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Consolidation analysis of lumpy fills using a homogenization method

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ABSTRACT: A homogenization method is developed for the Terzaghi-Rendulic consolidation theory to study the heterogeneous consolidation behavior of lumpy fill made of dredged clay lumps. A global problem and a local problem are defined. The global problem is of the same form as that of Terzaghi's consolidation theory, but the equivalent consolidation coefficients involve the heterogeneity of dredged materials. The predicted consolidation settlement is compared with those obtained from a centrifuge model study on lumpy fill.

1 INTRODUCTION

Recent coastal development works in Singapore lead to high demand of dumping grounds for soils dredged from the seabed. On the other hand, land reclamation works require large quantities of fill material. A research study is being carried out at the National University of Singapore to evaluate the feasibility of using dredged soils as reclamation fill. Along the West Coast of Singapore, the seabed soils generally consist of residual soils and weathered rocks of sedimentary origin with insitu standard penetration resistance of at least 20 blows/30 cm. During dredging operation, soils are typically removed from the seabed using a grab resulting in lumps with sizes ranging from 0.5 m to 1.5 m. The exterior of these lumps would be significantly softened while their inner cores remain relatively stiff for a long period. When these lumps are placed as reclamation fill, the profile of the fill can be expected to be highly variable due to the presence of inter-lump voids.

The consolidation characteristics of reclamation fill made up of such clay lumps are rather complex because when the clay lumps consolidate, the inter-lump voids also close up simultaneously. Hence conventional consolidation theories are not applicable to analyze the consolidation behavior of lumpy fill. In this paper, a homogenization method for the Terzaghi-Rendulic consolidation theory is put forward to study the heterogeneous consolidation problem of lumpy fill.

2 GOVERNING EQUATIONS OF THE CONSOLIDATION PROBLEM

Wang et al. (1997) developed the following continuity equation for a soil-water mixture by means of micromechanics:

$$\frac{\partial \widetilde{H_i^0}}{\partial x_i} + \frac{\partial \varepsilon_v}{\partial t} = 0 \tag{1}$$

where the Darcy's law for specific discharge, $\widetilde{H_i^0}$, is given by

$$\widetilde{H_i^0} = -K_{ij}\frac{\partial u^\varepsilon}{\partial x_j} \tag{2}$$

where ε_v is volumetric strain, x_i is the ith component of $\boldsymbol{x}$-coordinates, t the real time, u^ε is pore water pressure, and K_{ij} the permeability of the lumpy fill.

Thus, the equation of continuity is

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial u^\varepsilon}{\partial x_j}\right) = \frac{\partial \varepsilon_v}{\partial t} \tag{3}$$

Now the key is how to introduce the constitutive law of soil skeleton into the continuity equation. For elastoplastic materials, the general constitutive relation can be expressed as

$$d\varepsilon_{ij} = C_{ijkl}\, d\sigma'_{kl} \tag{4}$$

or

$$\frac{d\varepsilon_v}{dt} = C_{iijj}\frac{d\bar{\sigma}}{dt} + C_{iikl}\frac{dS_{kl}}{dt} - C_{iijj}\frac{du^\varepsilon}{dt} \tag{5}$$

where ε_{ij} is strain components, C_{ijkl} the compliance coefficients, $\bar{\sigma}$ is the mean total stress, S_{ij} is the derviatoric stress, and subscripts i, j, k, l refer to the indices which take 1, 2, 3 for three-dimension coordinates. Terzaghi's consolidation theory assumes that the mean total stress $\bar{\sigma}$ keeps constant during consolidation and the dilatancy of soil skeleton is ignorable, that is, the effect of dilantancy on excess pressure

$$C_{iikl}\frac{dS_{kl}}{dt} = 0$$

At this time, the continuity equation becomes

$$\frac{\partial u^\varepsilon}{\partial t} = \frac{\partial}{\partial x_i}\left(M^\varepsilon_{ij}\frac{\partial u^\varepsilon}{\partial x_j}\right) \qquad \text{on} \quad S_s \tag{6}$$

where M^ε_{ij} is consolidation coefficient and S_s is the domain for the soil-water mixture.

The boundary condition is given by

- Given excess pore pressure

$$u^\varepsilon = \tilde{u}^\varepsilon \qquad \text{on} \quad S_T \tag{7}$$

where $\tilde{u}^\varepsilon$ is the pore water pressure on the pore water pressure boundary S_T.

