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ORIGINAL PAPER

# Prediction of the long-term settlement of the structures built on a reclaimed coral reef island: an aircraft runway

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## Abstract

Airport runways built on reclaimed coral calcareous sand foundation on coral reef islands is a type of important infrastructure for marine science observation, marine disaster relief, and marine supplies. Creep behavior of coral calcareous sand foundation under long-term loading applied by overlying structures could cause continuous foundation settlement; and excessive settlement may affect the normal service ability of airport runways built on coral reef islands. In this study, it is aimed to predict the long-term settlement of an airport runway built on a reclaimed coral reef island in the South China Sea (SCS) adopting a finite element method. Firstly, two improved Burgers creep models are proposed based on some laboratory triaxial test results; and then, they are embedded into the finite element software ABAQUS using the User Material Subroutine (UMAT) interface. Secondly, the two proposed improved Burgers creep models are validated by a series of triaxial creep tests for the coral calcareous sands sampled from a reclaimed coral reef island in SCS. Meanwhile, the parameters describing the creep behavior of the coral calcareous sands in SCS are calibrated for the subsequent numerical analysis. Thirdly, the long-term settlement of an airport runway built on a reclaimed coral reef island in SCS is numerically predicted adopting the two proposed improved Burgers creep models and the calibrated parameters. The computational results show that the settlement of the airport runway is in the range of 6.7 to 19.9 mm in the future 50 years, satisfying the requirement of Chinese design code MH/T 5027-2013. Finally, parametric analysis is performed to screen the significance and sensitivity of the parameters describing the creep behavior of the coral calcareous sands.

**Keywords** Long-term settlement · Reclaimed coral reef islands · Improved Burgers creep model · Aircraft runway on coral reef island · Creep of coral sands

## Introduction

Airport runways built on reclaimed coral calcareous sand foundation on the top of natural coral reef islands can provide great convenience for the marine observation, marine rescue and marine supplies. In the period of World War II, an airport runway had been built by the USA on Guam which was an island consisting of volcanic formations, limestone formations, and coral reef limestone formations. In December 2007, an aircraft runway with a length 1150 m firstly was successfully constructed on the Taiping Island, which is a natural coral reef island in the South China Sea (SCS). Most recently, three aircraft runways with a length about 3000 m also are successfully constructed by China on reclaimed coral calcareous sand foundation on some natural coral reef islands in SCS. In the design of aircraft runways built on coral reef islands, the long-term settlement of the aircraft runways is one of the main concerns for engineers, because the post-construction long-term settlement will directly significantly affect the normal service of aircraft runways. A typical example is that the reclaimed foundation of the Kansai airport in Japan has sunk maximally around 10 m at some local positions (Mesri and Funk 2014; Puzrin et al. 2010) in the past 30 years after completion. The excessive settlement has greatly increased the maintenance cost of the airport and caused the runway's inability to normally serve in

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rainstorm due to water accumulation. Therefore, the prediction of the post-construction settlement of aircraft runway is a crucial part in the design.

In order to quantitatively study the long-term settlement of a structure's foundation, a series of investigation on soil creep behavior have been conducted. Nishihara (1952, 1958) proposed a creep constitutive model to describe the primary and the secondary creep deformation of soil when the soil was in a stable creep stage. Singh and Mitchell (1968) proposed an empirical relationship for the stress-strain-time of soil based on the results of a series of triaxial creep tests. However, this empirical relationship was only applicable when the deviatoric stress was in the range of 20 to 80% of the peak deviatoric stress. Mesri et al. (1981) proposed a power function for the strain development of soil via time. However, the creep deformation predicted by the Mesri model did not converge with time. Typically, the Burgers creep model was proposed to describe the viscoelastic deformation of material based on the idea that a Maxwell body and a Kelvin body were connected in series (Dorfman and Faller 1982). The creep deformation predicted by Burgers model also could not converge with time, similar to that of Mesri model. After that, Murayama (1983); Murayama et al. (1984) further proposed a creep constitutive model based on a series of triaxial creep tests for sand. Based on the classic Burgers model, Fu and Huang (2008) further proposed an improved Burgers model. This improved Burgers model can distinguish the instantaneous elastic deformation, viscoelastic deformation, and viscous flow deformation of materials; and the creep deformation predicted by this improved Burgers model was converged by introducing an exponential function. Later, He et al. (2011) also improved the classic Burgers model by changing the power of time from 1 to a parameter which was in the range of 0 to 1.

Except for the creep mathematical model, some researchers conducted a large number of creep tests to study the creep behavior of soil, for example, Lv et al. (2017) comparatively studied the creep behavior of coral calcareous sand and silica sand by performing triaxial tests. It was found that the volumetric, axial, and shear creep of coral calcareous sand could reach up to approximately 5, 20, and 10 times those of silica sand, respectively. Enomoto et al. (2016) carried out a series of triaxial creep tests for gravel soil to analyze the creep behavior in a more comprehensive way. Recently, Ye and Cao (2019) and Cao and Ye (2019) carried out a series of triaxial creep tests for coral calcareous sands sampled from the reclaimed coral reef island in SCS. It is found that the initial deformation of coral calcareous sands before creep is positively related to the applied deviatoric stress and inversely related to the effective confining pressure. Based on this finding, a four-parameter creep model relating the creep deformation to time, deviatoric stress, and effective confining pressure is proposed by Cao and Ye (2019).

Generally, the long-term settlement of structures after completion can be quantitatively monitored (Jiang and Lin (2010), Shen et al. (2014), Di et al. (2016), Shi et al. (2018) or numerically predicted. However, it is difficult for the monitoring systems to sustain for more than 10 years. If the long-term settlement of structures after more than 10 years is desired, the numerical prediction is the only feasible way. On this aspect, a series of works have been performed in recent decade. Wongsaroj et al. (2013) employed numerical simulation to study the consolidation settlement characteristics of tunnels built in London clay strata. Their computational results was comparable with field monitoring records. Pramthawee et al. (2017) established a creep constitutive model considering the confining pressure, stress ratio and deviatoric stress at first. Then this creep model was integrated into a modified hardening soil model to predict the long-term settlement of a high rockfill dam. Zhang et al. (2018a) evaluated the long-term settlement of a circular mat foundation built on clay strata adopting fractional derivatives. Qiu et al. (2018) investigated the long-term settlement of a tunnel using numerical method. Their predicted results was also comparable with field data. Zhang et al. (2018b) combined the one-dimensional creep tests with the FLAC software to simulate the post-construction settlement of a high fill foundation built on loess. Their results showed that the settlement of the foundation could approach to stable state after 3 to 4 years. And the post-construction settlement mainly occurred in the first year. Yao et al. (2019) predicted the long-term settlement of a high-speed railway foundation and compared their numerical simulation results with the monitoring results. It is indicated that numerical simulation is reliable and feasible to predict the long-term settlement of structures.

In recent years, several aircraft runways have been successfully constructed on the reclaimed coral calcareous sand foundation on some coral reefs in the South China Sea (SCS). Due to the fact that these newly reclaimed coral sand foundation are relatively loose relative to the naturally deposited foundation (Wang et al. 2009; Shahnazari and Rezvani 2013), the post-construction long-term settlement of the aircraft runways should be paid attention and quantitatively evaluated, making sure that the aircraft runways could normally be used in their designed service period. To the authors' knowledge, there is basically no work to numerically predict the long-term settlement of aircraft runway built on the newly reclaimed coral sand foundation in literature so far. In this study, the Burgers creep models respectively improved by Fu and Huang (2008) and He et al. (2011) are further improved at first based on the triaxial test results for the reclaimed coral calcareous sand conducted by Cao and Ye (2019). The two improved Burgers creep models are incorporated into the ABUQUS computation platform through the User Material Subroutine (UMAT) interface; and the validation work is also performed. Finally, based on the two improved Burgers creep models, the long-term settlement of aircraft runway built on the reclaimed coral sand foundation in SCS is predicted. The computational results show that the post-construction subsidence of the aircraft runway is in the range of 6.7 to 19.9 mm in the future 50 years. The Code for Geotechnical Engineering Design of Airport MH/T 5027–2013 released by the Civil Aviation Administration of China (2013) requires that the long-term settlement of an aircraft runway must be less than 200 mm. Therefore, the long-term settlement of the aircraft runway built on the reclaimed coral reef island can satisfy the requirement of the national specification.

## Creep model

A creep constitutive model is to be used to describe the relationship between stress-strain-time of materials. In literature, there are several types of creep models that have been proposed, for example, Mesri model, Burgers model, and so on. Among them, Burgers model and its improved forms are widely used to predict the long-term deformation of foundation and the long-term settlement of structures. In this study, the Burgers models also are adopted.

### Burgers creep model

#### Classic Burgers creep model

The classic Burgers creep model (Burgers et al. 1982) was proposed based on the idea that a Kelvin body and a Maxwell body were connected in series (as illustrated in Fig. 1). There are four parameters to describe the creep behavior of materials.

The stress-strain-time equation is formulated as the following:

$$\varepsilon = \frac{q}{E_0} + \frac{q}{E_1}\left(1 - e^{-\frac{E_1}{\eta_1}t}\right) + \frac{q}{\eta_2}t \tag{1}$$

where $\varepsilon$ is the total strain, $q$ is the stress, $t$ is the time variable, $E_0$ and $E_1$ are the elastic modulus, and $\eta_1$and $\eta_2$ are the viscosity coefficient. $q/E_0$ is the initial deformation before creep occurring. Due to the fact that the power of time variable $t$ is one, the creep strain $\varepsilon$ described by Eq. (1) will increases with the time. As a result, the classic Burgers model is a non-convergence model.

