ratio is larger than 30%. However, the EBGEO method significantly underestimates the stress taken by the column when the area replacement ratio is less than 23%.

The average settlements on both the soft soil and DCM column decrease with increasing the area replacement ratio. The difference between the long-term settlements with creep and those without considering creep also decreases with increasing the area replacement ratio, as shown in Figure 11. Since the EBGEO method overestimates the vertical stress on soil and underestimates the stress on the column, the average settlement on the soil is overestimated and the average settlement on the column is underestimated. When the area replacement ratio is larger than 30%, the settlement of the column caused by the vertical stress which is calculated by the EBGEO method is close to the long-term settlement with no creep, while the settlement based on the BS 8006 method is close to the long-term settlement with creep.

According to the numerical results, it is necessary to consider the influence of creep when the area replacement ratio is less than <23% in this study. However, when the area replacement is as high as 30%, the creep influence is so small that it can be neglected.

4.2 Young's modulus

The Young's modulus of the DCM column might be another important factor to influence the efficiency of the DCM column on controlling settlements and transferring load. Yin (2001) presented the relationship between the Young's modulus and the peak deviator stress of the cement-mixed HKMD, based on a series of consolidated undrained triaxial tests. For different dosages of the cement-mixed HKMD, the values of E'_{50} varies from 2.05 MPa to 84.55 MPa. In this study, the values of E'_{50} for the parametric study was selected based on the abovementioned range and listed in Table 2.

Figure 12 shows the influence of Young's modulus on the stresses taken by soft soil and the DCM column. As the Young's modulus increases, the stress acting on soil decreases while the stress on the column increases. However, in the cases of high values of Young's modulus, the stress responses are no longer sensitive to the Young's modulus of the columns. It should be noted that the columns (or piles) mentioned in both EBGEO method and BS 8006 method are very stiff, such as concrete piles with a higher Young's modulus than that of DCM columns. Therefore, the influence of the Young's modulus of columns (or piles) is not considered in those design methods. Since the Young's modulus of the DCM columns highly depends on the water content of the initial soils, cement content, and time, a good dosage of the DCM columns not only improves the bearing capacity of the composite ground but also affects the loading transfer.

Figure 13 illustrates the influence of the Young's modulus on average settlements of the soft soil and the column. As the Young's modulus increases, the average settlements of both the soft soil and column decrease. The settlement on the DCM column based on the EBGEO method is close to the long-term settlement with no creep, while the settlement on the column based on the BS 8006 method is close to the long-term settlement with creep. Since the stress acting on the soft soil is overestimated by the EBGEO method, the result based on the EBGEO method should be the upper limit of the settlement on the soft soil. However, if consider the creep effect of the soft soil, the EBGEO method might also underestimate the settlement on the soft soil when the Young's modulus of the DCM column is less than 5 MPa, as presented in Figure 13.

4.3 Cohesion and friction angle

The shear strength parameters of the DCM column, such as cohesion c' and friction angle φ' might influence the performance of the DCM column-improved composite ground. Based on a series of consolidated undrained triaxial tests, Yin (2001) reported the different values of those two parameters of the cement-mixed HKMD with different water and cement contents. The values of the cohesion and friction angle of the DCM column used in this parametric study are listed in Table 2. Other parameters are kept the same as those in Section 3.

Figure 14 shows that the cohesion of the DCM column has no effect on loading transfer between the soft soil and the column. As the cohesion increases, the average settlements of the composite ground have a slight increase at t_{EOP}. But the long-term settlements are not sensitive to the cohesion of the DCM column, as shown in Figure 15.

Figure 16 shows that the stress acting on the soft soil decreases slightly with increasing the friction angle at t_{EOP}. The stress taken by the column has a slight increase when increasing the friction angle at t_{EOP}. However, the long-term stresses are not sensitive to the friction angle of the DCM column. When increasing the friction angle of the DCM column, the average settlement on the column has a slight decrease, as shown in Figure 17.

For conservative consideration, columns (or piles) are supposed to be designed within their elastic range. Therefore, the shear strength of the columns (or piles), are not necessary to be considered in the existing design methods, especially for concrete pile-supported embankments. For the columns filled by granular soils, the friction angle of the granular soils can largely influence the behavior of the columns (Ambily and Gandhi, 2007). For the DCM columns, the friction angle would influence the performance of the composite ground if the columns start to yield.

4.4 Permeability

There is an argument that whether DCM columns have an identical function as stone columns or sand columns which can be treated as vertical drains (Yin and Fang, 2006; Chai *et al*., 2006; Horpibulsuk *et al*., 2012). The void ratio and permeability of cement-treated soils can be either larger or smaller than the untreated soils depending on the soil types, mixing methods, stress state of surrounding soil (Chew *et al*., 2004; Kitazume and Terashi, 2013). For the HKMD, there is no sufficient data to prove that the permeability of the clay is increased or decreased after mixing with cement. In this study, the coefficient of permeability of the DCM column is normalized by the coefficient of permeability of the surrounding soft soil to investigate the influence of the permeability of the column on controlling settlements, improving the creep and transferring load. The values of the normalized permeability are listed in Table 2.

Figure 18 and Figure 19 show that the normalized permeability of the DCM only affects the stress and settlement responses of the composite ground at t_{EOP}. No matter whether to consider or ignore the creep effect of the soft soil, the long-term stresses and settlements are not sensitive to the permeability of the column. Compared with the case of lower permeability, the case of higher permeability owns a smaller value of t_{EOP} resulting in a less creep deformation ($\varepsilon_{creep} = \mu^* \ln(t_{EOP} / t_0)$, t_0 is the reference time corresponding to $t_e = 0$), since the higher permeability of the DCM column accelerates the consolidation process of the soft soil.. Therefore, the total settlement on the soft soil at t_{EOP} decreases with increasing the permeability of the DCM column. For the long-term settlements and vertical stress, the identical values of $t_{Long-term}$ (100000 days) are selected, so that the creep settlements at the cases of different permeability are the same ($\varepsilon_{creep} = 0$, if no creep effect). Therefore, the permeability does not affect the long-term settlement and stress responses of the composited soft ground.

4.5 Stiffness of geosynthetic reinforcement

Geosynthetic reinforcements can also contribute to loading transfer from the soft soil to the DCM column owing to tensioned membrane effect (Han and Gabr, 2002). Based on a summary of several case studies of basal reinforced piled embankment done by van Eekelen *et al*. 2015, the values of the stiffness of the geosynthetic reinforcement are taken as 500 kN/m, 1000 kN/m, and 5000 kN/m in this study.

Figure 20 shows that the stress acting on the soft soil decreases as the stiffness of the geosynthetic reinforcement increases, while the stress taken by the DCM column increases as the stiffness of the reinforcement increases. As a result, the average settlement on the soft soil decreases with increasing the stiffness of the reinforcement, while the average settlement on the DCM column increases slightly with increasing the stiffness, as Figure 21 reveals. It indicates that the tensioned membrane effect of the geosynthetic enhances with increasing the its stiffness. However, neither EBGEO nor BS 8006 can consider the influence of the stiffness of the reinforcement.

4.6 Discussions

EBGEO method is based on the multi-shell arching theory to calculate the vertical stresses taken by the columns and the subsoils. However, this method underestimates the stress on the column and overestimates the stress acting on the soft soil, since this method does not consider the loading transferred through the reinforcement to the columns, which is termed as “load part B” by van Eekelen *et al*. (2011). The loads to the columns and subsoil are termed as “load part A” and “load part C”, respectively. In this study, the Hewlett and Randolph method suggested by BS 8006 was used to calculate the stress on the column. Since BS 8006 ignores the subsoil support (load part C =0), the stress taken by the column is overestimated. When calculating the stress acting on the soil, the EBGEO result is the upper limit while the BS 8006 result is the lower limit. When calculating the stress taken by the columns, the EBGEO result is the lower limit, while the BS 8006 result is the upper limit. However, both of EBGEO and BS 8006 cannot provide good results in both stress response and settlement response, especially the long-term performance with creep effect of soft soil. New methods are needed in the future to solve this issue.

5. Conclusions

In this study, finite element simulations were carried out by PLAXIS 2D on a DCM column-treated soft soil ground in axisymmetric condition under embankment load. The responses of settlements and load transfer were analyzed by comparing the results for soft soil with and without creep. A parametric study was conducted to study the influences of different parameters on the performance of the composite ground. In addition, the simulated results were compared with EBGEO and BS 8006 predictions. According to numerical results, analyses, and discussions, the main conclusions are drawn as follows:

a) The DCM column exhibits good efficiency on controlling settlements and transferring load from soft soil to DCM columns. The load transfer can induce an unloading process on soft soil, resulting a higher stress concentration ratio on the DCM column compared with that for soft soil without creep, which makes the clay into the over-consolidated state with a smaller creep strain rate.

b) The stress acting on the soft soil and the stress taken by the column decrease with increasing the area replacement ratio. The settlements on the soft soil and the column decrease with increasing the area replacement ratio.

c) The influence of the creep effect of the soft soil on loading transfer can be largely reduced when the area replacement ratio is high enough (*ARR* > 30% in this study).

d) The stress acting on the soft soil decreases with increasing the Young's modulus of the DCM column, while the stress taken by the column increases with increasing the Young's modulus of the column. Settlements on the soft soil and the column decrease with increasing the Young's modulus of column.

e) Cohesion and friction angle of the DCM column have a little effect on the performance of the composite ground. This is mainly because the column is still within the elastic range.

f) The tensioned membrane effect of the geosynthetic reinforcement increases with the stiffness of the reinforcement.

g) EBGEO method can provide an upper limit of the stress acting on the soft soil and a lower limit of the stress taken by the column, while BS 8006 method can provide an upper limit of the stress taken by the column.

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References

Abusharar, S.W., Zheng, J.J., Chen, B.G., Yin, J.H., 2009. A simplified method for analysis of a piled embankment reinforced with geosynthetics. Geotext. Geomembr. 27(1):39-52.

Airport Authority Hong Kong, 2012. Expansion of Hong Kong International Airport into a Three-Runway System Project profile.

http://www.epd.gov.hk/eia/register/profile/latest/esb250/esb250.pdf

Ambily, A.P., Gandhi, S.R., 2007. Behavior of stone columns based on experimental and FEM analysis. J. Geotech. Geoenviron. Eng. 133(4), 405-415.

Ariyarathne, P., Liyanapathirana, D.S., 2015. Review of existing design methods for geosynthetic-reinforced pile-supported embankments. Soils. Found. 55(1):17-34.

Augustesen, A., Liingaard, M., Lade, P.V., 2004. Evaluation of time-dependent behavior of soils. Int. J. Geomech. 4(3):137-56.

Brinkgreve, R.B., Kumarswamy, S., Swolfs. W.M., 2015. PLAXIS 2D 2015. User manual, Plaxis bv.

BS 8006, 2010. Code of Practice for Strengthened/Reinforced Soils and Other Fills. British Standard Institution, UK.

Casagrande, A., 1936. The determination of pre-consolidation load and it's practical significance. In Proc. Int. Conf. Soil Mech. Found. Eng., Cambridge, Massachusetts, 1936, 3, 60.

Chai, J.C., Onitsuka, K., Hayashi, S., 2006. Discussion: Physical modelling of consolidation behavior of a composite foundation consisting of a cement-mixed soil column and untreated soft marine clay. Géotechnique 56(8):579-582.

Chen, R.P., Chen, Y.M., Han, J., Xu, Z.Z., 2008. A theoretical solution for pile-supported embankments on soft soils under one-dimensional compression. Can. Geotech. J. 45(5):611-623.

