Application of Adaptive Time Steps in the Settlement Analysis of Local Material - Applying to DakYen dam in Vietnam

Quang Hung Nguyen, Hoang Hung Vu

Abstract: Accuracy improvement and convergence of the solution of finite element problems are of interest to many scientists. The Biot consolidation theory is used to investigate the adaptive time steps in the construction process, water accumulation and operation of local material dams which is designed according to Cam-Clay material model. From the principles of Biot consolidation theory, basing on energy errors control to provide time steps to control effective stress field as well as pore water pressure in the body and foundation dam. The investigation is very significant for the construction of local material dams, especially for dams using embankment material with high clay content such as DakYen dam in Vietnam.

Keywords: Adaptive time steps, Error control, Local material dams, DakYen dam.

I. INTRODUCTION

During the construction process as well as during the reservoir process, the dam is always subject to variable load. Under the effect of external load, stresses in soil particles as well as stresses in water in the soil are constantly changing. This change completely depends on the dispersion of water pressure in the pore. Finally, overcoming the stable permeability pressure, the water pressure in the pore gradually diminishes. The external load is also gradually transferred to the soil particles resulting in soil being compressed to a stable level. This whole process is called consolidation. The purpose of the coherent analysis process is to understand the variability of the permeability process as well as the pore pressure in the dam and the sticky substrate. At the same time, it is also possible to understand the time settlement process of the dam and ground. This issue is very significant in assessing the stability of dams and ground [1].

II. THEORY

A. Biot consolidation equation

The basic assumption of the Biot theory [2-4, 9]: Apart permeability, the soil properties is homogeneous isotropic, permeable soil properties do not change over space and time, regardless of inertial forces.

(1) Balance equation

For homogeneous soil isotropic, combines the equilibrium equation and the effective stress principle obtained:

\[
\begin{align*}
\frac{\partial^2 u}{\partial x^2} + d_1 \left( \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + (d_2 + d_4) \left( \frac{\partial^2 v}{\partial x \partial y} + \frac{\partial^2 v}{\partial x \partial z} + \frac{\partial^2 \varphi}{\partial y \partial z} \right) - \frac{\partial \varphi}{\partial x} &= 0 \\
\frac{\partial^2 v}{\partial y^2} + d_1 \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2} \right) + (d_2 + d_4) \left( \frac{\partial^2 v}{\partial x \partial y} + \frac{\partial^2 \varphi}{\partial y \partial z} + \frac{\partial^2 \varphi}{\partial x \partial z} \right) - \frac{\partial \varphi}{\partial y} &= 0 \\
\frac{\partial^2 \varphi}{\partial z^2} + d_1 \left( \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} \right) + (d_2 + d_4) \left( \frac{\partial^2 \varphi}{\partial x \partial y} + \frac{\partial^2 \varphi}{\partial x \partial z} + \frac{\partial^2 \varphi}{\partial y \partial z} \right) - \frac{\partial \varphi}{\partial z} &= 0
\end{align*}
\]

Where:

\[
\begin{align*}
d_1 &= E_s \\
d_2 &= \frac{\mu}{1 - \mu} E_s \\
d_3 &= \frac{E}{2(1 + 2\mu)} \\
E &= \frac{E(1 - \mu)}{(1 + \mu)(1 - 2\mu)}
\end{align*}
\]

\(u, v, w\) are displacements on the x, y and z axes respectively.

\(\varphi\): pore pressure.

(2) Continuous equation

Continuous equation

\[
\gamma_n \left[ k_n \left( \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \right) \right] = \frac{\partial}{\partial x} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)
\]

Where:

\(\gamma_n = \gamma_{ps} g\): Weight of water in pore

\(k_n\): coefficient of permeability

B. Basic equations of space

Considering the calculation domain at two times \(t_n \leq t_{n+1}\), and variables, respectively \([\delta]_n\), \([\delta]_{n+1}\), \([p]_n\), \([p]_{n+1}\). In the period \(\Delta t = t_{n+1} - t_n\) with \([\delta] = [\Delta \delta] / \Delta t\) and , selecting linear function: [3], [5], [6], [9]

\[
\begin{align*}
[K] [\Delta \delta] + [C] [\Delta p] &= [\Delta \mathbf{R}_e] \\
[C] [\Delta \delta] - \theta \Delta[H] [\Delta p] &= [\Delta \mathbf{R}_p]
\end{align*}
\]

Where:

Vector increased the load during the period \(\Delta t\).
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\[
\{\Delta F\} = \begin{bmatrix} \Delta F_1 \\ \Delta F_2 \end{bmatrix}, \quad \text{Vector marginal increase in load periods } \Delta t
\]

\[
\{\Delta R_q\} = \Delta t\{R_q\} + [H]\{p\}_a \text{: Vector increases traffic in the period } \Delta t
\]

\[\theta\]: Integral parameter, can be selected within 0.5~1.0.