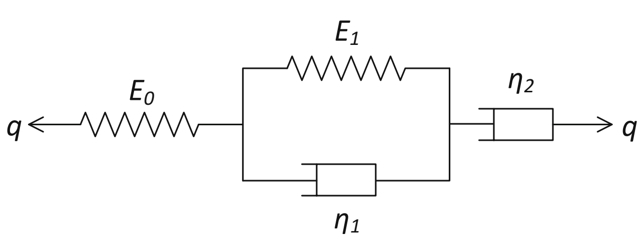



**Fig. 1** Schematic diagram of the classic Burgers creep model in which a Kelvin body and a Maxwell body are connected in series

#### Kong's Burgers creep model

In the classic Burgers creep model, the creep strain linearly increase with time, as demonstrated in Eq. (1). In order to describe the nonlinear creep deformation of materials with time, He et al. (2011) proposed a nonlinear Burgers creep model by replacing the viscous element in the Maxwell body with a soft-matter element, as shown in Fig. 2. The soft-matter element is a kind of ideal material between the ideal solid and the ideal fluid.

The creep strain in the Kong's Burgers creep model is formulated as:

$$\varepsilon = \frac{q}{E_0} + \frac{q}{E_1}\left(1 - e^{-Rt}\right) + \frac{q}{C}t^{\beta} \tag{2}$$

where $R = E_1/\eta_1$, $\eta_1$ is viscosity coefficient; $C = \xi \cdot \Gamma(1+\xi)$, $\xi$ and $\beta$ are the parameters of the soft-matter element. When $\beta =$ 0, the soft-matter element becomes a spring, representing an ideal solid. When $\beta = 1$, it becomes a viscous damper, representing an ideal fluid. When $0 < \beta < 1$, the soft-matter element represents a kind of material between the ideal solid and the ideal fluid. Even though the Kong's Burgers creep model could describe the nonlinear creep deformation of materials, the creep strain predicted by this model will not converge with time, similar to that of classic Burgers creep model. However, the incremental rate of the creep strain will be extremely slow comparing with that predicted by the classic Burgers creep model in the later stage.

#### Huang's Burgers creep model

As illustrated above, it has been known that the creep strain predicted by the classic Burgers creep model and the Kong's Burgers creep model both are not converged with time. In order to solve the problem of convergence for stabilized materials, Fu and Huang (2008) extended the pure viscous element $\eta_2$ in the classic Burgers model (Fig. 1) to a generalized nonlinear dashpot, as shown in Fig. 3. The expression of Huang's Burgers creep model is:

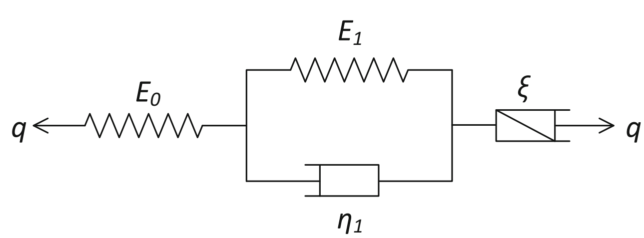



**Fig. 2** Schematic diagram of the Kong's Burgers creep model, in which a soft-matter element is used to describe the nonlinear creep deformation of materials

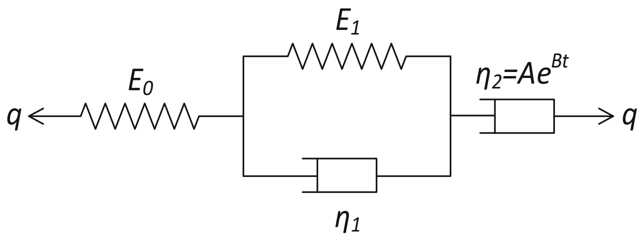



**Fig. 3** Schematic diagram of the Huang's Burgers creep model

$$\varepsilon=\frac{q}{E_0}+\frac{q}{E_1}\left(1-e^{-\tau t}\right)+\frac{q}{AB}\left(1-e^{-Bt}\right) \tag{3}$$

where $A$ and $B$ are the model parameters of the nonlinear dashpot, respectively, $\tau=E_1/\eta_1$. When the value of $B$ infinitely approaches to 0, it leads to $\eta_2=A$. As a result, the nonlinear dashpot can be degraded into a linear viscous damper, and Eq. (3) is equivalent to Eq. (1). It means that the Huang's Burgers creep model can be degraded into the classic Burgers model. In Eq. (3), it can be seen that the strain predicted by Huang's Burgers creep model will definitely converge with time.

## Improved Burgers creep model

In Eqs. (1), (2), and (3), it is found that the parameter $E_0$ which is adopted to determine the initial strain of materials before creep (can be referred as initial deformation modulus of materials) is considered to be a constant in the above mentioned three creep models. However, previous researches (Zhang et al. 2018a, 2018b, 2018c; Cao et al. 2017) revealed that the deformation modulus of granular materials is not a constant value, but dependent on the confining pressure and applied deviatoric stress. Based on this point, Huang's and Kong's Burgers models will be further improved in this study according to the laboratory test data.

To understand the time-dependent creep behavior of coral calcareous sand, recently, Ye and Cao (2019) and Cao and Ye (2019) performed a series of triaxial tests for the samples coming from the reclaimed coral reef islands in SCS. Based on their test results, Cao and Ye (2019) find that the initial deformation before creeping of the coral calcareous sand is positively correlated with the applied deviatoric stress, $q$, and is inversely related to the effective confining pressure, $p$, as illustrated in Fig. 4. Based on this finding, the following nonlinear relationship is proposed by Cao and Ye (2019):

$$\varepsilon_0=K\frac{(q/P_a)^m}{(p/P_a)^n} \tag{4}$$

where $q$ is the deviatoric stress and $p$ is the effective confining pressure. $P_a=101.3$ kPa is the atmospheric pressure, playing the non-dimensional role. $K$, $m$, and $n$ are the parameters related to the structural properties of soil. They are all dimensionless quantities. According to Cao and Ye (2019)'s test results shown in Fig. 4, it is found that the initial strain $\varepsilon_0$ of the coral calcareous sand soils from SCS before creeping have a very good linear relationship with the non-dimensional quantity $(q/P_a)^m/(p/P_a)^n$, regardless of being the dense state or loose state. The $R^2$ both are greater than 0.92.

According to Eq. (4), and combining relationship between the applied deviatoric stress and initial strain:

$$q=E_0\varepsilon_0 \tag{5}$$

The relationship between the initial deformation modulus $E_0$ of soil and the effective confining pressure $p$, deviatoric stress $q$ is formulated as:

$$\frac{q}{\varepsilon_0}=E_0=\frac{q}{K}\frac{(p/P_a)^n}{(q/P_a)^m} \tag{6}$$

Substituting Eq. (6) into Eq. (2), the improved Kong's Burgers creep model becomes:

$$\varepsilon=K\frac{(q/P_a)^m}{(p/P_a)^n}+\frac{q}{E_1}\left(1-e^{-\frac{E_1}{\eta_1}t}\right)+\frac{q}{C}t^{\beta} \tag{7}$$

Substituting Eq. (6) into Eq. (3), the improved Huang's Burgers creep model becomes:

$$\varepsilon=K\frac{(q/P_a)^m}{(p/P_a)^n}+\frac{q}{E_1}\left(1-e^{-\frac{E_1}{\eta_1}t}\right)+\frac{q}{AB}\left(1-e^{-Bt}\right) \tag{8}$$

## Finite element implementation

The creep strain described in Eq. (7) and Eq. (8) actually are established under the condition of one-dimensional stress state. However, the stress state in soil foundation actually is three-dimensional in the numerical computation of the long-term settlement of structures. Therefore, it is necessary to build a connection between Eqs. (7) and (8) and the three-dimensional stress state, making sure Eqs. (7) and (8) are applicable in two/three-dimensional numerical modeling. Fu and Huang (2008) proposed a method to build this connection. They extended the classic plastic theory into the creep analysis of soil foundation. It was assumed that the development of shear creep strain induced by deviatoric stress still satisfied the classic plastic potential surfaces in stress space, and there is no the volumetric creep strain under confining pressure. And the one-dimensional creep strain and deviatoric stress in Eqs. (7) and (8) were replaced by the equivalent Von Mises strain and the equivalent Von Mises stress; more detailed information can be found in Fu and Huang (2008).

The two improved Burgers creep models proposed in this study are programmed and embedded into the finite element analysis software ABAQUS through the User Material Subroutine (UMAT) Interface. The algorithm flow chart is illustrated in Fig. 5. Since the two improved Burgers creep

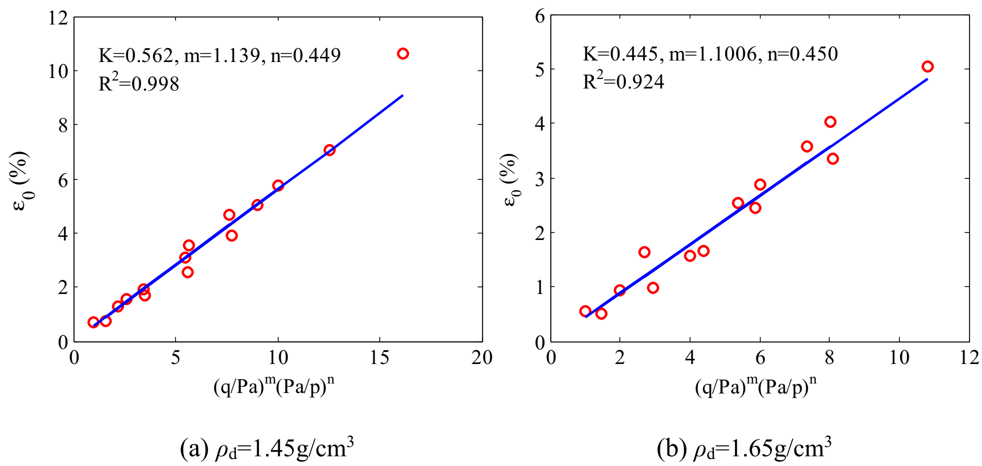



**Fig. 4** Relationship between initial strain $\varepsilon_0$ of the coral calcareous sand soils from SCS and the applied deviatoric stress $q$, effective confining pressure $p$ by Cao and Ye (2019). (**a**) $\rho d = 1.45 \text{g/cm}^3$. (**b**) $\rho d = 1.65 \text{ g/cm}^3$

models consider the effects of deviatoric stress and confining pressure on the material's deformation modulus, the actual deformation modulus at each point in the soil foundation of structures is no longer a constant value, but is determined depending on the magnitude of the effective confining pressure and the deviatoric stress. In this study, the treatment of the