- Flux

a) Flux boundary

$$-\boldsymbol{n} \bullet K^\varepsilon \bigtriangledown u^\varepsilon = \tilde{q}^\varepsilon \quad \text{on } S_m \tag{8}$$

Where K^ε is a tensor of permeability, its components are K^ε_{ij}. $\boldsymbol{n}$ is the outer unit vector normal to the boundary surface. $\bigtriangledown$ is the gradient operator, $\tilde{q}^\varepsilon$ is the specific discharge on discharge boundary S_m.

b) Mixed boundary

$$-\boldsymbol{n} \bullet K^\varepsilon \bigtriangledown u^\varepsilon = \tilde{q}^\varepsilon + \gamma(u^\varepsilon - \bar{u}) \quad \text{on } S_n (9)$$

where γ is a parameter, and $\bar{u}$ is the pore water pressure outside the mixed boundary S_n.
The initial condition is

$$u^\varepsilon = u^\varepsilon_0 \qquad \text{when} \qquad t = t_0 \tag{10}$$

3 LAPLACE TRANSFORMATION SPACE

The Laplace transformation and numerical inverse Laplace transformation are employed to obtain the general solutions. The methodology is shown in Fig.1.The forms in Laplace space are as follows (p is Laplace parameter). The consolidation coefficients $\hat{M}^\varepsilon_{ij}$ are assumed of time independence.

$$(p\hat{u}^\varepsilon - u^\varepsilon_0) = \frac{\partial}{\partial x_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^\varepsilon}{\partial x_j}\right) \tag{11}$$

where the $\wedge$ denotes the variables in Laplace space. The Boundary condition is given by

- Given excess pore pressure

$$\hat{u}^\varepsilon = \hat{\tilde{u}}^\varepsilon \qquad \text{on} \quad S_T \tag{12}$$

- Flux

a) Flux boundary

$$-\boldsymbol{n} \bullet \hat{K}^\varepsilon \bigtriangledown \hat{u}^\varepsilon = \hat{\tilde{q}}^\varepsilon \qquad \text{on } S_m \tag{13}$$

b) Mixed boundary

$$-\boldsymbol{n} \bullet \hat{K}^\varepsilon \bigtriangledown \hat{u}^\varepsilon = \hat{\tilde{q}}^\varepsilon + \gamma(\hat{u}^\varepsilon - \hat{\bar{u}}) \text{ on } S_n (14)$$

The problem above is only associated with spatial co-ordinates with fast oscillatory coefficients. For such a complicated structure, direct calculation will take a long time and makes the solution complicated. It is necessary to find an effective medium that has the same macro-response and that can involve microstructural effect. Homogenization theory(Sanchez-Palencia 1980; Wang 1996) is a good alternative.