Chew, S.H., Kamruzzaman, A.H.M., Lee, F.H., 2004. Physicochemical and engineering behavio of cement treated clays. J. Geotech. Geoenviron. Eng. 130(7):696-706.

Das, B.M., 2010. Geotechnical engineering handbook. J. Ross Publishing.

Deb, K., Chandra, S., Basudhar, P.K., 2007. Nonlinear analysis of multilayer extensible geosynthetic sheet-reinforced granular bed on soft soil. Geotech. Geol. Eng. 25(1):11-23.

EBGEO, 2010. Empfehlungen für den Entwurf und die Berechnung von Erdkörpern mit Bewehrungen aus Geokunststoffen e EBGEO, vol. 2. German Geotechnical Society, Auflage, ISBN 978-3-433-02950-3 (in German). Also available in English: Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements e EBGEO, 2011. ISBN: 978-3-433-02983-1 and digital in English ISBN: 978-3-433-60093-1.

Feng, W.Q., Yin, J.H., 2017. A new simplified Hypothesis B method for calculating consolidation settlements of double soil layers exhibiting creep. Int. J. Numer. Anal. Methods Geomech. 41:899-917.

Gangakhedkar, R., 2004. Geosynthetic reinforced pile supported embankments. Doctoral dissertation, University of Florida.

Graham, J., Crooks, J.H., Bell, A.L., 1983. Time effects on the stress-strain behavior of natural soft clays. Géotechnique 33(3):327-40.

Guido, V.A., Kneuppel, J.D., Sweeney, M.A., 1987. Plate loading tests on geogrid reinforced earth slabs. In Proc. Geosynth. 87, New Orleans, USA. 216-225.

Han, J., Arkins, K., 2002. Case studies of geogrid-reinforced and pile-supported earth structures on weak foundation soils. Proc. Int. Deep Found. Congress, Orlando, ASCE 2002:668-679.

Han, J., Gabr, M.A., 2002. Numerical analysis of geosynthetic-reinforced and pile-supported earth platforms over soft soil. J. Geotech. Geoenviron. Eng. 128(1): 44-53.

Han, J., Wayne, M.H., 2000. Pile-soil-interactions in geosynthetic reinforced platform/piled embankments over soft soil. In Proc 79th Annual Transportation Research Board Meeting. Washington, D.C., 27.

Hewlett, W.J., Randolph, M.F., 1988. Analysis of piled embankments. Ground. Eng. 21(3), 12–18.

Horpibulsuk, S., Chinkulkijniwat, A., Cholphatsorn, A., Suebsuk, J., Liu, M.D., 2012. Consolidation behavior of soil–cement column improved ground. Comput. Geotech. 43:37-50.

Huang, J., Han, J., 2009. 3D coupled mechanical and hydraulic modeling of a geosynthetic-reinforced deep mixed column-supported embankment. Geotext. Geomembr. 27(4), 272-280.

Huang, J., Han, J., 2010. Two-dimensional parametric study of geosynthetic-reinforced column-supported embankments by coupled hydraulic and mechanical modelling. Comput. Geotech. 37(5):638-648.

Jamsawang, P., Voottipruex, P., Boathong, P., Mairaing, W., Horpibulsuk, S., 2015a. Three-dimensional numerical investigation on lateral movement and factor of safety of slopes stabilized with deep cement mixing column rows. Eng. Geol. 188, 159-167.

Jamsawang, P., Voottipruex, P., Jongpradist, P., Bergado, D.T., 2015b. Parameters affecting the lateral movements of compound deep cement mixing walls by numerical simulations and parametric analyses. Acta Geotech. 10(6), 797-812.

Jamsawang, P., Boathong, P., Mairaing, W., Jongpradist, P., 2016. Undrained creep failure of a drainage canal slope stabilized with deep cement mixing columns. Landslides, 13(5), 939-955.

Jiang, Y., Han, J., Zheng, G., 2014. Influence of column yielding on degree of consolidation of soft foundations improved by deep mixed columns. Geomech. Eng, 6(2), 173-194.

Kitazume, M., Terashi, M., 2013. The deep mixing method. CRC press.

Lai, H.J., Zheng, J.J., Zhang, J., Zhang, R.J., Cui, L., 2014. DEM analysis of “soil”-arching within geogrid-reinforced and unreinforced pile-supported embankments. Comput. Geotech. 61:13-23.

Liu, H.L., Ng, C.W., Fei, K., 2007. Performance of a geogrid-reinforced and pile-supported highway embankment over soft clay: case study. J. Geotech. Geoenviron. Eng. 133(12):1483-1493.

Liu, K.W., Rowe, R.K., 2015. Numerical study of the effects of geosynthetic reinforcement viscosity on behavior of embankments supported by deep-mixing-method columns. Geotext. Geomembr. 43(6):567-578.

Low, B.K., Tang, S.K., Choa, V. 1994. Arching in piled embankments. J. Geotech. Eng. 120(11):1917-1938.

Madhav, M., Suresh, K., Peter, E., 2010. Effect of creep on settlement of granular pile reinforced ground. Int. J. Geotech. Eng. 4(4):495-505.

Marston, A., Anderson, A.O., 1913. The theory of loads on pipes in ditches and tests of cement and clay drain tile and sewer pipe Bulletin

Mun, B., Kim, T., Moon, T., Oh, J., 2012. SCM wall in sand: Numerical simulation and design implications. Eng. Geol. 151, 15-23.

Rogbeck, Y., Gustavsson, S., Sodergren, I., Lindquist, D., 1998. Reinforced piled embankments in Sweden-design aspects. In Proc 6th Int Conf Geosynth, Atlanta, Georgia, 2, 755-762.

Rowe, R.K., Taechakumthorn, C., 2011. Design of reinforced embankments on soft clay deposits considering the viscosity of both foundation and reinforcement. Geotext. Geomembr. 29(5):448-461.

Sexton, B.G., 2014. The influence of creep on the settlement of foundations supported by stone columns. PhD thesis, National University of Ireland, Galway, Ireland.

Sexton, B.G., Sivakumar, V., McCabe, B.A., 2017. Creep improvement factors for vibro-replacement design. Proc. Inst. Civil Eng.-Gr Improv. 170(1):35-56.

Terzaghi, K., 1943 Theoretical soil mechanics. New York: Wiley.

van Eekelen, S.J.M., Bezuijen, A., van Tol A.F., 2011. Analysis and modification of the British Standard BS8006 for the design of piled embankments. Geotext. Geomembr. 29(3):345-359.

van Eekelen, S.J.M., Bezuijen, A., Lodder, H.J., van Tol, A.F., 2012a. Model experiments on piled embankments. Part I. Geotext. Geomembr. 32:69-81.

van Eekelen, S.J.M., Bezuijen, A., Lodder, H.J., van Tol, A.F., 2012b. Model experiments on piled embankments. Part II. Geotext. Geomembr. 32:82-94.

van Eekelen, S.J.M., Bezuijen, A., van Tol, A.F., 2013. An analytical model for arching in piled embankments. Geotext. Geomembr. 39:78-102.

van Eekelen, S.J.M., Bezuijen, A. van Tol, A.F., 2015. Validation of analytical models for the design of basal reinforced piled embankments. Geotext. Geomembr. 43(1):56-81.

van Santvoort, G.P.T.M., 1995. Geosynthetics in Civil Engineering. Balkema, Rotterdam, the Netherlands, 37-39.

Voottipruex, P., Suksawat, T., Bergado, D.T., Jamsawang, P., 2011. Numerical simulations and parametric study of SDCM and DCM piles under full scale axial and lateral loads. Comput. Geotech. 38(3), 318-329.

Wu, P.C., Yin, J.H., Feng, W.Q., Chen, W.B., 2019. Experimental Study on a Geosynthetic-Reinforced Sand Fill over Marine Clay with or without Deep Cement Mixed Soil Columns under Different Loadings. Underground Space.

Yapage, N., Liyanapathirana, S., Leo, C.J., Poulos, H.G., Kelly, R.B., 2013. Towards the development of a new design guideline for geosynthetic reinforced column supported embankments. Aust. Geomech. J. 48(3):35-49.

Yapage, N., Liyanapathirana, S., 2018. Behavior of geosynthetic reinforced column supported embankments. J. Eng. Des. Tech.16(1):44-62.

Yin, J.H., 2001. Stress-strain-strength characteristics of soft Hong Kong marine deposits without or with cement treatment. Lowland Technol. Int. 3(1):1-13.

Yin, J.H., Fang, Z., 2006. Physical modelling of consolidation behavior of a composite foundation consisting of a cement-mixed soil column and untreated soft marine clay. Géotechnique 56(1):63-68.

Yin, J.H., Graham, J., 1989. Viscous–elastic–plastic modelling of one-dimensional time-dependent behavior of clays. Can. Geotech. J. 26(2):199-209.

Yin, J.H, Graham, J., Clark, J.I. Gao, L., 1994. Modelling unanticipated pore-water pressures in soft clays. Can. Geotech. J. 31(5):773-778.

Yin, J.H., Lai, C.K., 1998. Strength and stiffness of Hong Kong marine deposits mixed with cement. Geotech. Eng. 29(1).

Yin, J.H., Zhu, J.G., 1999. Measured and predicted time-dependent stress-strain behavior of Hong Kong marine deposits. Can. Geotech. J. 36(4):760-766.

Yin, Z.Y., Karstunen, M., Chang, C.S., Koskinen, M., Lojander, M., 2011. Modelling time-dependent behavior of soft sensitive clay. J. Geotech. Geoenviron. Eng. 137(11):1103-13.

Zhao, L.S., Zhou, W.H., Geng, X., Yuen, K.V., Fatahi, B., 2019. A closed-form solution for column-supported embankments with geosynthetic reinforcement. Geotext. Geomembr. 47(3):389-401.

Table 1. Parameter values used in the numerical analysis

Material	γ kN/m^3	ν'	E'_{50} MPa	J kN/m	OCR	κ^*	λ^*	μ^*	k_x m/day	k_y m/day	c' kPa	φ' °
Soft soil	16	0.15	-	-	2	0.0217	0.174	0.0076	3.5×10^{-4}	1.9×10^{-4}	0.1	30
Fills	20	0.3	12	-	-		-	-	1.0	1.0	0.1	34
DCM column	20	0.2	40.5	-	-	-	-	-	3.5×10^{-4}	1.9×10^{-4}	87	46
Geosynth-etic	-	-	-	5000	-	-	-	-	-	-	-	-

Table 2. Values of parameters

Parameters	Unit	Values
ARR	-	10%, *23%, 30%, 40%
c'	kPa	50, *87, 130
φ'	°	20, 30, *46
E'_{50}	MPa	5, 10, 20, *40.5, 80
k_{column} / k_{soil}	-	0.1, *1, 10
J	kN/m	500 1000 5000*

* Values used in the reference.