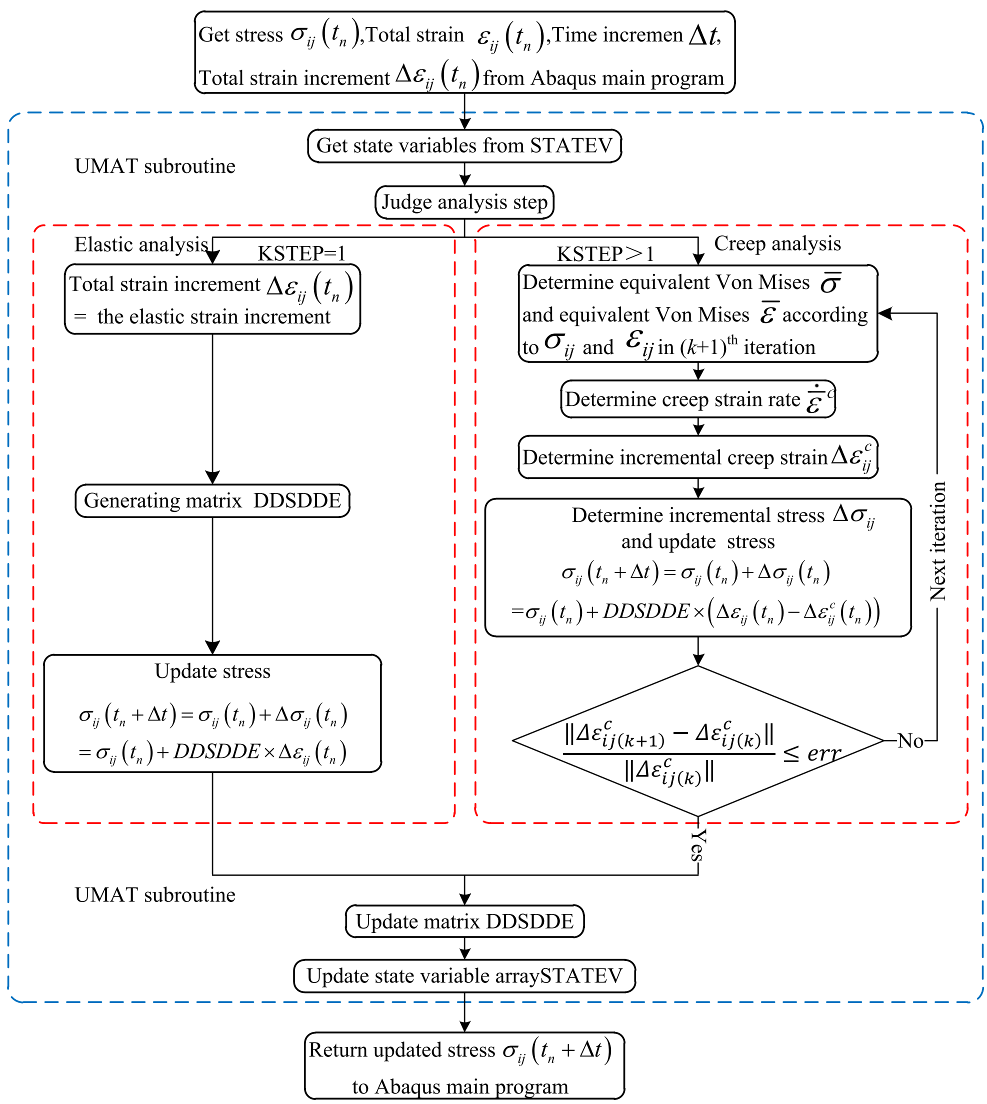



**Fig. 5** The algorithm flow chart of the UMAT subroutine in ABAQUS software

material's deformation modulus is more reasonable, especially in the case involving high ground stress. In numerical simulation, inappropriate stress and strain value would be obtained if the material's deformation modulus is simply regarded as a constant value. As a result, a great error would be brought to the result of predicted settlement of structures.

## Verification of the improved Burgers creep models

To understand the creep characteristics of the coral calcareous sand, Ye and Cao (2019) and Cao and Ye (2019) carried out a series of triaxial creep tests for the coral calcareous sand sampled from a reclaimed coral reef island in South China Sea. Here, the two improved Burgers creep models proposed in this study, as well as the UMAT subroutine integrated into ABAQUS, are validated using the experimental data provided by Ye and Cao (2019), and Cao and Ye (2019).

Firstly, a three-dimensional cylinder geometric model of coral calcareous sand is established, as shown in Fig. 6. The size of the cylinder geometric model is the same with the samples in the triaxial creep test. Its diameter is 61.8 mm and the height is 120 mm. The cylinder geometric model is meshed using an 8-node hexahedral solid element (C3D8) with a size of 4 mm. There are totally 8400 elements and 9486 nodes are generated. The line displacement and angular displacement on the bottom of the geometric model are fixed in x, y, and z direction. The confining pressure $p$ is applied to the lateral side of the model and the deviatoric stress $q$ is applied on the top of the model. The two improved Burgers creep models proposed in this study are adopted to numerically predict the creep deformation of the coral calcareous sand samples coming from SCS. The loading scheme is consistent with that of the laboratory tests conducted by Ye and Cao (2019) and Cao and Ye (2019), which are listed in Table 1.

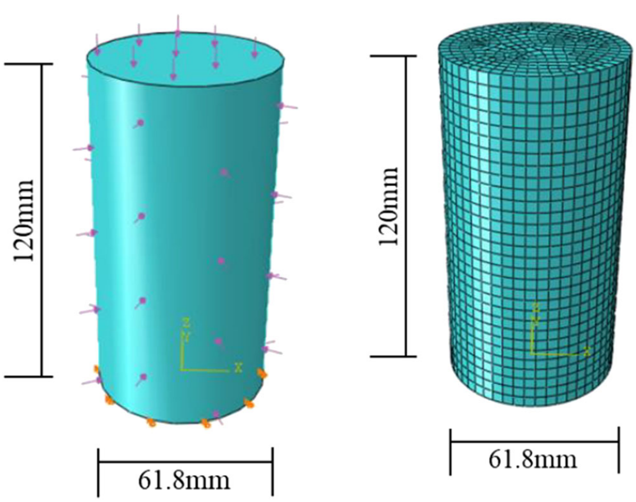



**Fig. 6** Schematic diagram of the cylinder geometrical model and the numerical mesh used for verification

**Table 1** Loading scheme of the triaxial creep test for coral calcareous sand conducted by Ye and Cao (2019), Cao and Ye (2019)

| $\rho_d$ (g/cm$^{3)}$ | $p$ (kPa) | $q$ (kPa) | | | |
|---|---|---|---|---|---|
| 1.45 | 100 | 200 | 300 | 450 | 600 |
| 1.65 | 400 | 500 | 1000 | 1500 | 2000 |

$\rho_d$: dry density, $p$: confining pressure, $q$: deviatoric stress

Before starting the numerical verification, it is necessary to calibrate the parameters for the two improved Burgers creep models proposed in this study. Based on the triaxial creep test data of creep deformation time conducted by Ye and Cao 2019, and Cao and Ye (2019) for the coral calcareous sand sampled from a reclaimed coral reef island in the South China Sea, the model parameters of the two improved creep models are successfully calibrated by the way of mathematical data fitting. The fitting results for the model parameters of the two improved creep models are listed in Tables 2 and 3.

The numerical results of the creep deformation predicted by ABAQUS are compared with the experimental results provided by Ye and Cao (2019), and Cao and Ye (2019), as shown in Figs. 7 and 8. It is found that numerical results predicted by the two improved Burgers creep models proposed in this study agree very well with the experimental data. This verification indicates that the two improved Burgers creep models proposed in this study is effective and applicable to predict the creep deformation of coral calcareous sand foundation.

## Application in practical engineering

### Engineering background

It is known that three large-scale aircraft runways have been successfully constructed by China on reclaimed coral calcareous sand foundation on some coral reef islands in SCS. In the section, one of the aircraft runways is taken as the typical example to predict the long-term settlement of the aircraft runways built on reclaimed coral calcareous sand foundation. To understand the geological stratum condition, a great of in-site drilling work have been carried out in the runway foundation on the SCS coral reel islands after the completion of the reclamation project. Totally there are about 30 boreholes with a depth of 30–200 m have been drilled on each coral reef island. The typical drilling cores in the aircraft runway foundation are shown in Fig. 9. According to the drilling data, it is found that there are approximately three geological stratums in the SCS coral reef islands. The first layer is the reclaimed loose coral calcareous sand with a thickness of 6 m. It is

**Table 2** Parameters of the improved Kong's Burgers model for the coral calcareous sand sampled from a reclaimed coral reef island in the South China Sea

| $\rho_d$ (g/cm$^3$) | $p$ (kPa) | $q$ (kPa) | $E_1$ (MPa) | $\eta_1$ (GPa min) | $C$ (MPa) | $\beta$ | $K$ | $m$ | $n$ |
|---|---|---|---|---|---|---|---|---|---|
| 1.45 | 100 | 200 | 315 | 13.9 | 499 | 0.1474 | 0.562 | 1.139 | 0.449 |
| | | 300 | 345 | 32.7 | 443 | 0.1394 | | | |
| | | 450 | 299 | 12.8 | 637 | 0.1522 | | | |
| | | 600 | 189 | 6.44 | 616 | 0.1616 | | | |
| 1.65 | 400 | 500 | 1079 | 93.9 | 2520 | 0.1638 | 0.445 | 1.1006 | 0.45 |
| | | 1000 | 732 | 63 | 1920 | 0.1841 | | | |
| | | 1500 | 958 | 79.2 | 2140 | 0.1749 | | | |
| | | 2000 | 1390 | 196 | 1950 | 0.1963 | | | |

composed largely of calcareous sand and a small amount of coral gravels. The second layer looks similar with the first reclaimed layer. However, the second layer is not the reclaimed body, but the naturally deposited stratums, referred to as the original calcareous sand. The second layer is also loose and largely composed of calcareous sand and a small amount of coral gravels. The thickness of the second layer is about 30 m. The third layer is coral reef limestone when the depth is greater than 36 m. Due to the fact that the third layer of coral reef limestone is dense and hard (uniaxial compressive strength is greater than 20 MPa), its creep deformation is apparently small relative to the overlying loose coral calcareous sand. The long-term settlement of structures built on reclaimed coral reef islands mainly attribute to the creep deformation of the loose coral calcareous sand in the first and second layers. According to this recognition, only the first and second layer (total thickness is 36 m) are considered in the computational geometrical model to predict the long-term settlement of the aircraft runway built on reclaimed coral calcareous sand foundation.