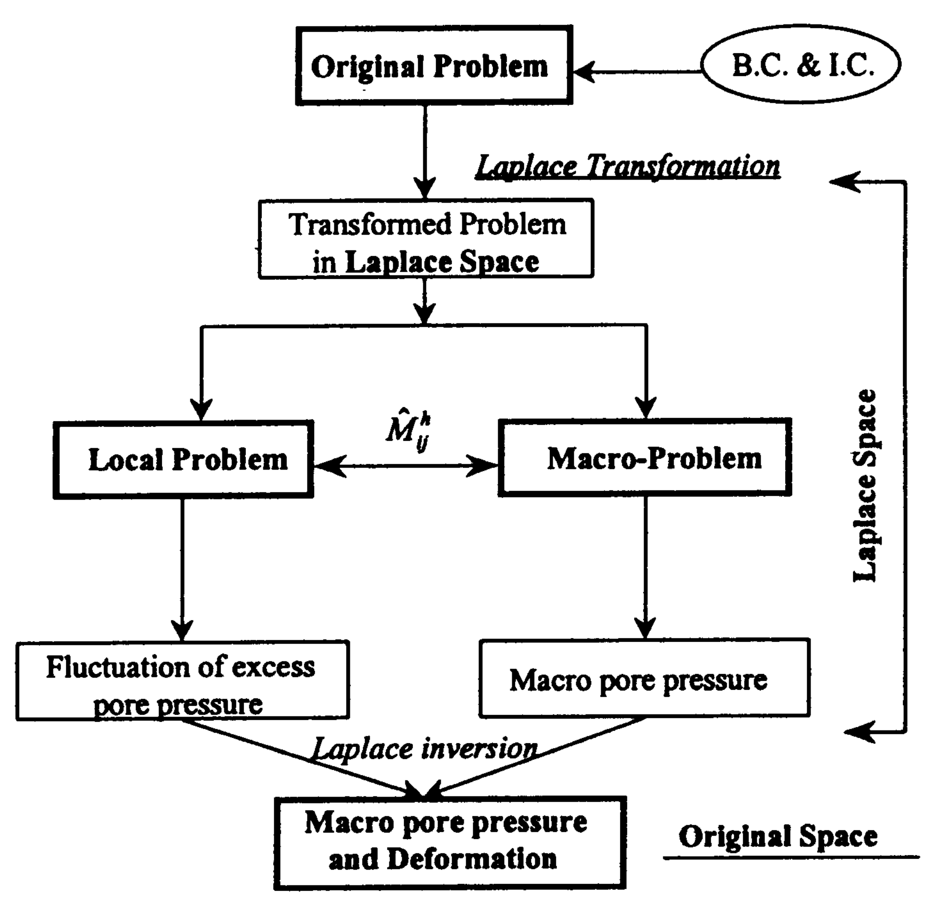


Fig. 1 Flowchart of analytical method

4 ASYMPTOTIC SPATIAL EXPANSION

The fundamental function, excess pore pressure u^ε, is assumed to be expanded as the series of scaling parameter ε.

$$\hat{u}^\varepsilon(\boldsymbol{x},\boldsymbol{y};p) = \hat{u}^0(\boldsymbol{x},\boldsymbol{y};p)+\varepsilon\hat{u}^1(\boldsymbol{x},\boldsymbol{y};p)+\cdots \quad (15)$$

and each term satisfies Y-periodicity, that is

$$\hat{u}^\alpha(\boldsymbol{x},\boldsymbol{y};p) = \hat{u}^\alpha(\boldsymbol{x},\boldsymbol{y}+\boldsymbol{Y};p) \quad (16)$$

$$\text{and} \quad \boldsymbol{y} = \frac{\boldsymbol{x}}{\varepsilon} \qquad (\alpha = 0,1,2,\cdots) \quad (17)$$

Eq. (16) means that $\hat{u}^\alpha(\boldsymbol{x},\boldsymbol{y};p)$ takes values that are almost the same in neighbouring, but very different in long distance. Such a function is called 'locally periodic'. The differential chain is

$$\frac{d}{dx_i} \Longrightarrow \frac{\partial}{\partial x_i} + \frac{1}{\varepsilon}\frac{\partial}{\partial y_i} \quad (18)$$

and

$$\hat{M}^\varepsilon \nabla \hat{u}^\varepsilon = \hat{M}^\varepsilon_{ij}\left(\frac{\partial \hat{u}^\varepsilon}{\partial x_j}\boldsymbol{i} + \frac{1}{\varepsilon}\frac{\partial \hat{u}^\varepsilon}{\partial y_j}\boldsymbol{i}\right) \quad (19)$$

The two-rank differential should be

$$\begin{aligned}
&\nabla \bullet \left(\hat{M}^\varepsilon \nabla \hat{u}^\varepsilon\right) \\
&= \frac{\partial}{\partial x_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^\varepsilon}{\partial x_j}\right) + \frac{1}{\varepsilon^2}\frac{\partial}{\partial y_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^\varepsilon}{\partial y_j}\right) \\
&\quad + \frac{1}{\varepsilon}\left[\frac{\partial}{\partial y_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^\varepsilon}{\partial x_j}\right) + \frac{\partial}{\partial x_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^\varepsilon}{\partial y_j}\right)\right]
\end{aligned} \quad (20)$$

Therefore, Eq. (11) is expanded as

$$\sum(\,\bullet\,)\varepsilon^\beta = 0 \quad (\beta = -2,-1,0,1,2,\cdots) \quad (21)$$

because Eq. (21) holds for any ε. This infers that

a) ε^{-2}-term

$$\frac{\partial}{\partial y_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^0}{\partial y_j}\right) = 0 \quad (22)$$

That means

$$\hat{u}^0(\boldsymbol{x},\boldsymbol{y};p) = \hat{u}^0(\boldsymbol{x};p) \quad (23)$$

Eq. (23), being the leading term, is of special meanings. Its existence means that the homogenization method is applicable.

b) ε^{-1}-term

$$\left[\frac{\partial}{\partial x_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^0}{\partial y_j}\right) + \frac{\partial}{\partial y_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^0}{\partial x_j}\right)\right] + \frac{\partial}{\partial y_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^1}{\partial y_j}\right) = 0 \quad (24)$$

$\hat{u}^1$ is determined by Eq. (24) if $\hat{u}^0$ is given. This is called as a **local problem**:

$$\frac{\partial}{\partial y_i}\left[\hat{M}^\varepsilon_{ij}\left(\frac{\partial \hat{u}^1}{\partial y_j} + \frac{\partial \hat{u}^0}{\partial x_j}\right)\right] = 0 \quad (25)$$