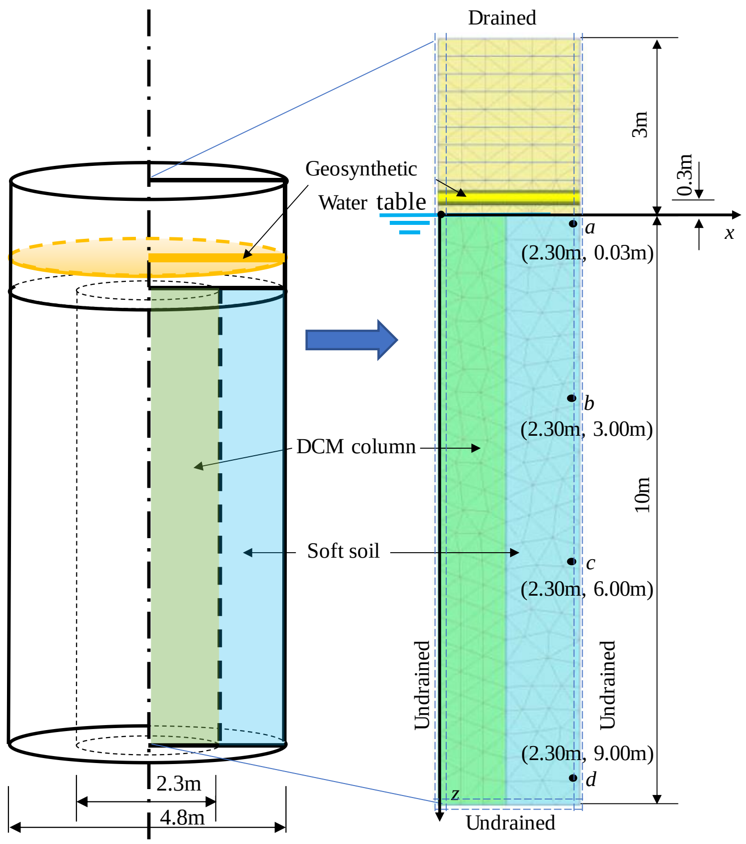

Figure 1. Schematic diagram of the finite element model

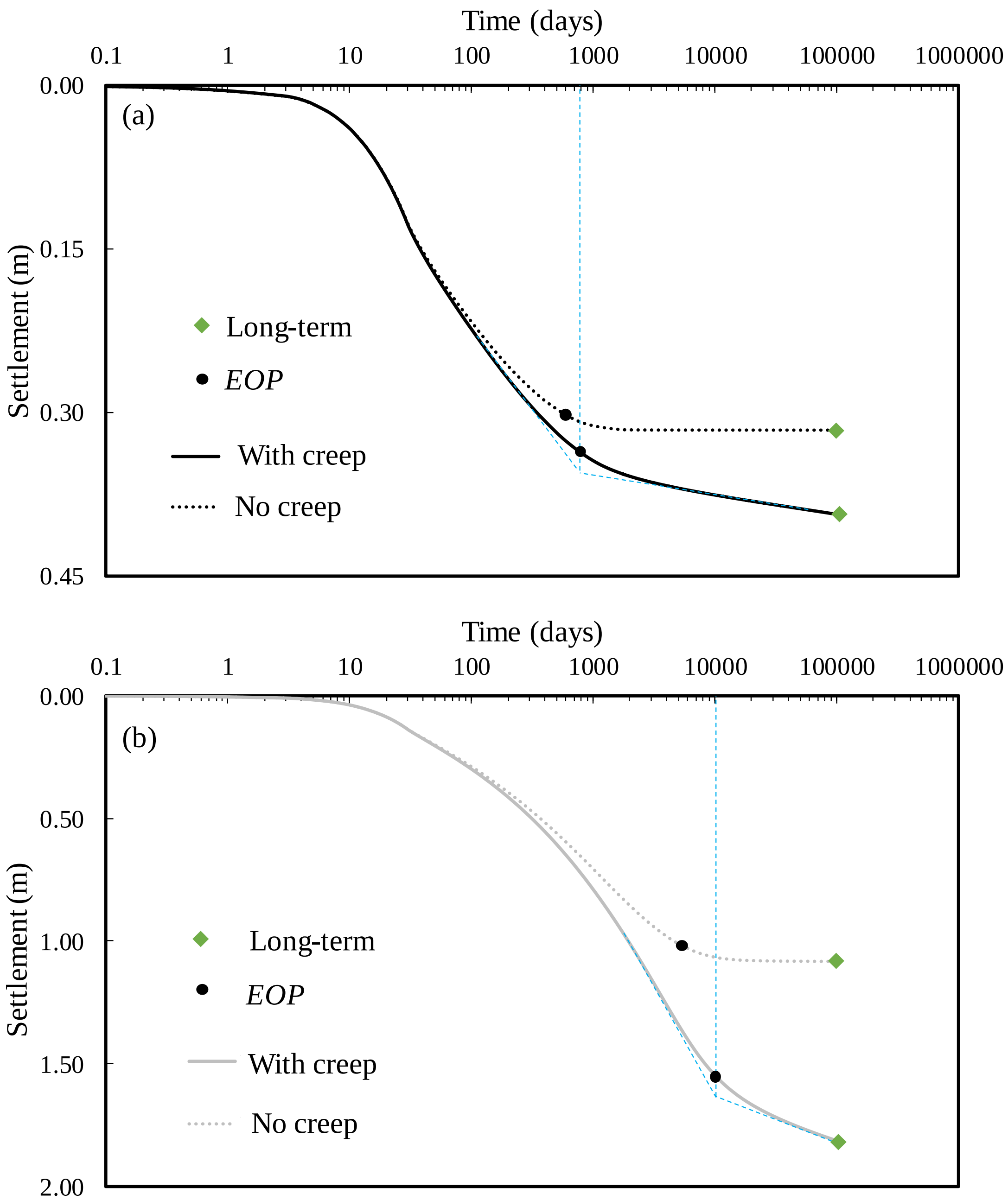

Figure 2. Comparison of soft soil ground settlements *versus* time (a) treated by DCM column; (b) without DCM column (No creep: 1% of the value of μ^* used in the case of soil with creep)

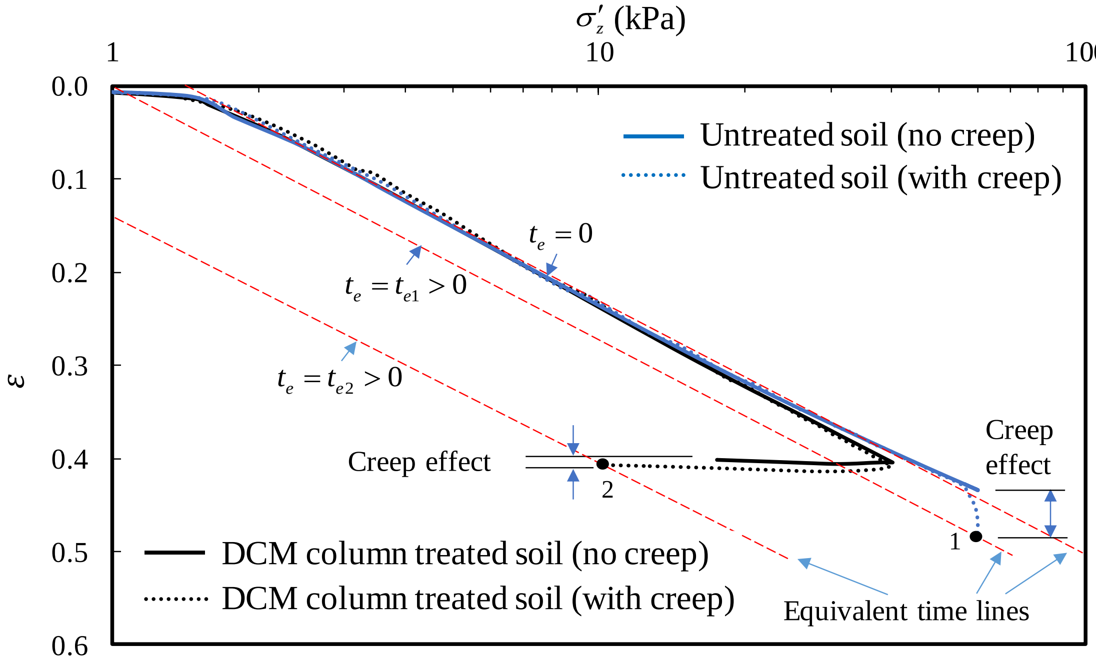

Figure 3. The relationship between ε and $\log(\sigma_z')$ of point *a* in soft soil ground

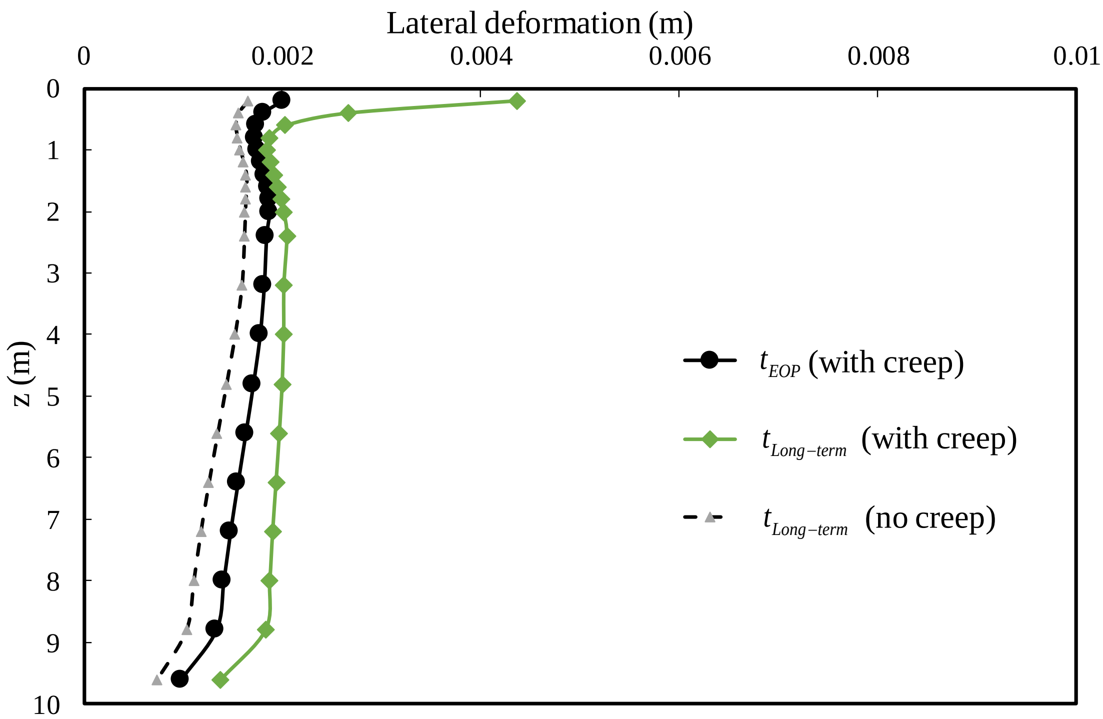

Figure 4. Lateral deformation of the DCM column

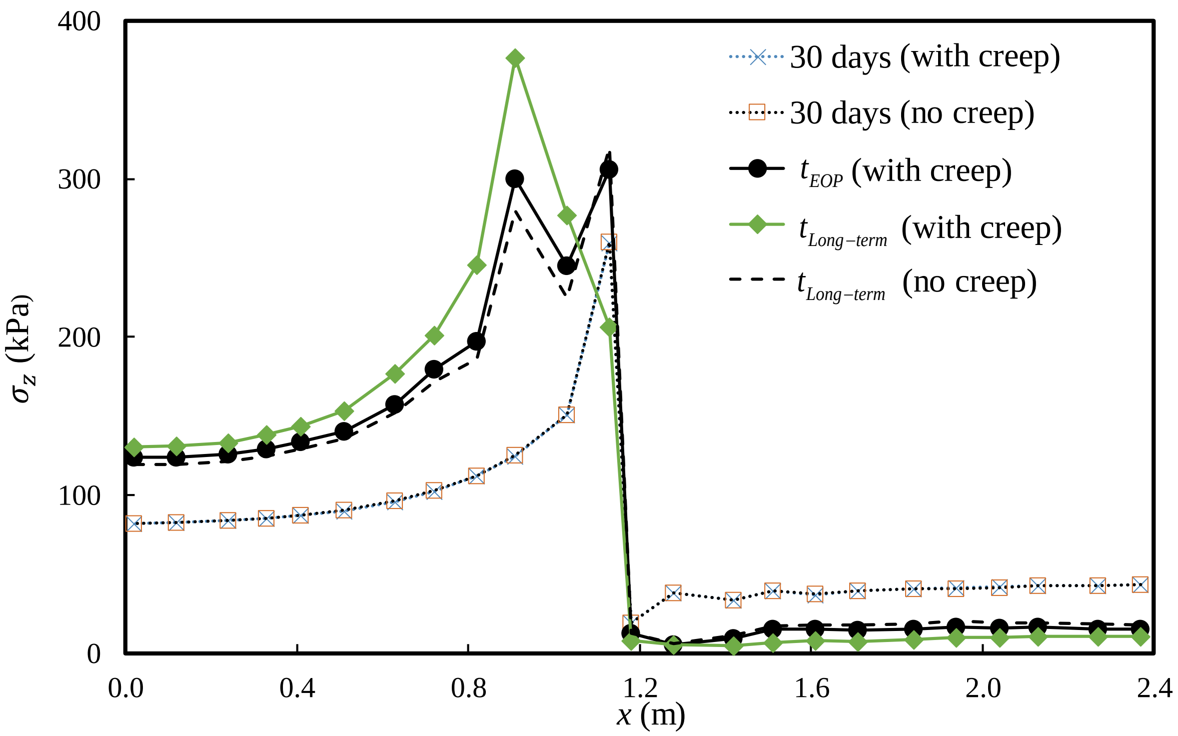

Figure 5. Horizontal distribution of σ_z taken by DCM column and surrounding soft soil (z=0)