## Geometrical model and parameters

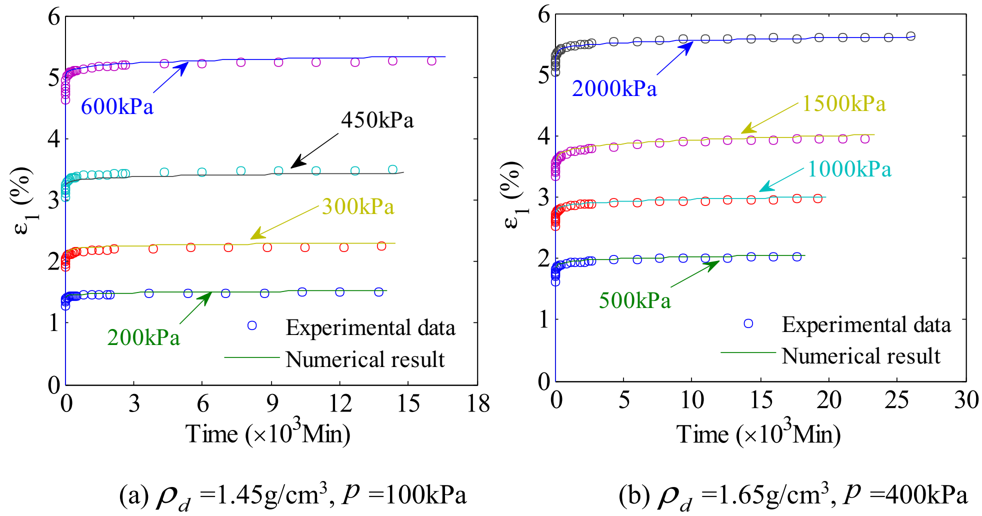
The geometrical model is illustrated in Fig. 10. An aircraft runway with a width of 50 m is constructed on the reclaimed coral calcareous sand foundation on a coral reef islands. The length and thickness of the computational geometrical model is set as 300 m and 36 m, respectively. In computation, the two lateral sides of the geometrical model are fixed only in a horizontal direction; and the bottom of the geometrical model is fixed both in horizontal and vertical directions. The distance from the lateral ends of the aircraft runway to the lateral sides of the geometrical model is 125 m, which is enough to eliminate the effect of the fixed lateral sides.

The dry density of the first and second layers have been measured at in-site using the drilling cores. The dry density of the first layer (thickness = 6 m) and second layer (thickness = 30 m) is about 1.45 g/cm$^3$ and 1.65 g/cm$^3$, respectively. According to the long-term observation of the underground water elevation on the reclaimed coral reef in the past 3 years, the monitor data shows that the underground water level fluctuates between 2.5 m and 3.5 m below the ground surface within 1 year. Based on this, the underground water level is set as 3 m below the ground surface in this study. Due to the effect of buoyancy, the dry density is used in computation in the range of 0–3 m below the ground surface; and the buoyant density is used in the range of 3 to 36 m below the ground surface. Finally, there are four types of materials in the geometrical model. They are the original calcareous sand, labeled as 1; the reclaimed calcareous sand beneath the SWL, labeled as 2; the reclaimed calcareous sand over the SWL, labeled as 3; and the concrete runway, labeled as 4. The aircraft runway is made of concrete. The elastic constitutive model is used to describe its behavior. The density of the concrete runway is set

**Table 3** Parameters of the improved Huang's Burgers model for the coral calcareous sand sampled from a reclaimed coral reef island in the South China Sea

| $\rho_d$ (g/cm$^3$) | $p$ (kPa) | $q$ (kPa) | $E_1$(MPa) | $\eta_1$ (GPa min) | $A$ (GPa) | $B$ | $K$ | $m$ | $n$ |
|---|---|---|---|---|---|---|---|---|---|
| 1.45 | 100 | 200 | 274 | 624 | 4.6 | 0.0343 | 0.562 | 1.139 | 0.449 |
| | | 300 | 235 | 302 | 6.5 | 0.0311 | | | |
| | | 450 | 317 | 653 | 5.0 | 0.036 | | | |
| | | 600 | 309 | 536 | 25 | 0.0416 | | | |
| 1.65 | 400 | 500 | 978 | 4080 | 54.5 | 0.0128 | 0.445 | 1.1006 | 0.45 |
| | | 1000 | 663 | 2780 | 62.9 | 0.0074 | | | |
| | | 1500 | 738 | 2841 | 73.5 | 0.0193 | | | |
| | | 2000 | 470 | 1590 | 24.2 | 0.0237 | | | |

**Fig. 7** Comparison of the numerical results with the experimental results (Ye and Cao (2019), and Cao and Ye (2019)) adopting the improved Kong's Burgers model. (**a**) $\rho_d = 1.45$ g/cm$^3$,$p = 100$ kPa. (**b**) $\rho_d = 1.65$ g/cm$^3$,$p = 400$ kPa




as 2800 kg/m$^3$ and its elastic modulus is set as 10 GPa. The basic properties of the four materials are listed in Table 4.

Material 4 is the concrete runway. It is not considered as a porous media in this study. Therefore, its void ratio is 0. The void ratio is determined adopting equation:

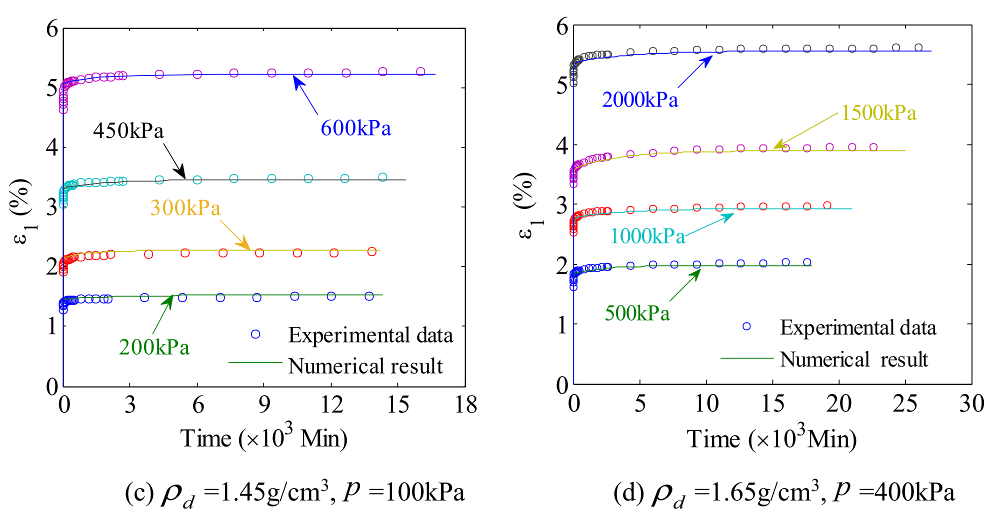
$$e = G_s \rho_w / \rho_d - 1 \quad (9)$$

where $G_s$ is the relative density of soil particles, $G_s = 2.83$ for coral calcareous sand. The buoyant density of material 1 and 2 is determined adopting equation:

$$\rho = \rho_d - \rho_w / (1 + e) \quad (10)$$

The aircraft runway and the reclaimed coral sand foundation are meshed by CPE4 element. Totally 100,800 elements and 102,085 nodes are generated. Adopting the improved Kong's Burgers model and the improved Huang's Burgers model proposed in this study, the long-term settlement of the aircraft runway built on reclaimed coral calcareous sand foundation is numerically predicted. Taking the center point on the runway surface as the observation point to record the vertical displacement in computation. The calibrated model parameters when $p = 100$ kPa and $q = 200$ kPa listed in Tables 2 and 3 are used in computation for the materials 2 and material 3 ($\rho_d$ = 1.45 g/cm$^3$); meanwhile, the calibrated model parameters when $p = 400$ kPa and $q = 500$ kPa listed in Tables 2 and 3 are used for the material 1 ($\rho_d$ = 1.65 g/cm$^3$). The model parameters used in computation for the two improved Burgers creep models proposed in this study are listed in Tables 5 and 6. Due to the fact that these model parameters are calibrated form the triaxial creep test data provided by Ye and Cao (2019), and Cao and Ye (2019), the reliability of these parameters can be guaranteed to some extent.