Under the periodicity condition $\hat{u}^1(\boldsymbol{x},\boldsymbol{y};p) = \hat{u}^1(\boldsymbol{x},\boldsymbol{y}+\boldsymbol{Y};p)$.

c) ε^0-term

$$\begin{aligned}
&\frac{\partial}{\partial y_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^2}{\partial y_j}\right) \\
&+\left[\frac{\partial}{\partial x_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^1}{\partial y_j}\right) + \frac{\partial}{\partial y_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^1}{\partial x_j}\right)\right] \\
&+\frac{\partial}{\partial x_i}\left(\hat{M}^\varepsilon_{ij}\frac{\partial \hat{u}^0}{\partial x_j}\right) - (p\hat{u}^0 - u^0_0) = 0
\end{aligned} \quad (26)$$

A volume average operator is defined as

$$< \bullet >= \frac{1}{|Y|}\int_Y \bullet dy \quad (27)$$

in a unit cell, and let

$$\hat{u}^1 = W^r(\boldsymbol{y})\frac{\partial \hat{u}^0}{\partial x_r} + C(\boldsymbol{x}) \quad (28)$$

where $W^r(\boldsymbol{y})$ is the characteristic function, being the function of local variable $\boldsymbol{y}$. Then, the **global problem** is obtained as

$$\frac{\partial}{\partial x_i}\left(M^h_{ir}\frac{\partial \hat{u}^0}{\partial x_r}\right) - (p\hat{u}^0 - u^0_0) = 0 \quad (29)$$

where

$$M^h_{ir} = \frac{1}{|Y|}\int_Y \hat{M}^\varepsilon_{ij}\left(\delta_{jr} + \frac{\partial W^r}{\partial y_j}\right)dy \quad (30)$$

M^h_{ir} is the equivalent or effective consolidation coefficient, and $\delta_{jr} = 1$ when $j = r$, and $\delta_{jr} = 0$ when $j \neq r$. Eq. (29) is of the same form as the conventional Terzaghi-Rendulic consolidation theory. The only difference is that the present consolidation theory involves the microstructural effect.

Macro-consolidation coefficients M_{ij}^h may be heterogeneous. Again, for the **local problem**, Eq. (25), is expressed in characteristic function W^r

$$\frac{\partial}{\partial y_i}\left(\hat{M}_{ij}^{\varepsilon}\frac{\partial W^r}{\partial y_j}\right)+\frac{\partial \hat{M}_{ir}^{\varepsilon}}{\partial y_i}=0 \tag{31}$$

with $W^r(\boldsymbol{y};p)=W^r(\boldsymbol{y}+\boldsymbol{Y};p)$.

5 DISCUSSION

5.1 *Weak form for a local problem*

Assume that weighting function V is of Y-periodicity. The weak form of the local problem denoted by Eq. (31) is

$$\int_Y \frac{\partial}{\partial y_i}\left(\hat{M}_{ij}^{\varepsilon}\frac{\partial W^r}{\partial y_j}\right)Vdy=-\int_Y \frac{\partial \hat{M}_{ir}^{\varepsilon}}{\partial y_i}Vdy \tag{32}$$

By using Y-periodicity, one has

$$\int_Y \hat{M}_{ij}^{\varepsilon}\frac{\partial W^r}{\partial y_j}\frac{\partial V}{\partial y_i}dy=-\int_Y \hat{M}_{ir}^{\varepsilon}\frac{\partial V}{\partial y_i}dy \tag{33}$$

From Lax-Milgram Lemma, W^r is uniquely determined if its mean value is assumed to be zero. Therefore, the weak form of a local problem is

$$\begin{cases}\text{Find } W^r\in V_y; \quad <W^k>=0 \\ \displaystyle\int_Y \hat{M}_{ij}^{\varepsilon}\frac{\partial W^r}{\partial y_j}\frac{\partial V}{\partial y_i}dy=-\int_Y \hat{M}_{ir}^{\varepsilon}\frac{\partial V}{\partial y_i}dy\end{cases} \tag{34}$$

The mechanical property of effective consolidation coefficient M_{ir}^h is symmetric and positive definite.