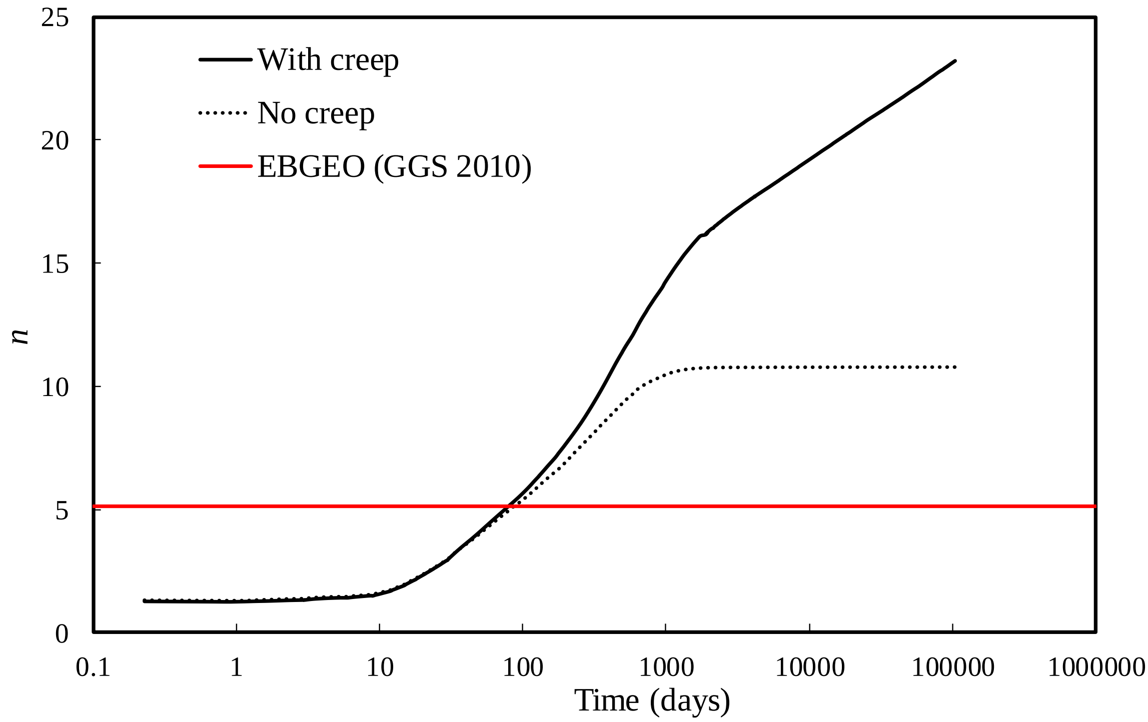

Figure 6. The relationship of n *versus* time

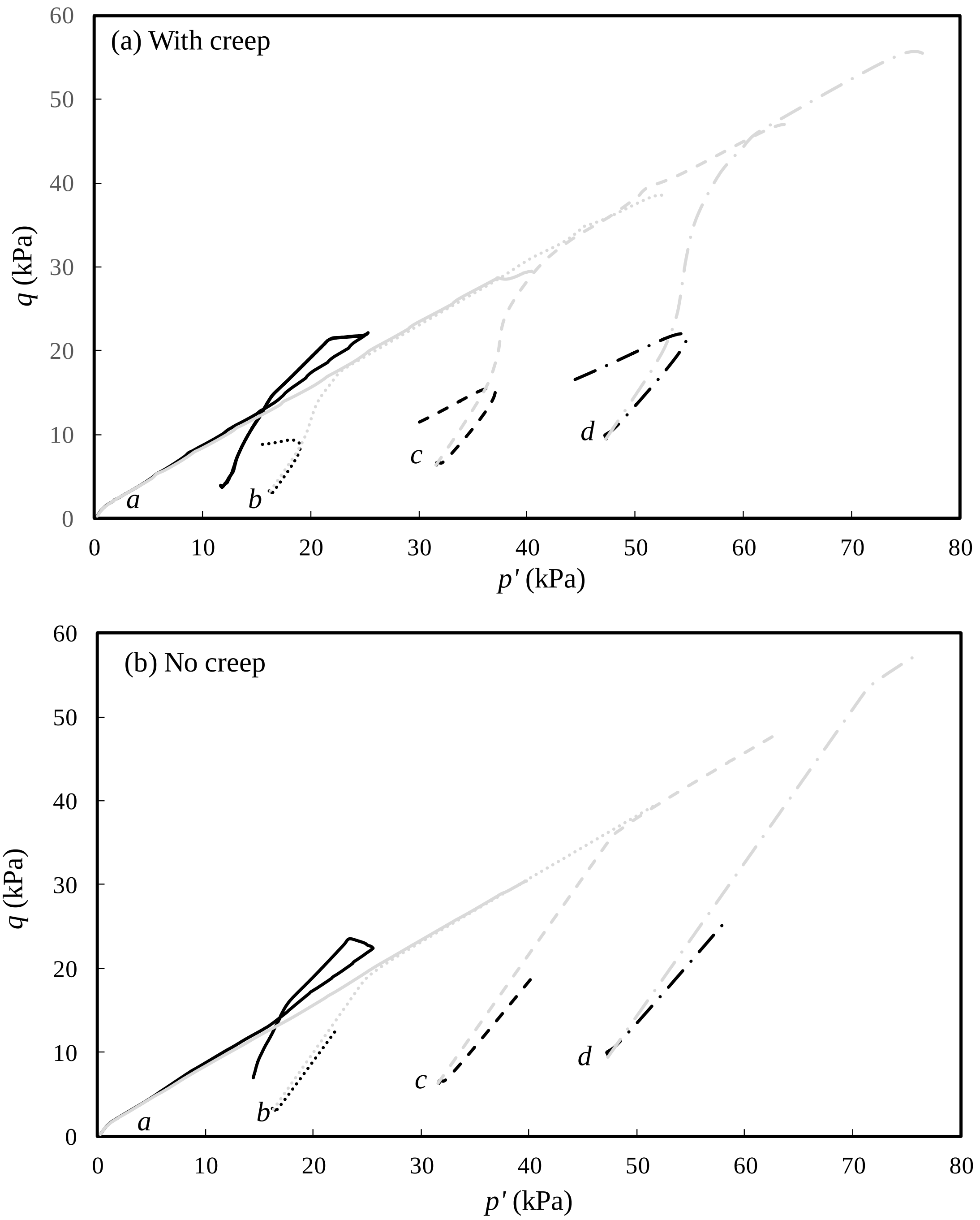

Figure 7. Stress paths of different points in soft soil with and without creep (for comparison, lines in grey colour are the cases without DCM column treatment)

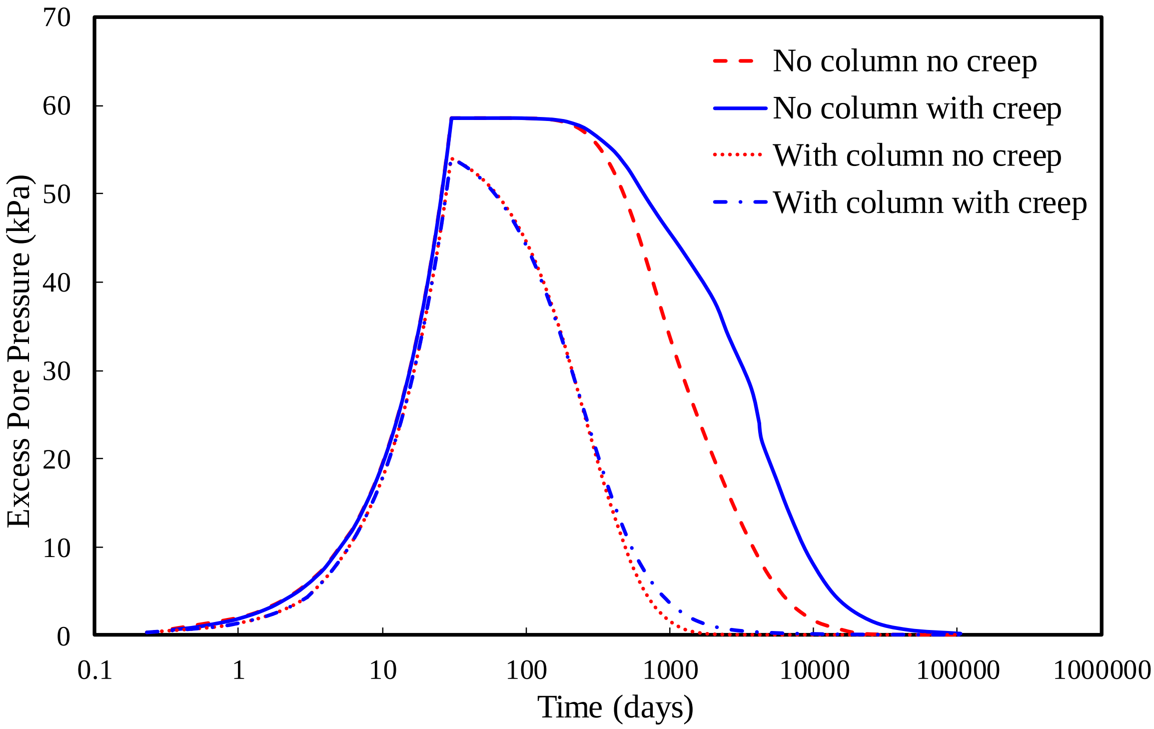

Figure 8. Excess pore pressures at point *d* in different cases

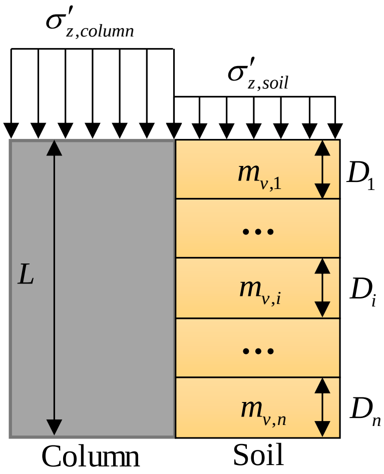

Figure 9. Schematic diagram for settlements calculation of DCM column and surrounding soil