C. Error control

Local error is calculated according to the formula: [3], [7-9]

\[
e^v = \Delta t \frac{1}{2} \left( u^{a}_{n+1} - u^n \right)
\]

\[
e^p = \Delta t \frac{1}{2} \left( \rho^a_{n+1} - \rho^n \right)
\]

(5)

D. Time step control

Considering the effect of stress and pore pressure, the Euclid error is used to control the time step in the calculation process. Pore pressure error: [9]

\[\eta^p = \|e^p\| = \Delta t \frac{1}{2} \left\| \rho^{a}_{n+1} - \rho^n \right\|\]

or \[\eta = \frac{\|e^p\|}{\|\rho\|_{\max}}\]

Stress error:

\[\eta^v = \|e^v\| = \Delta t \frac{1}{2} \left\| u^{a}_{n+1} - u^n \right\|\]

or \[\eta = \frac{\|e^v\|}{\|u\|_{\max}}\]

Calculation time step in the next period is calculated according to the formula:

\[\Delta t^u_{\text{new}} = \sqrt{\eta^v/\eta^u_{\text{old}}} \quad \Delta t^v_{\text{new}} = \sqrt{\eta^p/\eta^v_{\text{old}}}\]

(8)

\[\gamma_1 \eta_1 \leq \gamma^p_{\eta^p \gamma_1}, \quad \gamma_2 \eta_2 \leq \gamma^v_{\eta^v \gamma_2}, \quad \gamma_1 \in (0, 1.0)\]

\[\gamma_2 \geq 1.0\]

The control step must simultaneously satisfy two conditions of pore pressure error and stress error

E. Verification of computer program

Using the Fortran programming language, based on the above-mentioned theories set up SCRIP 04 calculation program.

SCRIP 04 program has several main features as follows:

Scope of calculation: Drainage, non-drainage, bi-directional consolidation problem, homogeneous or non-homogeneous elastic problem, limit state of soil (Cam-clay, modified Cam-clay) [10]

Element type: triangular element, quadrilateral, order 1 or 2, for the consolidation problem, increase the freedom of pore pressure

The calculation in the scope of this problem selects the element of triangle type with 6 nodal points with 7 integral points. For a two-dimensional problem, the above element has 15 degrees of freedom with 12 displacement degrees and 3 degrees of freedom due to pore pressure. Fig. 1. [9]

Fig. 1 shows the element and image of the integrator point used in the program. In which O represents the degree of freedom of displacement, ● represents the degree of freedom of pore pressure.

Using SCRIP04 program to calculate the example of one-way consolidation problem to check the accuracy of the program.

The example used here is shown in Fig. 2 with the following main parameters: \(\mu=0.301, E=3\) Mpa, \(k_v=10^5 \text{ cm/s}\), \(H=10\) m, \(q_o=100\) kPa, \(t_o=70\) d, upper surface drainage and undrained underside.

Results of calculating pore pressure, settlement, consolidation change over time with time step \(\Delta t=3.5\) d are shown in Fig. 3 and Fig. 4.

Fig. 3. Comparison of pore pressures

![Fig. 3. Comparison of pore pressures](image)
Calculation results comparing pore pressure based on theoretical and numerical methods are implemented by SCRIP 04 program shown in table 1 at times t = 14d, 42d, 70d, 140d (similar application Tv = 0.05, 0.15, 0.25, 0.5).