**Fig. 8** Comparison of the numerical results with the experimental results (Ye and Cao (2019), and Cao and Ye (2019)) adopting the improved Huang's Burgers model. (**c**) $\rho_d = 1.45$ g/cm$^3$,$p = 100$ kPa. (**d**) $\rho_d = 1.65$ g/cm$^3$,$p = 400$ kPa



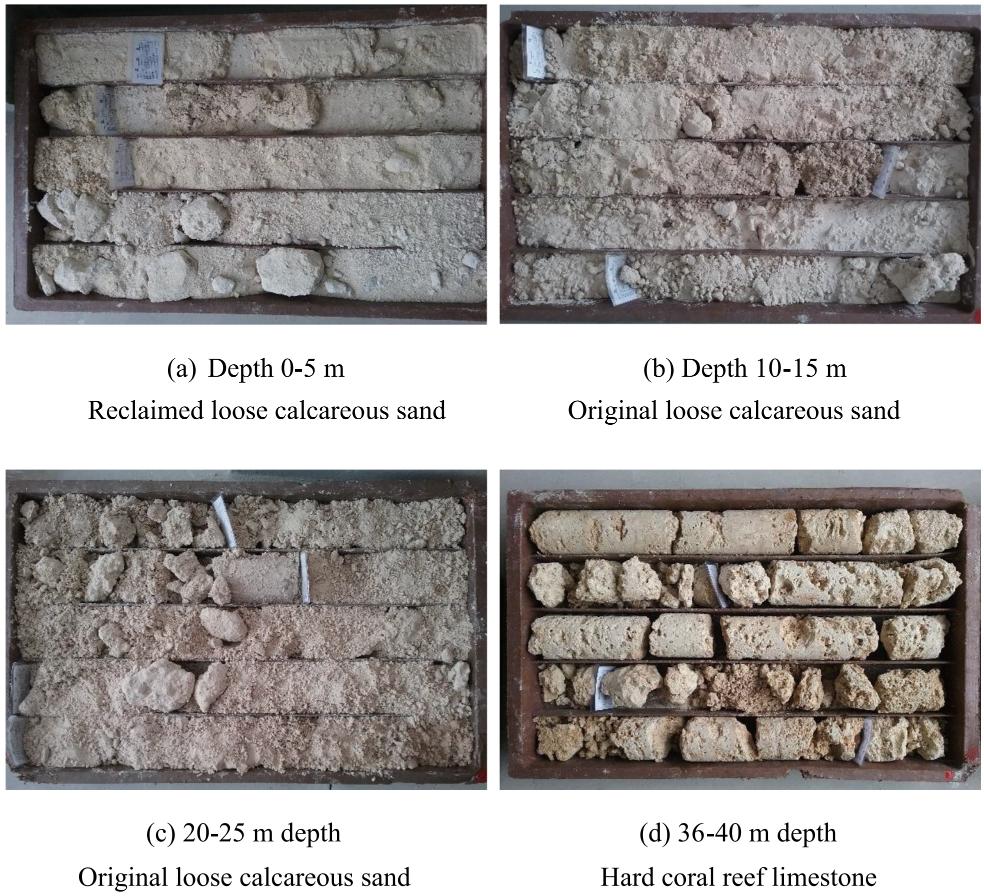



**Fig. 9** Photos of the typical drilling cores in the aircraft runway foundation (taking the ground surface as the zero elevation). (**a**) Reclaimed loose calcareous sand (depth 0–5 m). (**b**) Original loose calcareous sand (depth 10–15 m). (**c**) Original loose calcareous sand (depth 20–25). (**d**) Hard coral reef limestone (depth 36–40 m)

## Analysis of the long-term settlement results

### Initial state

In the process of the runway foundation reclamation and the runway construction, the runway foundation certainly undergoes a time-independent instantaneous elasto-plastic deformation under their own weight until an equilibrium state is reached. This state should be used as the initial condition for the subsequent creep settlement. Figure 11a shows the initial effective stress state of the aircraft runway and its coral calcareous sand foundation. Due to the gravity compression of

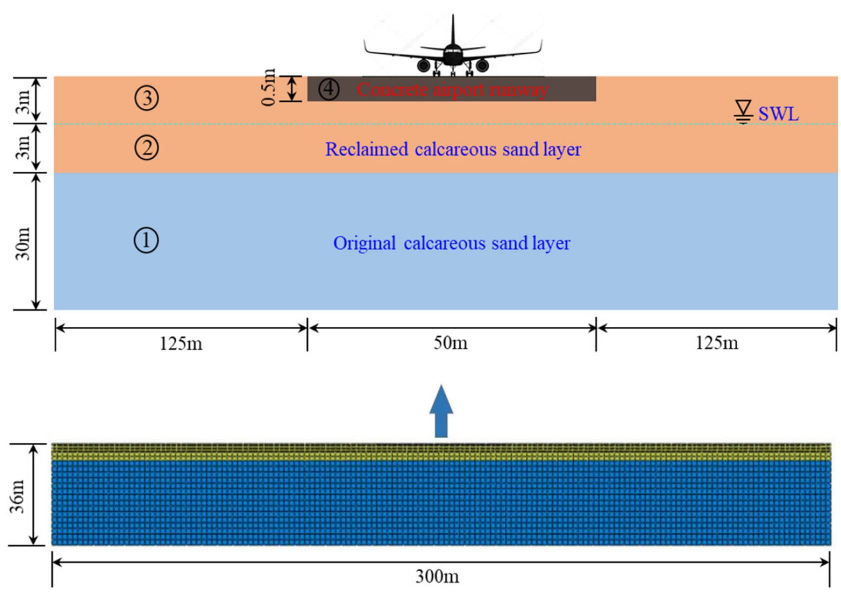



**Fig. 10** Schematic diagram of the geometrical model and FEM mesh for the aircraft runway and the reclaimed coral sand foundation in South China Sea (SCS) (taking the center point on the runway surface as the observation point to record the vertical displacement in computation)

**Table 4** Basic properties of the runway and soil foundation adopted in numerical computation

| Materials | Dry density $\rho_d$ (g/cm$^3$) | Density $\rho$ (g/cm$^3$) | Poisson's ratio $\nu$ | Void ratio $e$ |
|---|---|---|---|---|
| 1 | 1.65 | 1.123 | 0.3 | 0.9 |
| 2 | 1.65 | 0.939 | 0.28 | 0.96 |
| 3 | 1.45 | 1.45 | 0.28 | 0.96 |
| 4 | 2.8 | 2.8 | 0.2 | 0 |

the aircraft runway, the effective stress in the zone beneath the runway is slightly greater than the zone away from it. It can be seen in Fig. 11b that there are two shear stress concentration zones appear near to the lateral end sides of the runway, since that the density of the runway is significantly greater than that of the surrounding coral calcareous sand. The maximum shear stress reaches 4 kPa. Figure 11c illustrates the initial vertical displacement distribution of the runway and its soil foundation. It is known that the aircraft runway has subsided downward approximately 2.6 cm before creeping.

### Creep process analysis

Figure 12 (a) and (b) show the subsidence process due to the creeping (the initial elasto-plastic deformation is excluded) respectively. In Fig. 12 (a), the subsidence processes of the aircraft runway in the earliest 60 days predicted by the two improved Burgers creep models are illustrated. It can be found that the subsidence of the aircraft runway predicted by the improved Huang's Burgers creep model is greater than that predicted by the improved Kong's Burgers creep model within the earliest 10 days. However, the subsidence of the aircraft runway predicted by the improved Huang's Burgers creep model becomes converged thereafter, always keeps the value of 6.7 mm. Meanwhile, the subsidence of the aircraft runway predicted by the improved Kong's Burgers creep model always increases with time, without convergence occurring.

In Fig. 12 (b), the subsidence processes of the aircraft runway in the future 50 years are illustrated. It is found that the subsidence of the aircraft runway predicted by the improved Huang's Burgers creep model always keeps converged state. However, the result predicted by the improved Kong's Burgers creep model always keeps growing state in the future 50 years. But the growing rate of the creep subsidence gradually becomes slow with time. The creep subsidence of the aircraft runway predicted by the improved Kong's Burgers creep model is 15.6 mm at 10 years, 17.3 mm at 20 years, and 19.9 mm at 50 years, respectively.

It can be found from the computational results that the creep subsidence of the aircraft runway built on the reclaimed coral calcareous sand foundation predicted by the two improved Burgers creep models both are not great. The Code for Geotechnical Engineering Design of Airport MH/T 5027-2013 released in 2013 by the Civil Aviation Administration of China requires that the post-construction creep subsidence of aircraft runways must be less than 200 mm. Therefore, the subsidence of the aircraft runway built on the reclaimed coral calcareous sand foundation in South China Sea satisfies the requirement specified by Chinese national code.

The model parameters of the improved Kong's Burgers model for the reclaimed coral calcareous sand are calibrated adopting the creep experimental data provided by Ye and Cao (2019), and Cao and Ye (2019). It is well known that the creep behavior of materials actually is a long-term cumulative process. However, the creep experiments in the laboratory are usually terminated artificially after several months when the incremental deformation occurring in 1 day is less than 0.005 mm, rather than terminated at the moment when the creep deformation of soil sample becomes truly stable (which may take several years even decades). Therefore, it is impossible to obtain the data of the complete creep process by the creep experiments, only the test data of the partial creep process in several months can be obtained. As a result, it brings uncertainty to the model parameters calibrated adopting mathematical fitting used in computation. Therefore, the analysis of parameter sensitivity should be conducted.