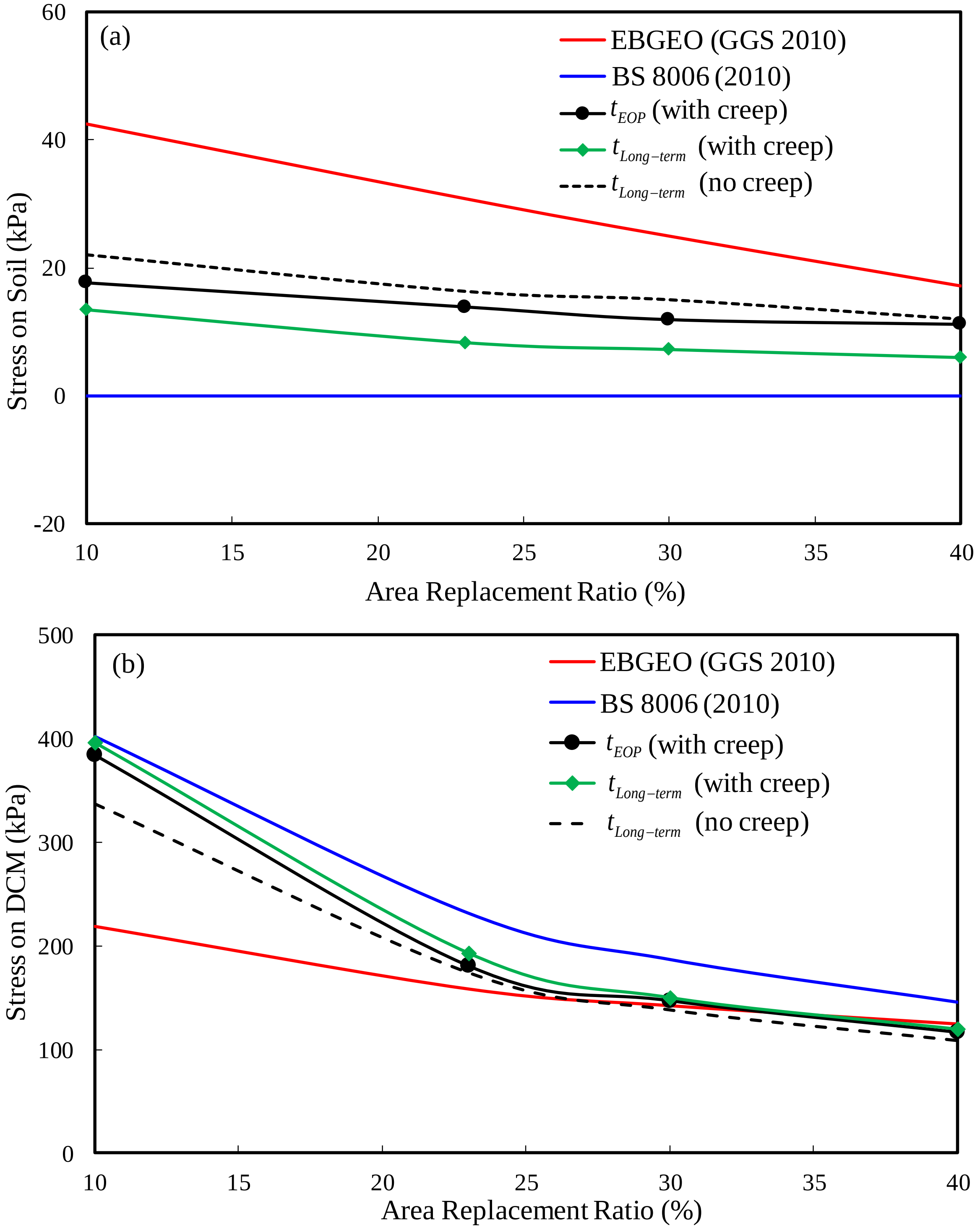

Figure 10. Average vertical stresses on (a) soil, (b) DCM column for different area replacement ratios

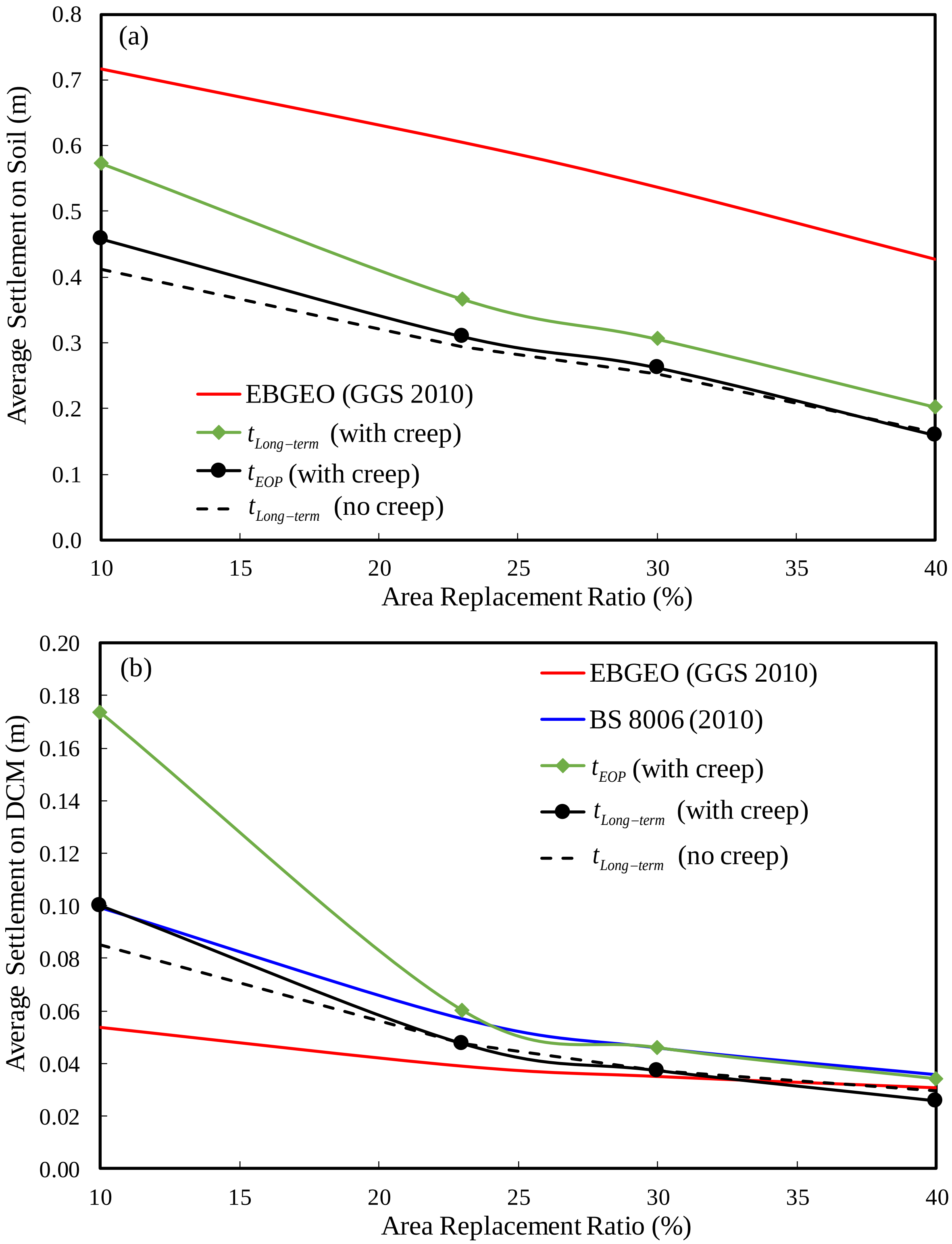

Figure 11. Average settlements on (a) soil, (b) DCM column for different area replacement ratios

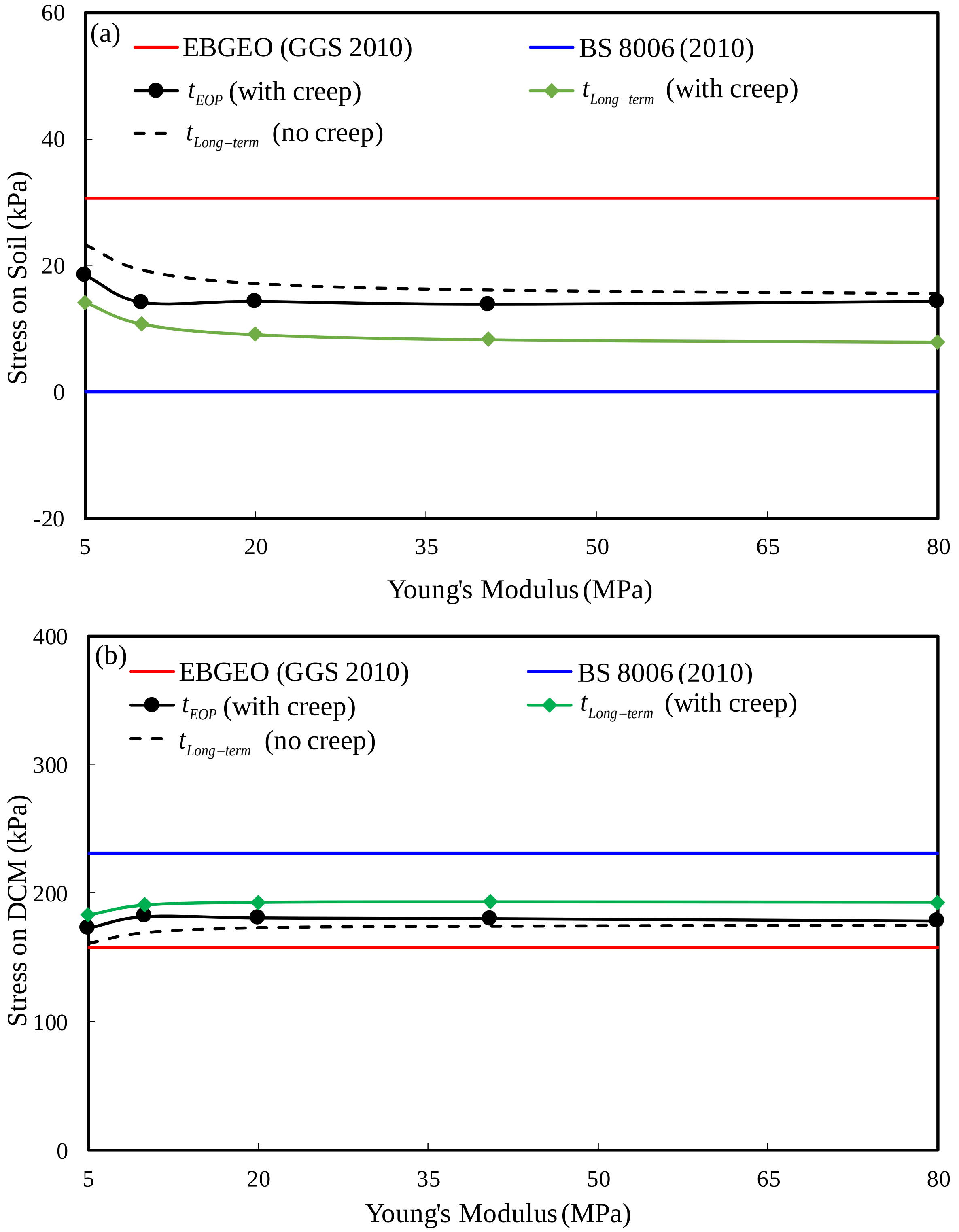

Figure 12. Average vertical stresses on (a) soil, (b) DCM column for different values of the Young's modulus of the DCM column