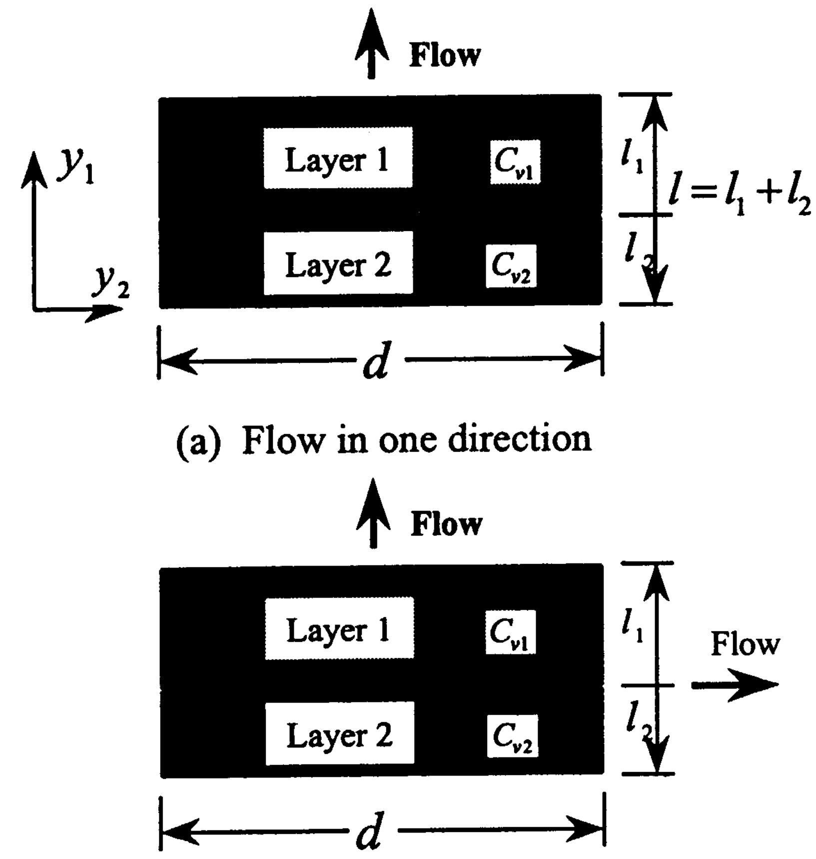
5.2 *Excess pore pressure*

Fluctuation of excess pore pressure is given by

$$\hat{u}^1=W^r(\boldsymbol{y})\frac{\partial \hat{u}^0}{\partial x_r}+C(\boldsymbol{x})$$

because $C(\boldsymbol{x})$ is a function of $\boldsymbol{x}$ co-ordinate. It should be classified as $\hat{u}^0(\boldsymbol{x})$. Thus, it is reasonable to assume that $C(\boldsymbol{x})\equiv 0$. At this time, the total excess pore pressure is

$$\hat{u}\approx\hat{u}^0+\varepsilon\hat{u}^1$$



(b) Flow in two directions

Fig. 2 Two-layer unit cell

6 APPLICATIONS

6.1 *Layer soil consolidation*

There is one macro-variable x and one micro-variable y. The period $\boldsymbol{Y}$ is a segment of length l, for example $(0,l)$ as the unit cell shown in Fig. 2. Thus

$$\frac{\partial \hat{u}^0}{\partial x_i}\Longrightarrow\frac{\partial \hat{u}^0}{\partial x} \qquad \frac{\partial W^r}{\partial y_j}\Longrightarrow\frac{\partial W}{\partial y} \tag{35}$$

The local problem becomes

$$\frac{\partial}{\partial y}(\hat{M}^{\varepsilon}\frac{\partial W}{\partial y})+\frac{\partial \hat{M}^{\varepsilon}}{\partial y}=0 \tag{36}$$

Its solution is

$$W=\int_0^y\frac{b}{\hat{M}^{\varepsilon}}da-y+C \tag{37}$$

$W(0)=W(l)$ determines the coefficient b. The homogenized consolidation coefficient $\hat{M}^h$ is

$$\frac{1}{\hat{M}^h}=\frac{1}{l}\int_0^l\frac{1}{\hat{M}^{\varepsilon}}da \tag{38}$$

Eq. (38) is suitable for a multi-layer medium.