As demonstrated by Eqs. (7) and (8), the improved Kong's Burgers creep model is a non-convergence model; meanwhile, the improved Huang's Burgers creep model is a converged model. Actually, it is impossible for us to know that the long-term creep behavior of the reclaimed coral calcareous sand is converged or unconverged, due to the fact the triaxial creep test in laboratory is impossible to be performed for

**Table 5** Parameters of the improved Kong's Burgers model used in computation

| Material | $E_1$ (MPa) | $\eta_1$ (GPa min) | $C$/MPa | $\beta$ | $K$ | $m$ | $n$ |
|---|---|---|---|---|---|---|---|
| 1 | 1079 | 93.9 | 2520 | 0.1638 | 0.445 | 1.1006 | 0.45 |
| 2 | 315 | 13.9 | 499 | 0.1474 | 0.562 | 1.139 | 0.449 |
| 3 | 315 | 13.9 | 499 | 0.1474 | 0.562 | 1.139 | 0.449 |

**Table 6** Parameters of the improved Huang's Burgers model used in computation

| Material | $E_1$ (MPa) | $\eta_1$ (GPa min) | $A$ (GPa) | $B$ | $K$ | $m$ | $n$ |
|---|---|---|---|---|---|---|---|
| 1 | 978 | 4080 | 54.5 | 0.0128 | 0.445 | 1.1006 | 0.45 |
| 2 | 274 | 624 | 4.6 | 0.0343 | 0.562 | 1.139 | 0.449 |
| 3 | 274 | 624 | 4.6 | 0.0343 | 0.562 | 1.139 | 0.449 |

decades. Based on this recognition, and combining the characteristics of convergence and non-convergence of the two models, it is suggested that the result predicted by the improved Kong's Burgers model could be taken as the upper limit value for the creep subsidence of the aircraft runway, and the result predicted by the improved Huang's Burgers model could be taken as the lower limit value of that. As a result, the predicted long-term creep subsidence of the aircraft runway built on the reclaimed coral calcareous sand foundation in the South China Sea is not a value, but should be in a range. Finally, it is predicted that the long-term subsidence of the aircraft runway is 6.7 to 15.6 mm at 10 years, 6.7 to 17.3 mm at 20 years, and 6.7 to 19.9 mm at 50 years, respectively. It can be observed in Fig. 11 that, the initial vertical subsidence related to the elasto-plastic deformation of the aircraft runway before creeping is approximately 2.6 cm. Meanwhile, the predicted long-term settlement of the aircraft runway is in the range of 6.7–19.9 mm, which is 26 to 67% of the initial elasto-plastic subsidence. The magnitude of this ratio is considerable. Therefore, the long-term creep settlement should be taken into consideration when estimating the whole settlement of structures built on reclaimed coral reef islands, not just the conventional elasto-plastic subsidence.

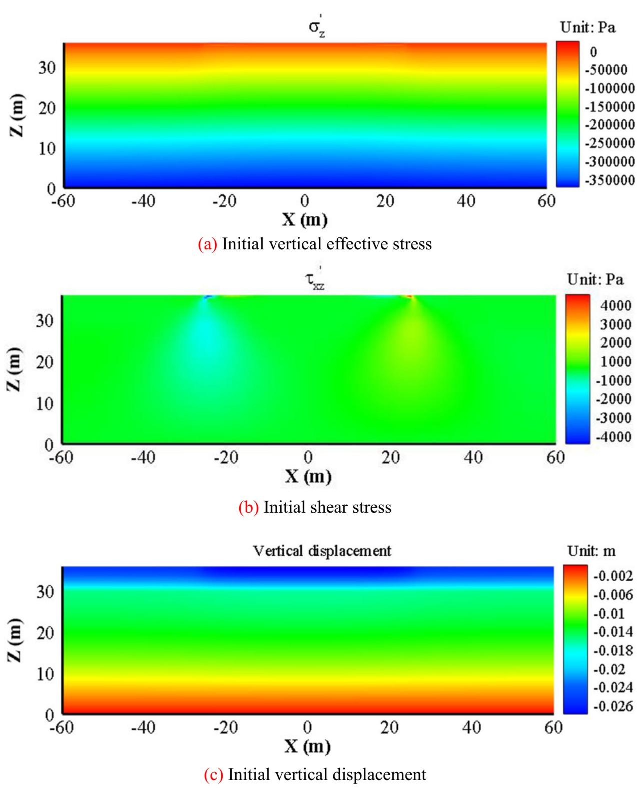
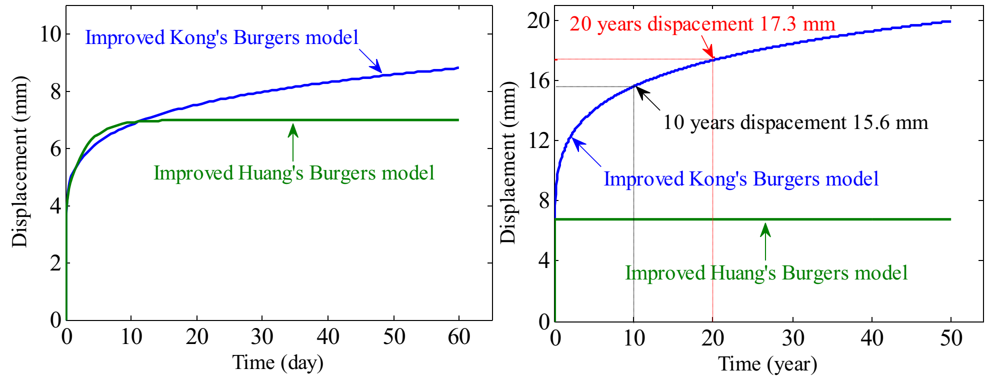



**Fig. 11** The stress and displacement distribution at the initial state before creeping in the coral sand foundation of runway foundation. (**a**) Initial vertical effective stress. (**b**) Initial shear stress. (**c**) Initial vertical displacement

## Parameters sensitivity analysis

In order to get a better understanding of the effects of the model parameters of the two improved Burgers models on the predicted long-term subsidence of the aircraft runway built on the reclaimed coral calcareous sand, sensitivity analysis is carried out in this section. In the sensitivity analysis, the model parameters of the two improved Burgers models are selected satisfying the orthogonality principle. The way is that, one of the model parameters of the two improved Burgers creep model is taken as five different values, meanwhile ensuring that the other parameters remain unchanged in computation. The values of the model parameters listed in Tables 5 and 6 are taken as the standard in this sensitivity analysis. The values of the model parameters of the two improved Burgers models selected for sensitivity analysis are listed in Tables 7 and 8, in which the standard values are labeled as italic characters. Totally, there are respectively 40 cases that need to be run for the improved Kong's Burgers creep model and the Huang's Burgers creep model. Finally, the subsidence of the aircraft runway at the future 50 years is taken as the typical result to screen the sensitivity of the computational results to the model parameters of the two improved Burgers creep models proposed in this study.

In Fig. 13, it can be seen that the long-term settlement of the aircraft runway at the 50 years basically remains unchanged when the parameter $\eta_1$ of materials 2 and 3 increases from 7.9 to 19.9 GPa min. Therefore, it is found that the computational result is not sensitive to the parameters $\eta_1$ of the improved Kong's Burgers creep model. When the parameter $\beta$ of materials 2 and 3 increases from 0.1074 to 0.1874 by 57%, the long-term settlement of the aircraft runway at the 50 years increases by 27%, so the computational result is moderately sensitive to the parameter $\beta$ of materials 2 and 3. When the parameter $C$ of materials 2 and 3 increases from 2.99 to 6.99 GPa by 133%, the long-term settlement of the aircraft runway at the 50 years reduces only by 10.5%, so the computational result is less sensitive to the parameter $C$ of materials 2




(a) 60-days (b) 50 years

**Fig. 12** Long-term settlement process of the aircraft runway built on the reclaimed coral calcareous sand foundation (noted: initial elasto-plastic deformation is excluded). (**a**) 60 days. (**b**) 50 years

and 3. Finally, when the parameter $E_1$ of materials 2 and 3 increases from 115 to 515 MPa by 347%, the long-term settlement of the aircraft runway at the 50 years decreases only by 3%. So, the computational results is also less sensitive to the parameter $E_1$ of materials 2 and 3 of the improved Kong's Burgers creep model.

It can be seen from Fig. 14 that long-term settlement of the aircraft runway at the 50 years also basically remains unchanged when the parameter $\eta_1$ of increases of material 1 from 73 to 113 GPa min. It means that the computational result is not sensitive to the parameter $\eta_1$ of the improved Kong's Burgers creep model. When the parameter $\beta$ of material 1 change from 0.1238 to 0.2038 by 65%, the settlement of the aircraft runway at 50 years increases from 9 to 37 mm by 310%. It is indicated that the computational result is highly sensitive to the parameter $\beta$ of material 1. When the parameter $C$ and $E_1$ of material 1 respectively increases from 1.52 to 3.52 GPa by 131%, from 0.479 to 1.679 GPa by 250%, the settlement of the aircraft runway at 50 years decreases by 107%, 17%, respectively. So, it is indicated that the computational result is moderately sensitive to the parameter $C$ of material 1, and is less sensitive to the parameter $E_1$ of material 1.

Overall, the computational results of the long-term settlement of the aircraft runway built on the reclaimed coral calcareous sand foundation is sensitive to the parameter $\beta$, a little sensitive to the parameter C, and basically not sensitive to the parameter C and $E_1$ if the improved Kong's Burgers creep model is used to describe the creep behavior of coral calcareous sand. Therefore, we should pay much more attention to appropriately calibrate the values of the parameter $\beta$ and $C$ of materials based on experimental data if the improved Kong's Burgers creep model is used in computation.