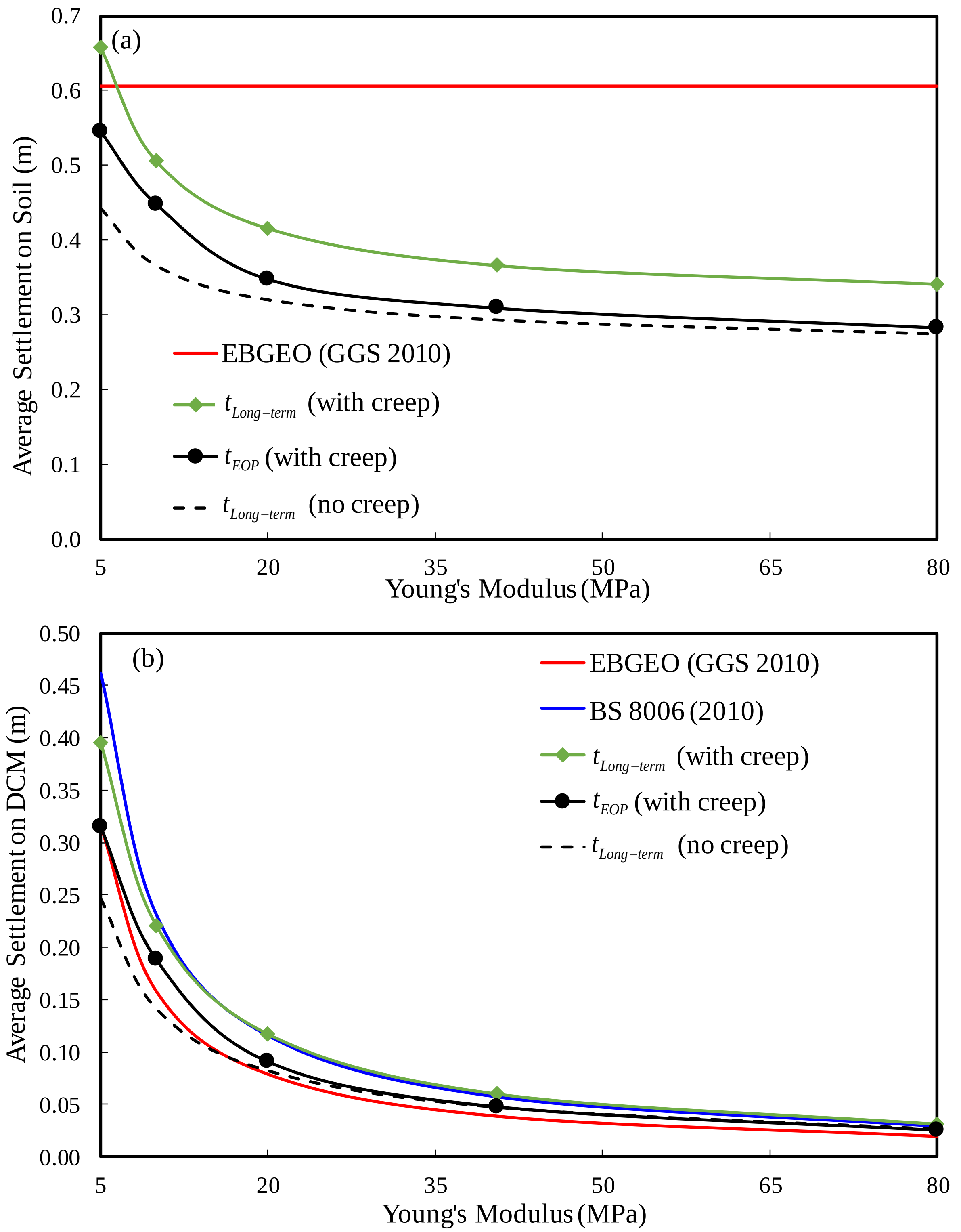

Figure 13. Average settlements on (a) soil, (b) DCM column for different values of the Young's modulus of the DCM column

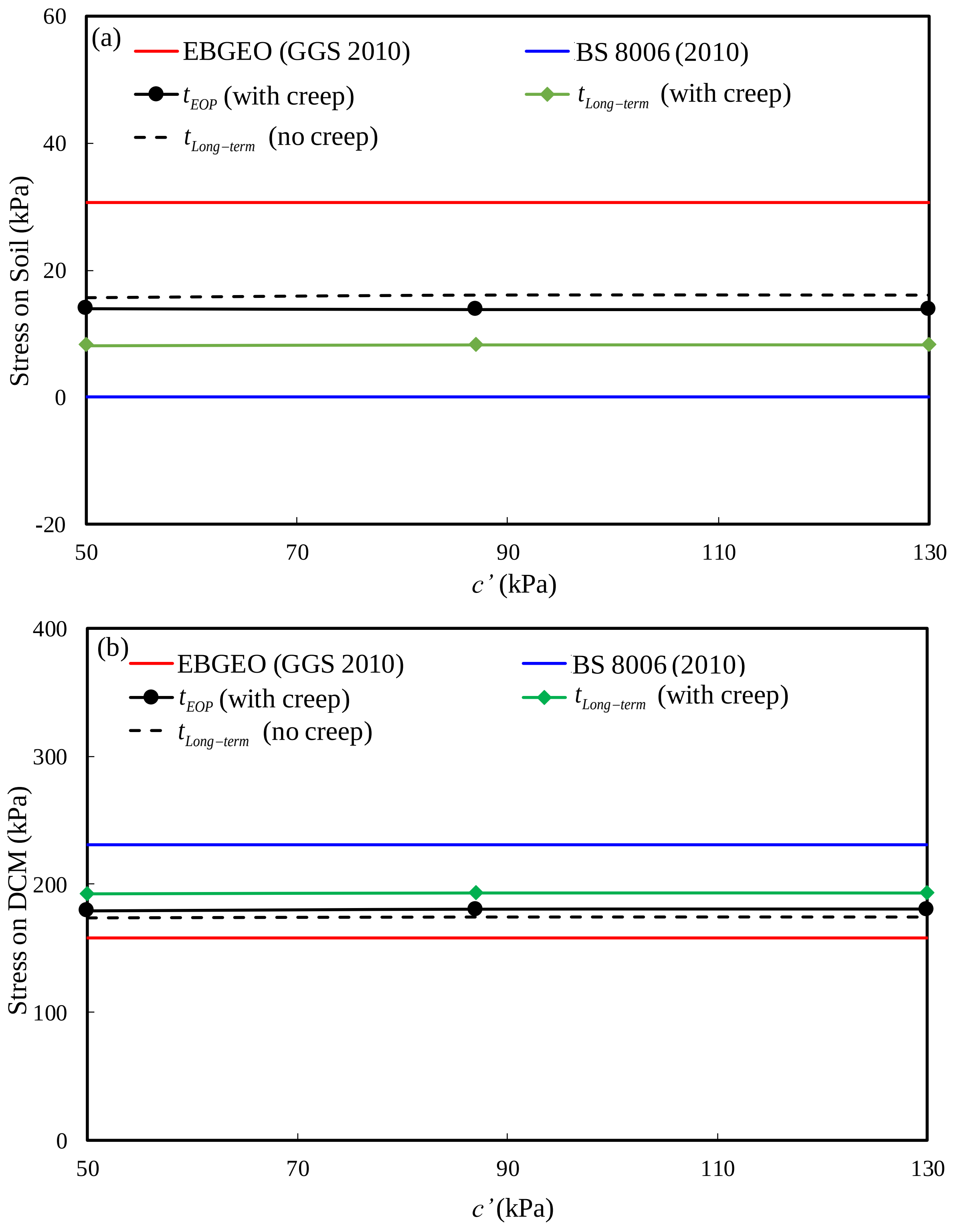

Figure 14. Average vertical stresses on (a) soil, (b) DCM column for different values of the cohesion of the DCM column

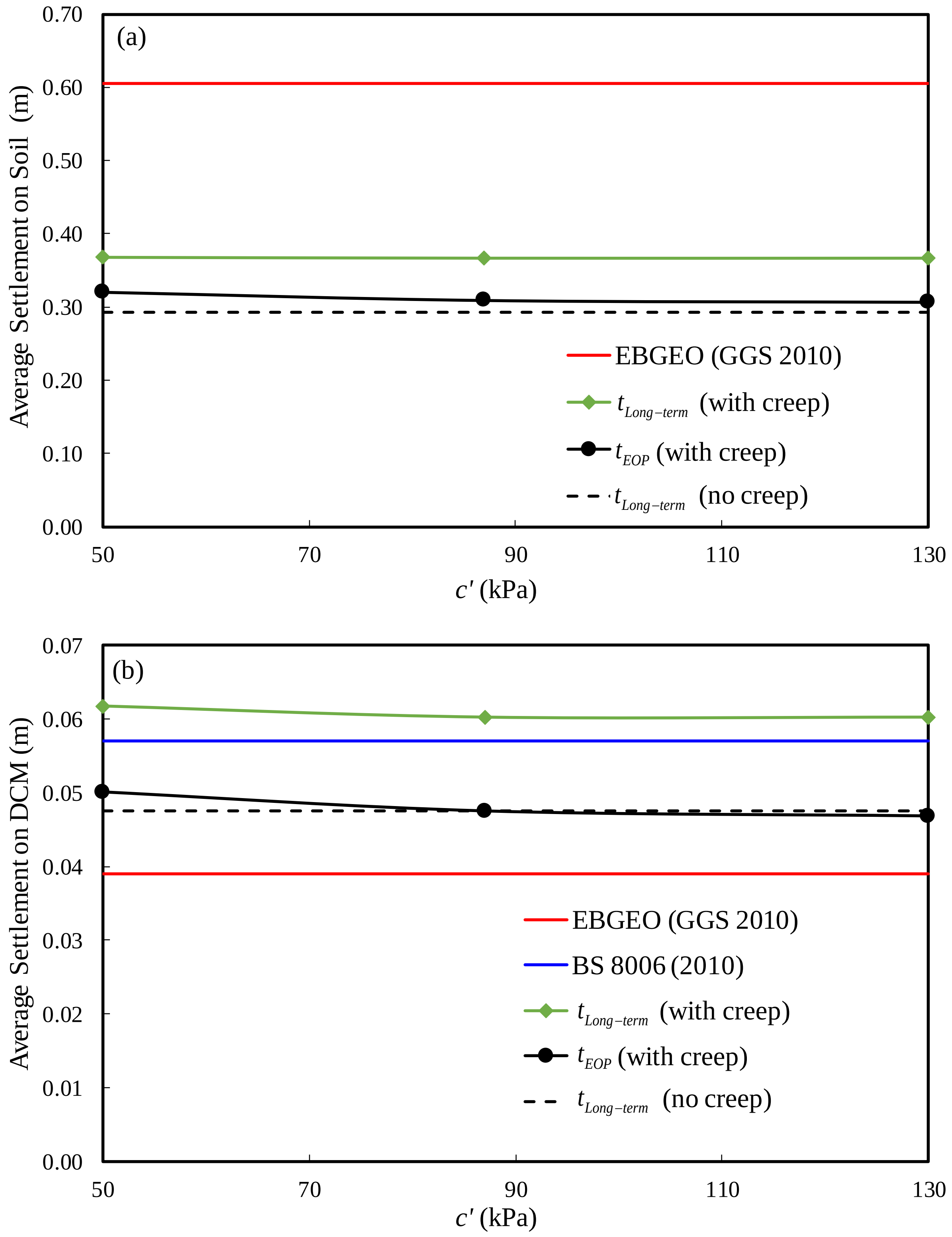

Figure 15. Average settlements on (a) soil, (b) DCM column for different values of the cohesion of the DCM column