The medium is assumed to be two-dimensionally periodic: That is, $\hat{M}_{ij}^{\varepsilon}=\hat{M}_{ij}^{\varepsilon}(y_1)$ and only $\hat{M}_{11}^{\varepsilon}\neq 0$ and $\hat{M}_{22}^{\varepsilon}\neq 0$. This is an axisymmetric problem.

$$\frac{\partial u^0}{\partial x_1}\neq 0 \qquad \frac{\partial u^0}{\partial x_2}=\frac{\partial u^0}{\partial x_3}\neq 0$$

The fluctuation is expanded as

$$u^1=W^1\frac{\partial u^0}{\partial x_1}+W^2\frac{\partial u^0}{\partial x_2} \tag{39}$$

From Eq. (31), the local problem is expressed as

$$\frac{\partial}{\partial y_1}(\hat{M}^{\varepsilon}_{11}\frac{\partial W^r}{\partial y_1}) + \frac{\partial}{\partial y_2}(\hat{M}^{\varepsilon}_{22}\frac{\partial W^r}{\partial y_2})$$

$$+\frac{\partial \hat{M}^{\varepsilon}_{1r}}{\partial y_1} + \frac{\partial \hat{M}^{\varepsilon}_{2r}}{\partial y_2} = 0 \qquad (40)$$

When $r = 1$, its solution is

$$W^1(y_1) = \frac{\int_0^{y_1} \frac{1}{\hat{M}^{\varepsilon}} da}{\frac{1}{l}\int_0^{l} \frac{1}{\hat{M}^{\varepsilon}} da} - y_1 + C \qquad (41)$$

When $r = 2$, the solution is that W^2=Constant because $\hat{M}^{\varepsilon}_{22}$ is just function of y_1, $\frac{\partial \hat{M}^{\varepsilon}_{22}}{\partial y_2} = 0$.. Therefore, the homogenized consolidation coefficient in the first direction is of the same form as the previous case. In the second direction, the homogenized consolidation coefficient $\hat{M}^h_2$ is

$$\hat{M}^h_2 = \frac{1}{l}\int_0^l \hat{M}^{\varepsilon}_{22} dy \qquad (42)$$

For multi-layer materials

$$\hat{M}^h_2 = \frac{1}{\sum_1^n l_n}(\sum_1^n l_n M^{n\varepsilon}_{22}) \qquad (43)$$

6.2 *General case*

Numerical inverse Laplace transformation is used here. Schapery (1962) proposed an analytical method such that

$$f(t) \approx \left[p\hat{f}(p)\right]|_{p=\frac{0.5}{t}} \quad f(t) \approx (2t)^{-1}\hat{f}(\frac{1}{2t}) \qquad (44)$$

where $f(t)$ is the original function, and $\hat{f}(p)$ is the function in Laplace space. This method will produce very large error when $t \to 0$ because of the singularity at $t = 0$. For our computation, the singularity at $t = 0$ is avoided by use of $p \times \bullet$ instead of only $\bullet$.

The above proposed method is applied to back analyze the centrifuge model tests on dredged lumpy materials (Leung et al., 1996). This is a one-dimensional consolidation problem in macroscale. But the microstructure of lumpy fill is complicated. A simplified homogenized method is used to determine the homogenized consolidation coefficient $M^h_1(= C_v)$. The lumpy fill pores are divided into inter-lump voids and in-lump pores. The consolidation coefficient M_h reaches its lowest value $(C_v)_{min}$ at the complete closing of inter-lump void, while it reaches its peak value $(C_v)_{max}$ at the beginning of the loading. The $C_v - e$ curve is plotted in Fig. 3 which leads to the following implications. (a) At the initial stage, consolidation process is very fast. This makes deformation almost instant. Dissipation of excess pore water pressure is difficult to be measured. The deformation is steep at the beginning of loading. On the other hand, the stress-strain curve for lumpy fills shows that the initial deformation at low loading is huge and plastic (Leung et al. 1996). The lumpy balls change its shape completely or collapse. If this deformation is mixed with the conventional consolidation one, Terzaghi consolidation theory even the large deformation one (Gibson 1967) is not suitable. (b) For a long term, the consolidation follows the usual Terzaghi's consolidation theory. Usually, deformation is small and consolidation coefficient is stable. Terzaghi consolidation theory is applicable. (c) For the whole stage, if the initial stage is treated separately, the conventional Terzaghi's theory is applicable. Thus, for the whole process to be taken one stage, the deformation consolidation degree and dissipation consolidation degree is not identical.