It can be seen in Fig. 15 that the long-term settlement of the aircraft runway at the 50 years basically remains unchanged when the parameter $\eta_1$ of materials 2 and 3 increases from 400 to 900 GPa min, indicating the computational result is completely not sensitive to the parameter $\eta_1$ of materials 2 and 3 if the improved Hunag's Burgers creep model is used. When the parameter $A$ increases from 2.6 to 6.6 GPa by 154%, the parameter $B$ increases from 0.0303 to 0.0383 by 27%, and the parameter $E_1$ of materials 2 and 3 increases from 174 to 374 MPa by 115%, the long-term settlement of the aircraft runway at the 50 years respectively reduces by 12%, 2%, and 4%. It means that the computational result is less sensitive

**Table 7** The model parameters of the improved Kong's Burgers model for sensitivity analysis

| Medium | $E_1$ (MPa) | $\eta_1$ (GPa min) | $C$ (MPa) | $\beta$ |
|---|---|---|---|---|
| Materials 2 and 3 (reclaimed coral calcareous sand) | 115 | 7.9 | 299 | 0.1074 |
| | 215 | 10.9 | 399 | 0.1274 |
| | *315* | *13.9* | *499* | *0.1474* |
| | 415 | 16.9 | 599 | 0.1674 |
| | 515 | 19.9 | 699 | 0.1874 |
| Material 1 (original coral calcareous sand) | 479 | 73.9 | 1520 | 0.1238 |
| | 779 | 83.9 | 2020 | 0.1438 |
| | *1079* | *93.9* | *2520* | *0.1638* |
| | 1379 | 103.9 | 3020 | 0.1838 |
| | 1679 | 113.9 | 3520 | 0.2038 |

**Table 8** The parameters of the improved Huang's Burgers model for sensitivity analysis

| Medium | $E_1$ (MPa) | $\eta_1$ (GPa min) | $A$ (GPa) | $B$ |
|---|---|---|---|---|
| Materials 2 and 3 (reclaimed calcareous sand) | 174 | 424 | 2.6 | 0.0303 |
| | 224 | 524 | 3.6 | 0.0323 |
| | *274* | *624* | *4.6* | *0.0343* |
| | 324 | 724 | 5.6 | 0.0363 |
| | 374 | 824 | 6.6 | 0.0383 |
| Material 1 (original calcareous sand) | 778 | 2080 | 34.5 | 0.0088 |
| | 878 | 3080 | 44.5 | 0.0108 |
| | *978* | *4080* | *54.5* | *0.0128* |
| | 1078 | 5080 | 64.5 | 0.0148 |
| | 1178 | 6080 | 74.5 | 0.0168 |

to the parameters of $A$, $B$, and $E_1$ of materials 2 and 3 in the improved Huang's Burgers creep model.

It can be found in Fig. 16 that the computational result is also completely not sensitive to the parameters $\eta_1$ of material 1 if the improved Hunag's Burgers creep model is used. When parameter $A$ increases from 34.5 to 74.5 GPa by 115%, the parameter $B$ increases from 0.0088 to 0.0168 by 90%, and the parameter $E_1$ of material 1 increases from 0.778 to 1.178 GPa by 51%, the long-term settlement of the aircraft runway at the 50 years respectively reduces by 80%, 35%, and 15%. It is indicated that the computational result is sensitive to the parameters of $A$ of material 1, and less sensitive to the parameters of $E_1$ and $B$ of material 1. We should pay much more attention to appropriately calibrate the values of the parameter $A$ of materials based on experimental data if the improved Hunag's Burgers creep model is used in computation.

## Conclusion

Taking the construction project in the South China Sea (SCS) as the engineering background, the long-term settlement of an aircraft runway built on the reclaimed coral calcareous sand

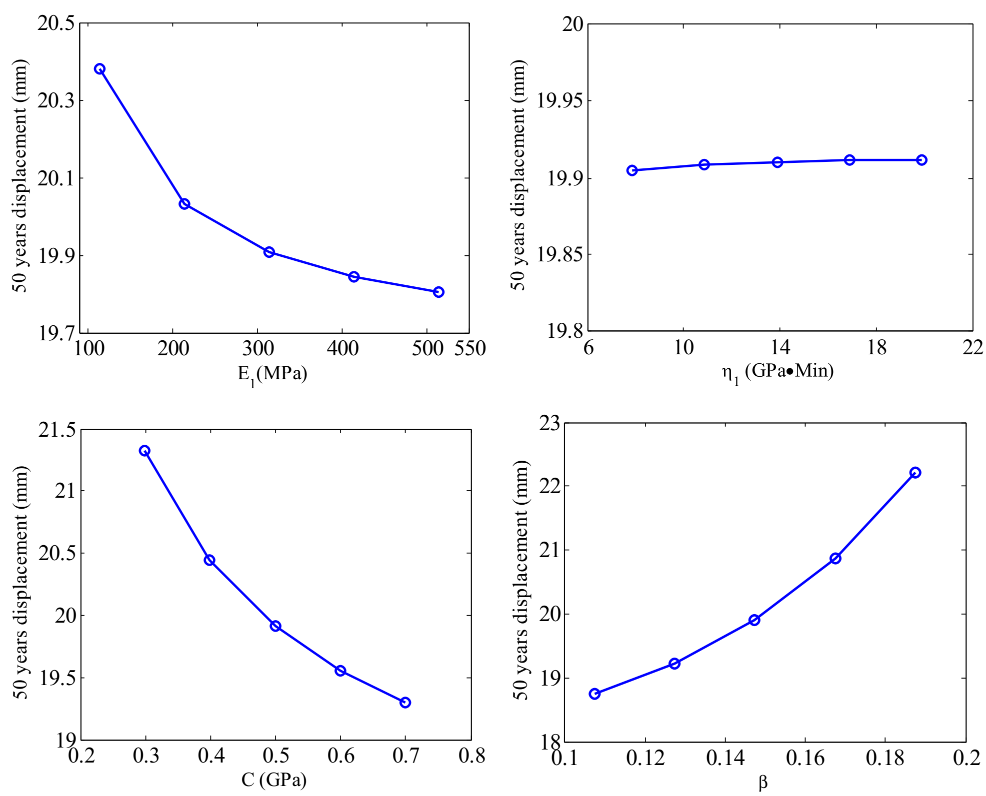



**Fig. 13** Results of the sensitivity analysis adopting the improved Kong's Burgers creep model, where the model parameters of material 1 remain unchanged, and the model parameters of materials 2 and 3 is changed

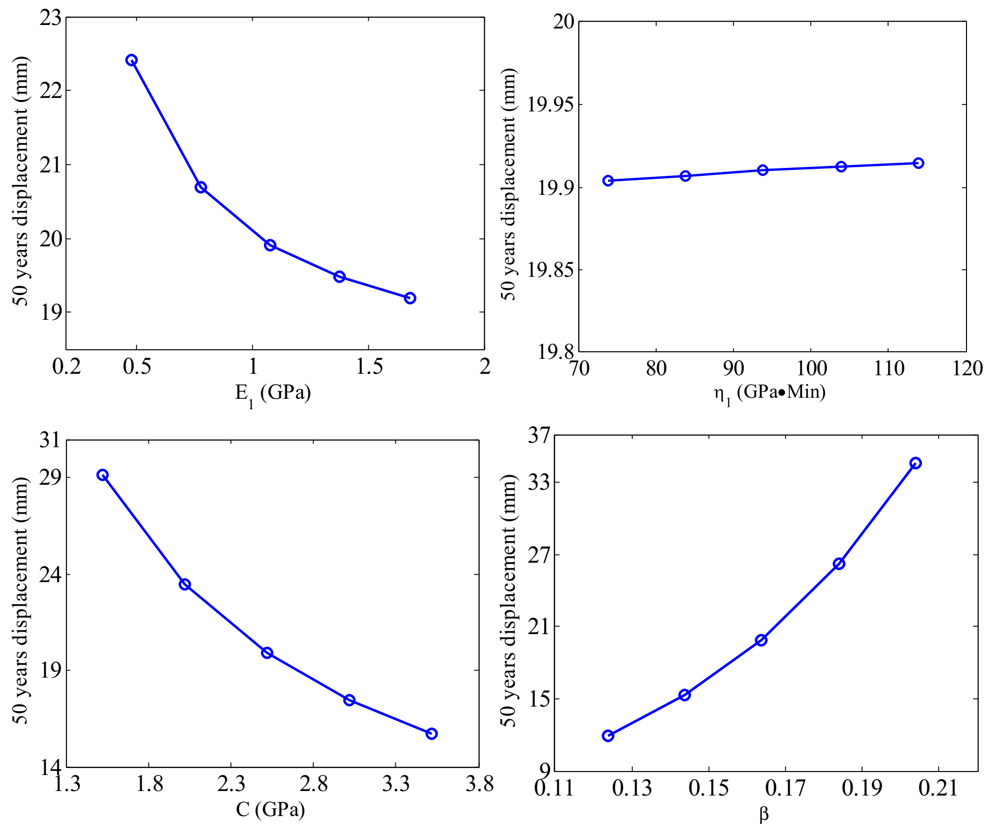



**Fig. 14** Results of the sensitivity analysis adopting the improved Kong's Burgers creep model, where the model parameters of materials 2 and 3 remain unchanged, and the model parameters of material 1 is changed

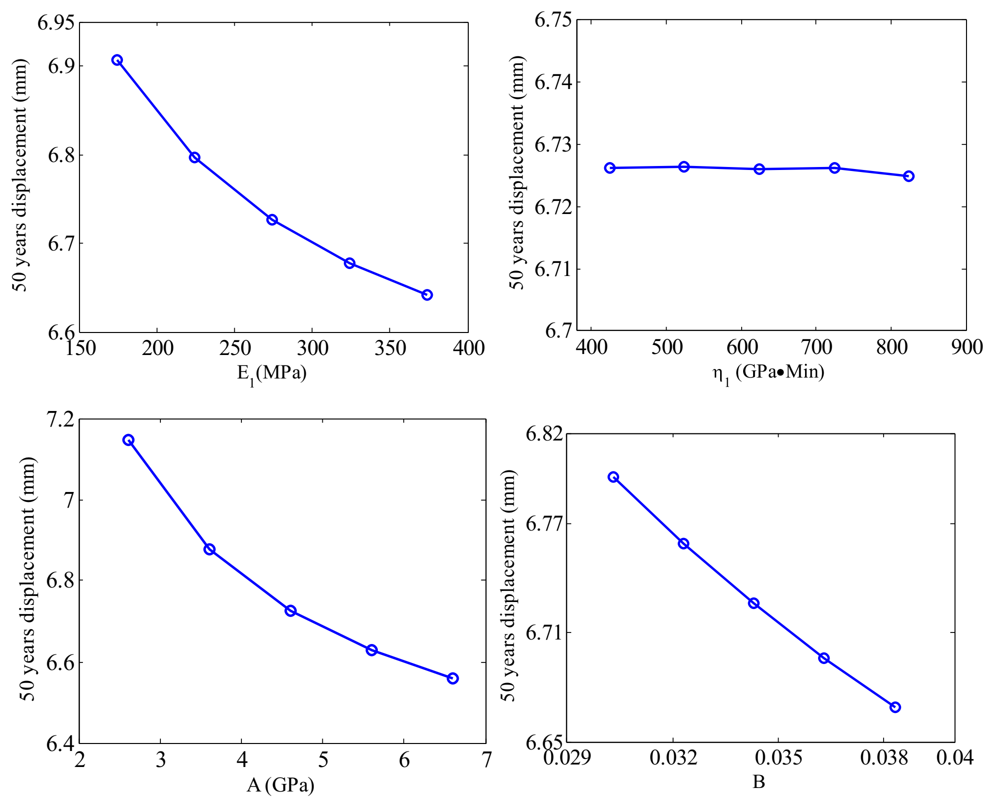



**Fig. 15** Results of the sensitivity analysis adopting the improved Huang's Burgers creep model, where the model parameters of material 1 remain unchanged, and the model parameters of materials 2 and 3 is changed