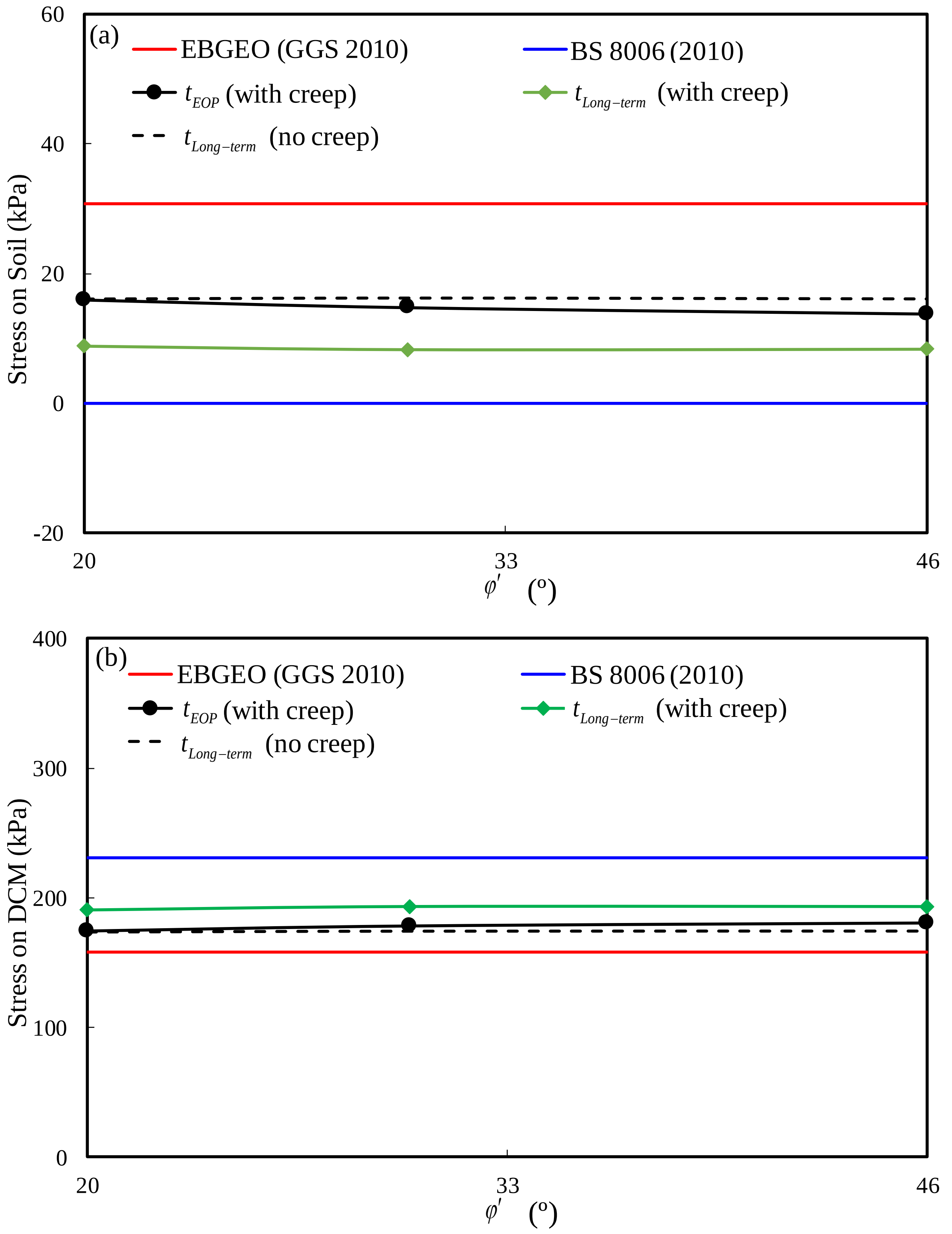

Figure 16. Average stresses on (a) soil, (b) DCM column for different values of the friction angle of the DCM column

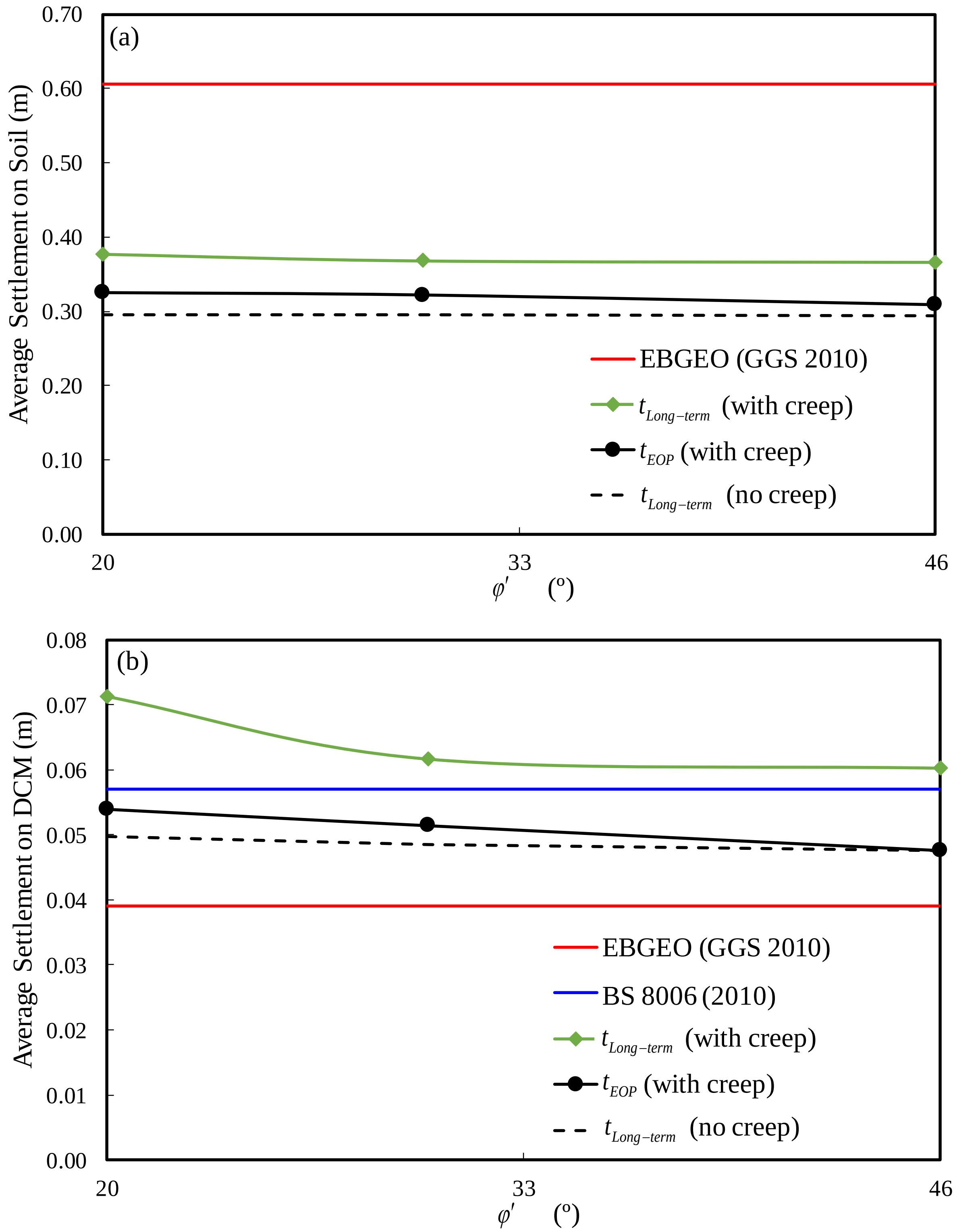

Figure 17. Average settlements on (a) soil, (b) DCM column for different values of the friction angle of the DCM column

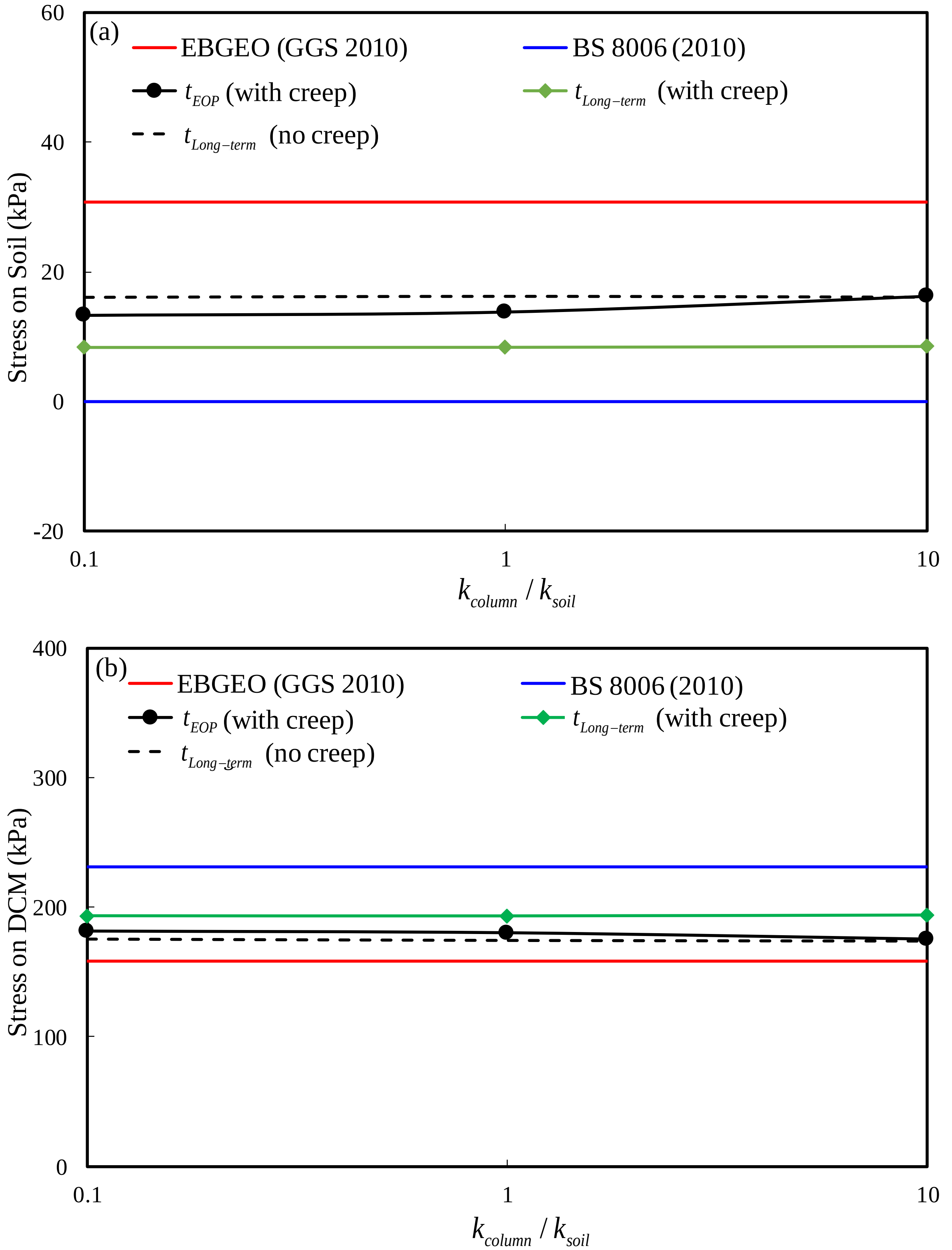

Figure 18. Average stresses on (a) soil, (b) DCM column for different values of the normalized permeability