(d) The lump softening with water is an important factor to affect the deformation and consolidation. The direct function of this softening is reducing the strength of a clay lumpy. The lumpy may collapse and transfer its excess pore water pressure into inter-lump voids. Therefore, the consolidation process for lumpy fills is not a complete dissipation process of excess pore water pressure. Because of its multi-scale property, the dissipation and gener-

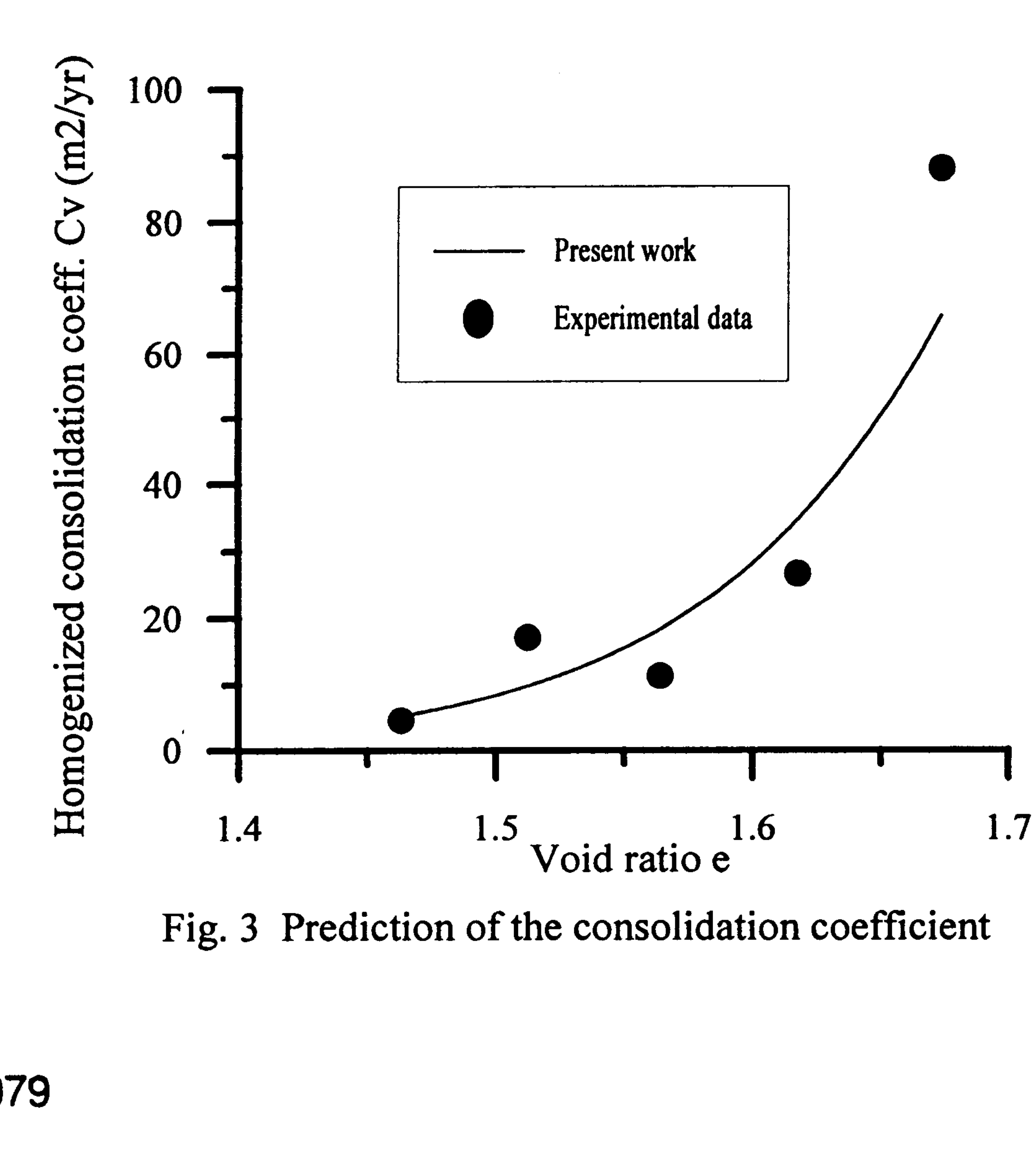


Fig. 3 Prediction of the consolidation coefficient

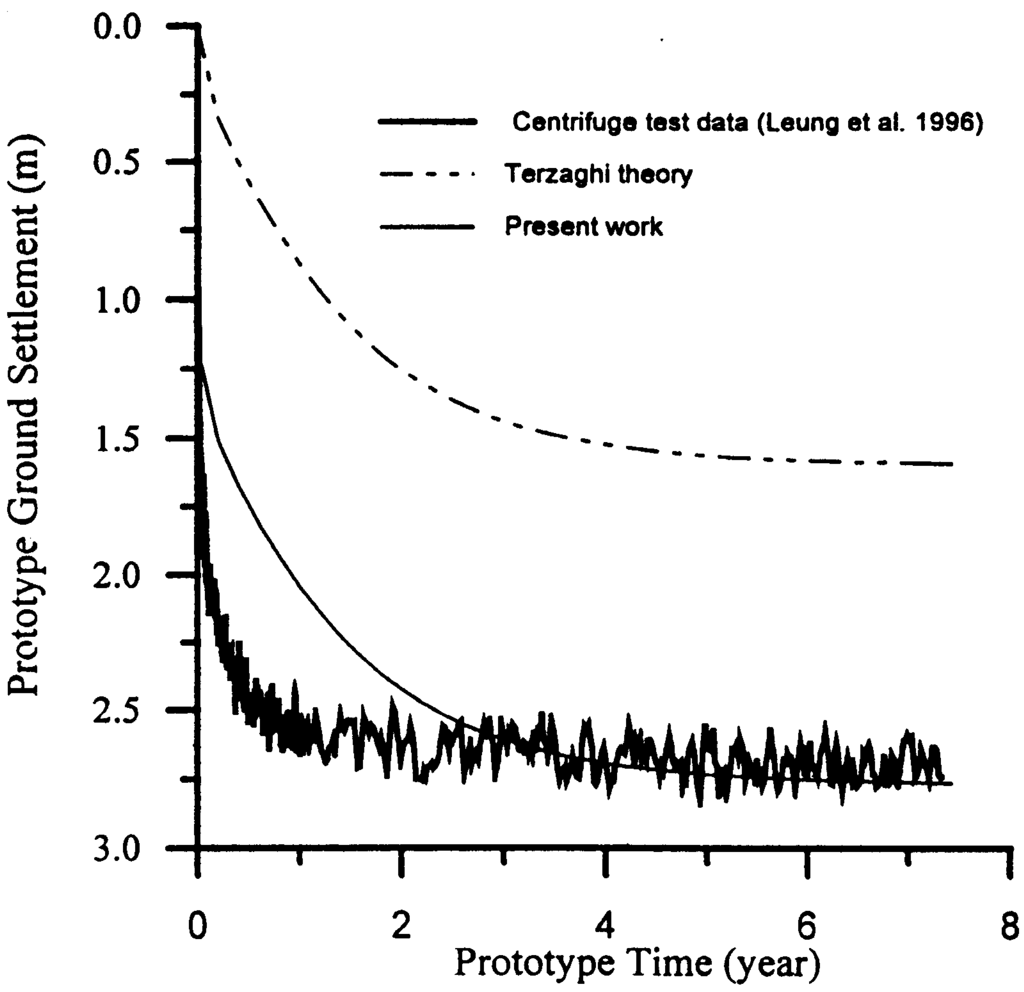


Fig.4 Comparison of prototype ground settlement

ation of excess pore water pressure in lumpy fills may exist at the same time, although the excess pore water in a lumpy ball dissipates. This coexistence depends on external loading, strength of a lumpy ball and other mechanical properties of clay.

In the centrifuge tests, the prototype height of the filling is 15 m and its final measured settlement is 2.6m, but its initial settlement is about 1.20m, as shown in Fig. 4. The prediction values from the present work are in fair agreement with the experimental data except for the initial settlement. At the beginning of loading, the microstructures of lumpy fill deform a lot. The inter-voids reduce significantly, thus the permeability reduces quickly and the consolidation coefficient changes drastically. This change makes the excess pore water pressure dissipate quickly. After that initial period, the microstructures becomes more and more stable. The consolidation is getting to the normal consolidation process. This is why the present work does still give poorer prediction at initial consolidation stage.

7 CONCLUSION

The heterogeneity of lumpy fills is analyzed by a homogenization method through a Terzaghi consolidation problem. The global and local problems are obtained. The global problem is of the same form as the conventional Terzaghi theory except for the values of consolidation coefficient. The heterogeneity of microstructures of lumpy fills is taken into consideration through the homogenized consolidation coefficient. The homogenized consolidation coefficient is analytically obtained for a two layer material. For a general lumpy filling, the homogenized coefficient is the function of inter-void ratio. The computation for a centrifuge test reveals some interesting mechanisms: (a) Coexistence is found for dissipation and generation of excess inter-void water pressure. This depends on loading and microstructures. The deformation is almost instant at the beginning of loading. The plastic deformation is the major source. This coexistence makes the consolidation degree for settlement and dissipation different. (b) Pore water pressure is heterogeneous in microstructure. The excess water pore pressure tends to become homogeneous with the breakage of lumpy balls. (c) For the long term, the behavior is dependent on external loading, mechanical property of clay balls. The conventional consolidation theory can be applied if the consolidation coefficient is revised according to the proposed method in this paper.

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