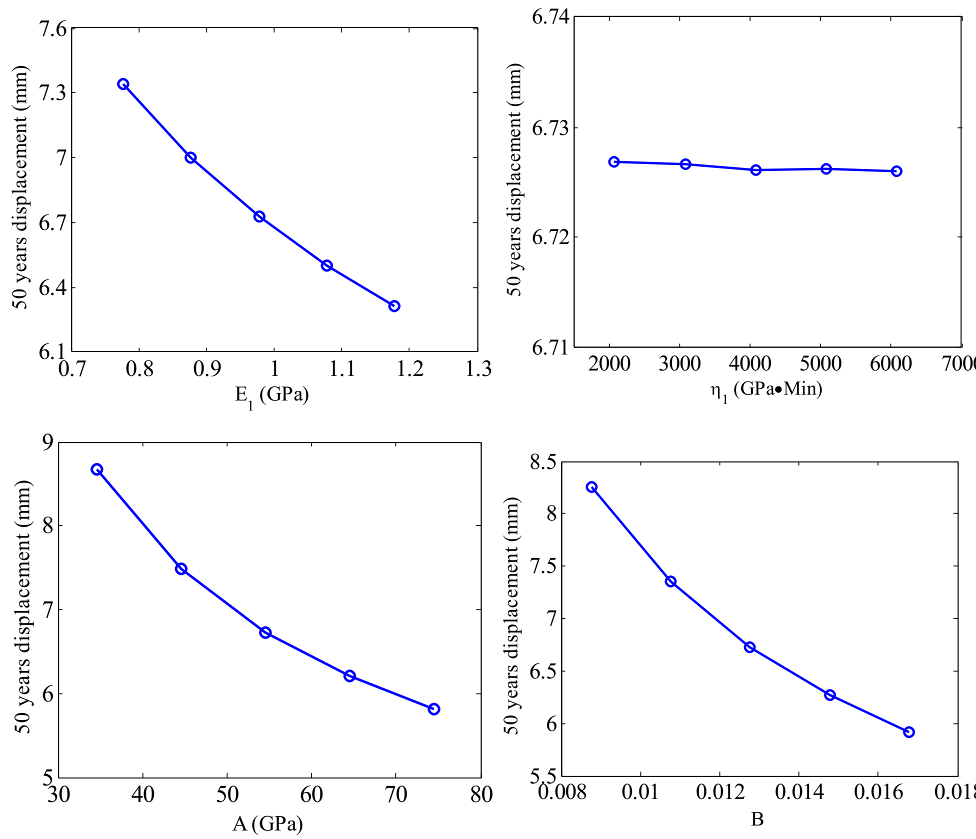



**Fig. 16** Results of the sensitivity analysis adopting the improved Huang's Burgers creep model, where the model parameters of materials 2 and 3 remain unchanged, and the model parameters of material 1 is changed

foundation is predicted adopting numerical analysis in this study. The following conclusions are obtained:

1. Two improved Burgers creep models are proposed and validated; and they have been successfully incorporated into the ABUQUS computation platform.
2. The two proposed improved Burgers creep models have been successfully used to predict the long-term settlement of the aircraft runway. The computational results indicate that the long-term settlement of an aircraft runway built on the reclaimed coral calcareous sand foundation is in the range of 6.7 to 19.9 mm in the future 50 years, satisfying the requirement specified by the Code for Geotechnical Engineering Design of Airport MH/T 5027-2013 released by the Civil Aviation Administration of China (2013).
3. Sensitivity analysis shows that the computational result is highly sensitive to the parameters $\beta$ in the improved Kong's Burgers creep model, and sensitive to the parameter A in the improved Huang's Burgers creep model. It is suggested to pay more attention to calibrate the two mentioned above parameters adopting laboratory creep test data.

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## References


Cao M, Ye JH (2019) Creep-stress-time four parameters mathematical model of calcareous sand in South China Sea. Rock Soil Mech 40(5):1771–1777

Cao WG, Yang S, Zhang C (2017) A statistical damage constitutive model of rocks considering the variation of the elastic modulus. Hydrogeol Eng Geol 44(3):42–48

Civil Aviation Administration of China (2013) Code for geotechnical engineering design of airport (MH/T 5027-2013). China Civil Aviation Press, Beijing

Di H, Zhou S, Xiao J, Gong QM, Luo Z (2016) Investigation of the long-term settlement of a cut-and-cover metro tunnel in a soft deposit. Eng Geol 204:33–40

Dorfman JR, Faller AJ (1982) Jan Burgers. Physics Today 35(1):84–85

Enomoto T, Koseki J, Tatsuoka F, Sato T (2016) Creep failure of natural gravelly soil and its simulation. Geotechnique 66(11):865–877

Fu KM, Huang XM (2008) The secondary development of modified burgers creep model based on ABAQUS general software. Highw Eng 03:132–137

He LJ, Kong LW, Wu WJ, Cai Y (2011) A description of creep model for soft soil with fractional derivative. Rock Soil Mech 32(S2):239–249

Jiang L, Lin H (2010) Integrated analysis of SAR interferometric and geological data for investigating long-term reclamation settlement of Chek Lap Kok Airport, Hong Kong. Eng Geol 110(3–4):77–92

Lv Y, Li F, Liu YW, Wang MY (2017) Comparative study of coral sand and silica sand in creep under general stress states. Can Geotech J 54(11):1601–1611

Mesri G, Funk JR (2014) Settlement of the Kansai international airport islands. J Geotech Geoenviron Eng 141(2):04014102

Mesri G, Febres-Cordero E, Shields DR, Castro A (1981) Shear stress-strain-time behaviour of clays. Geotechnique 31(4):537–552

Murayama S (1983) Formulation of stress-strain-time behavior of soils under deviatoric stress condition. Soils Found 23(2):43–57

Murayama S, Michihiro K, Sakagami T (1984) Creep characteristics of sands. Soils Found 24(2):1–15

Nishihara M (1952) Creep of shale and sandy-shale. J Geol Soc Jpn 58(683):373–377

Nishihara M (1958) Rheological properties of rocks I and II. Doshisha Eng Rev 8:85–115

Pramthawee P, Jongpradist P, Sukkarak R (2017) Integration of creep into a modified hardening soil model for time-dependent analysis of a high rockfill dam. Comput Geotech 91:104–116

Puzrin AM, Alonso EE, Pinyol NM (2010) Unexpected excessive settlements: Kansai international airport. In: Geomechanics of failures, 2rd edition. Springer, Dordrecht, page: 23–43

Qiu J, Liu H, Lai J, Lai HP, Che JX (2018) Investigating the long-term settlement of a tunnel built over improved loessial foundation soil using jet grouting technique. J Perform Constr Facil 32(5):04018066

Shahnazari H, Rezvani R (2013) Effective parameters for the particle breakage of calcareous sands: an experimental study. Eng Geol 159:98–105

Shen SL, Wu HN, Cui YJ, Yin ZY (2014) Long-term settlement behaviour of metro tunnels in the soft deposits of Shanghai. Tunn Undergr Space Technol 40:309–323

Shi YJ, Li MG, Chen JJ, Wang JH (2018) Long-term settlement behavior of a highway in land subsidence area. J Perform Constr Facil 32(5): 04018063

Singh A, Mitchell JK (1968) General stress-strain-time function for soils. J Soil Mech Found Div 94(1):21–46

Wang XZ, Wang R, Meng QS, Liu XP (2009) Study of plate load test of calcareous sand. Rock Soil Mech 30(01):147–151

Wongsaroj J, Soga K, Mair RJ (2013) Tunnelling-induced consolidation settlements in London Clay. Geotechnique 63(13):1103

Yao YP, Wang K, Wang ND, Zhang QL (2019) Prediction method on long-term settlement of high-speed railway subgrade under the influence of near-load. Chin J Geotech Eng 41(04):625–630

Ye JH, Cao M (2019) Preliminary study on the creep characteristics of calcareous sand from reclaimed coral reef islands in South China Sea. Chin J Rock Mech Eng 38(06):1242–1251

Zhang CC, Zhu HH, Shi B, Fatahi B (2018a) A long term evaluation of circular mat foundations on clay deposits using fractional derivatives. Comput Geotech 94:72–82

Zhang Y, Yu DW, Ye JH (2018b) Study on measurement methodology of tensile elastic modulus of rock materials. Rock Soil Mech 39(6): 2295–2303

Zhang YC, Gao F, Lu GS, Ma C, Zhao Y (2018c) Numerical simulation of high fill foundation settlement based on creep test of loess. Sci Technol Eng 18(30):220–227