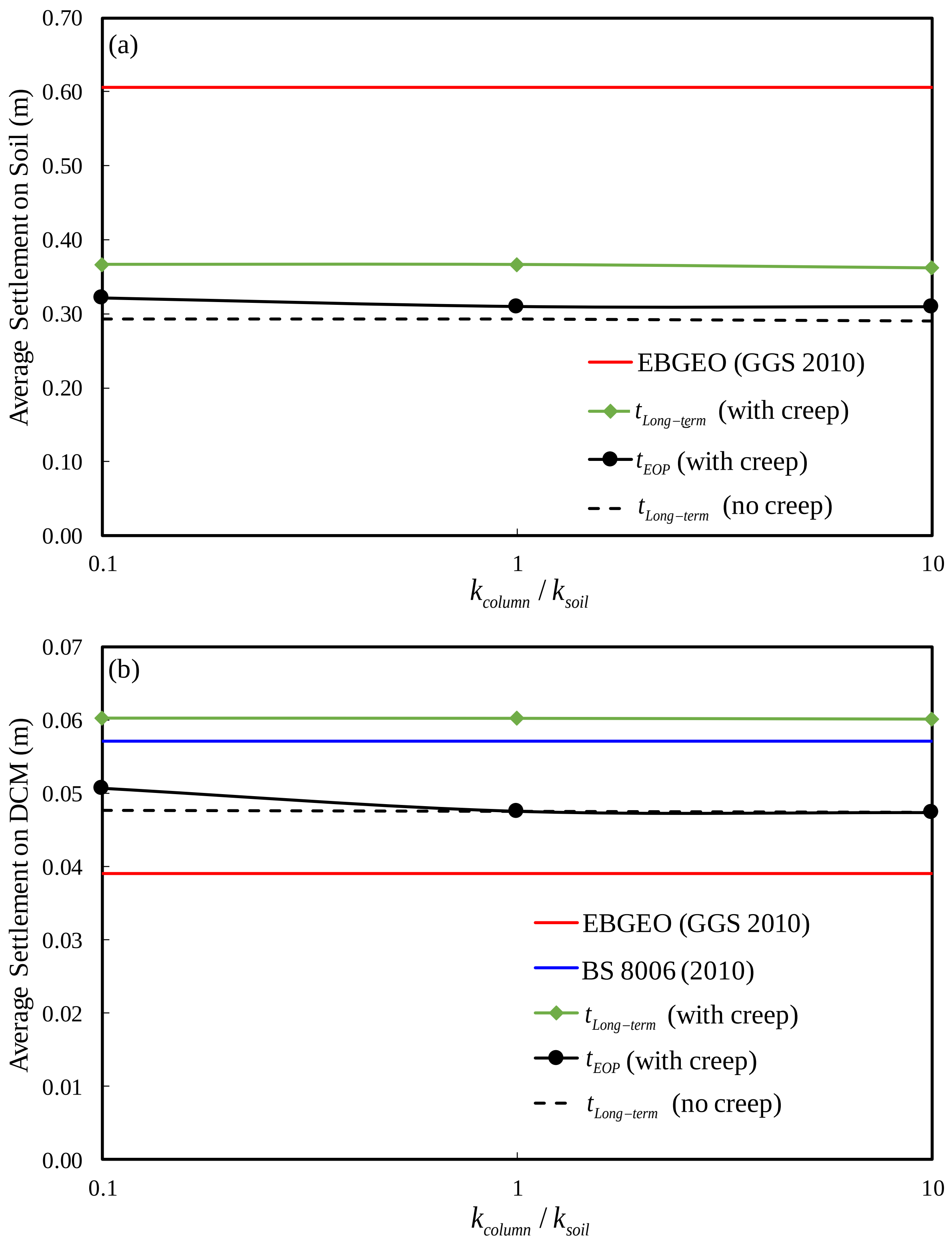

Figure 19. Average settlements on (a) soil, (b) DCM column for different values of the normalized permeability

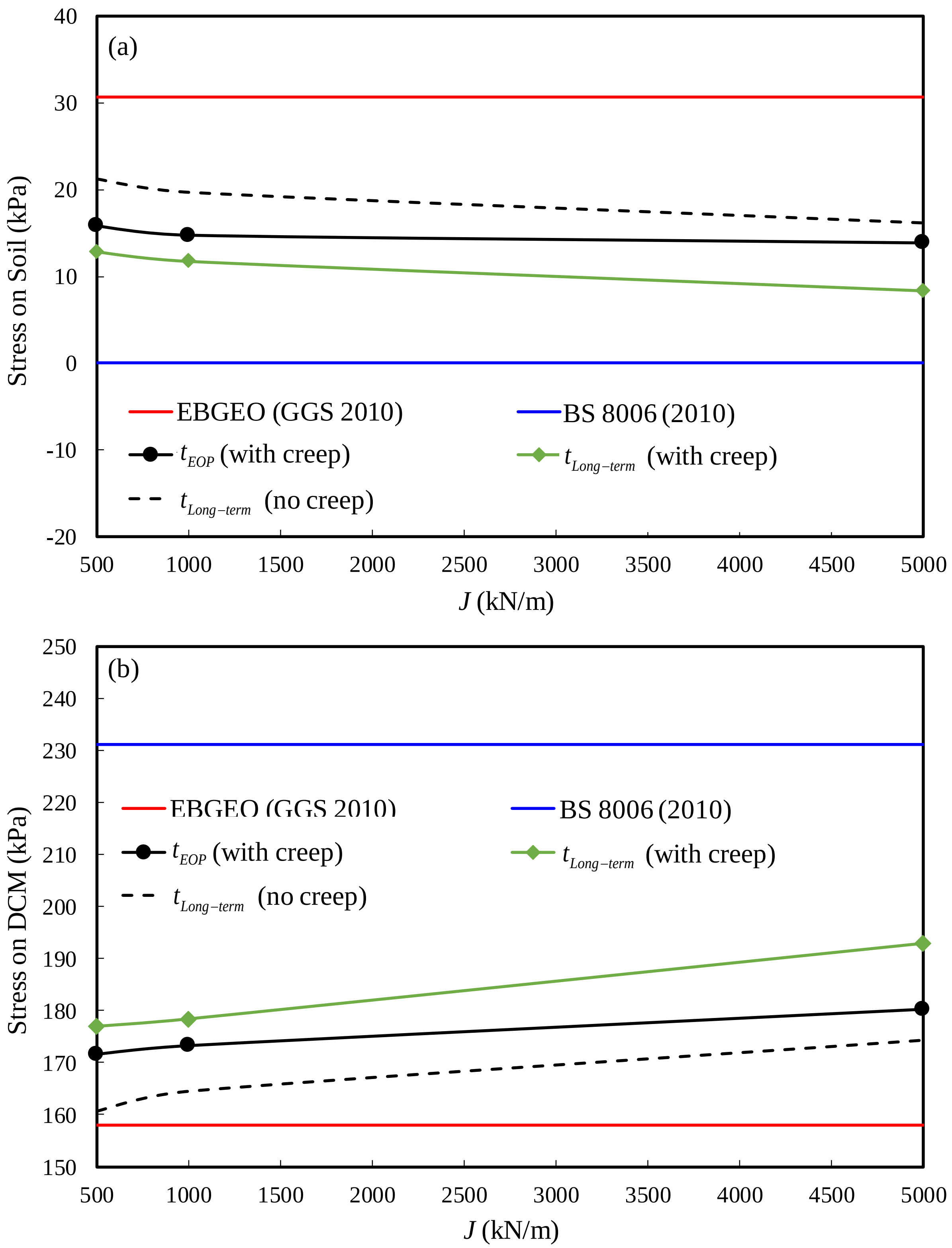

Figure 20. Average stresses on (a) soil, (b) DCM column for different values of the stiffness of the geosynthetic.

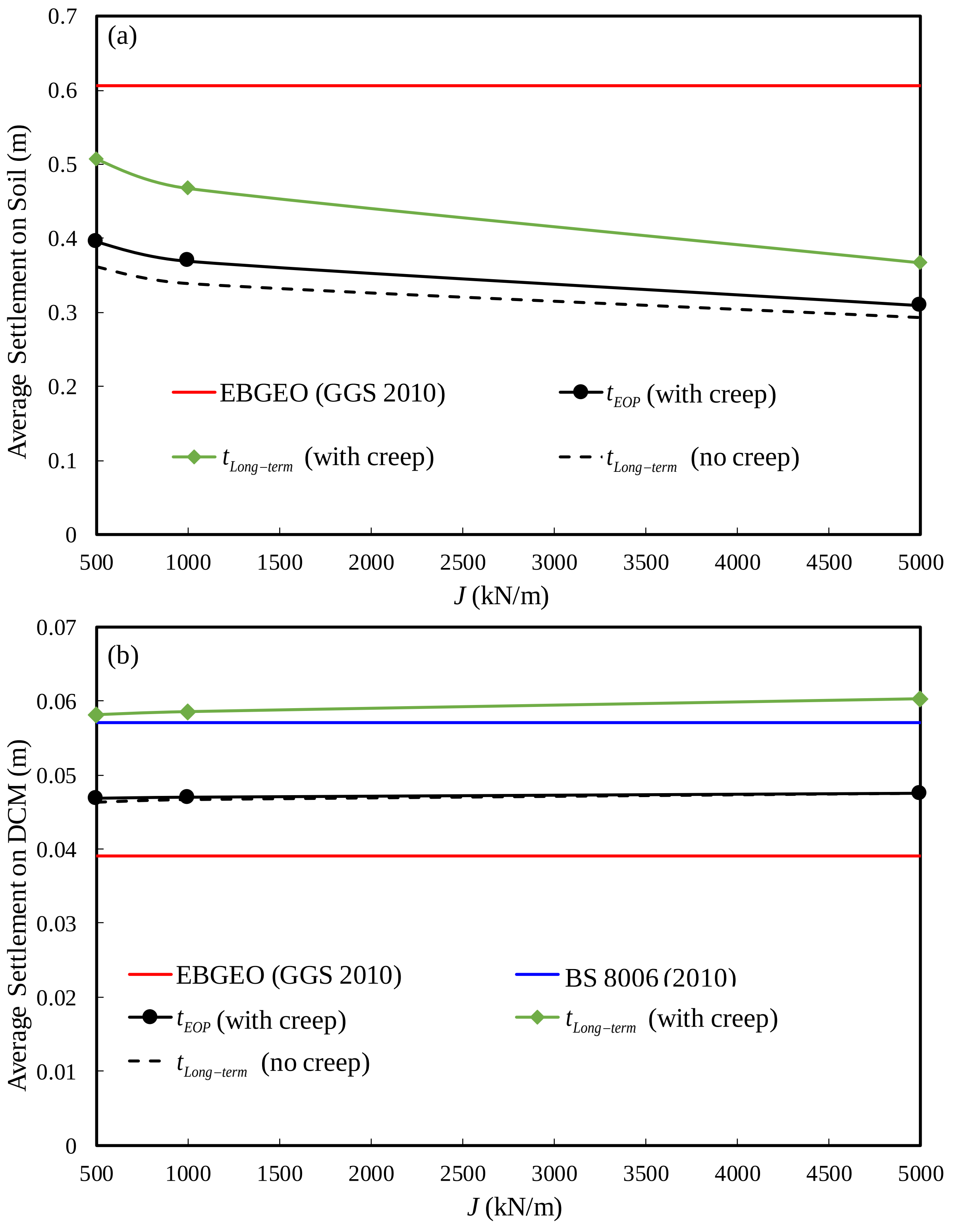

Figure 21. Average settlements on (a) soil, (b) DCM column for different values of the stiffness of the geosynthetic.