### Table 1. Pore pressure results comparison

<table>
<thead>
<tr>
<th>Time (d)</th>
<th>Theory</th>
<th>SCRIP 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>8.8</td>
<td>8.4</td>
</tr>
<tr>
<td>42</td>
<td>7.6</td>
<td>7.2</td>
</tr>
<tr>
<td>70</td>
<td>5.7</td>
<td>5.3</td>
</tr>
<tr>
<td>140</td>
<td>3.8</td>
<td>3.4</td>
</tr>
</tbody>
</table>

The analytical results in Fig. 3 and Fig. 4 as well as the values of settlement and consolidation in Table 1, Table 2 clearly show the similarity between the calculation by SCRIP 04 program and the complete numerical method, in accordance with the theory. Calculated results by SCRIP 04 program are extracted from point 8 with coordinates (0,0). These comparative evaluations have proved the accuracy of SCRIP 04 program.

### III. APPLYING FOR DAK YEN VIETNAM DAM

At the time of designing Dak Yen local dams, Vietnam is using the TCVN 11-77 dam design criteria as follows:

#### Table 3. Physical and mechanical criteria used in calculation

<table>
<thead>
<tr>
<th>Layer</th>
<th>γ_KTK</th>
<th>T</th>
<th>W (%)</th>
<th>φ (degree)</th>
<th>C</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>1.65</td>
<td>164 ± 2</td>
<td>15</td>
<td>0.20</td>
<td>5.10^{-5}</td>
<td></td>
</tr>
<tr>
<td>Layer 2</td>
<td>1.44</td>
<td>254 ± 2</td>
<td>15</td>
<td>0.20</td>
<td>1.10^{-5}</td>
<td></td>
</tr>
<tr>
<td>Layer 3</td>
<td>1.5</td>
<td>174 ± 2</td>
<td>12</td>
<td>0.17</td>
<td>1.10^{-4}</td>
<td></td>
</tr>
</tbody>
</table>

Recognizing the complexity of the embankment soil for the Dak Yen local dam, it was proposed to use additional compacting standards for both options $I = \frac{Y_K}{Y_{max}} \geq 0.97$ to assess the quality of Dak Yen dam.
In calculating the dam divided into 26 classes, each layer is 0.746m thick, the self-adaptive time step for each different class, the smallest is 1.473 days in the 3rd class, the average time is 15.938 – 16.712 days in the 8th grade and class 22 (cf Fig. 5 and Fig. 6), the longest time is 29.396 – 33.782 occurs in grades 12 and 13. The damming time used in the calculation is 180 days, the water retention time is 90 days. The results of pore water pressure variation at the point between the base of the dam and subsidence of the dam crest is shown in Fig. 7 and Fig. 8.

Basing on the analysis results of dispersion of pore water pressure as well as the effective stress field in the dam body and the base, the speed of dam construction can be proposed as follows:

IV. CONCLUSION

This paper is based on the Biot consolidation theory in order to improve the accuracy of the calculation, the paper has studied the self-adaptive time step in the consolidation process using the theory of biotransformation with Cam-clay material model. Using the principles have a copy to give the formula to control errors, which can control the error of stress field and pore pressure field. The results of this study aim to correct the process of deformation stress development. The research results applied to the local material dam Dak Yen - Vietnam is one of the relatively complex embankment dams. The research results are conducted for the construction phase of dams, water accumulation as well as operation of the dam. The results are very significant in the process of designing and construction of local materials. The problem of choosing the permissible error value \([\eta]\) still has many problems. Currently based solely on the experience of the calculator to determine this value. This paper uses 2 distinct errors \(\eta = \eta (u)\) and \(\eta = \eta (p)\) to control the error of stress field and pore pressure field is incomplete. In fact, these two schools have mutual interactions and effects. Therefore, the next study will combine only these 2 errors and give 1 error function \(\eta = \eta (u, p)\).

V. REFERENCES

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AUTHORS PROFILE

Quang Hung Nguyen was born in 1975 in Hanoi, Viet Nam. He received the Engineering’s degree and M.S. degrees in hydraulic construction from the Thuyloi University of Vietnam, in 1997 and 2000 and the PhD. degree in hydraulic structure from Wuhan University, China. Since 1998, he is a lecture in Faculty of Civil Engineering, Thuyloi University and becomes Associate Professor since 2009. From 2007 to 2013, he was Deputy Director of the Institute of Civil Engineering, designed and built many key projects of Vietnam. He is also principal investigator and member of many national science projects as well as Vietnam Ministry of Agriculture and Rural Development. Since 2013, he has been a senior expert in hydraulic construction of Vietnam Ministry of Construction. He is the Advisor of more than 200 bachelors, 40 masters, 2 PhD specialized in hydraulic construction.

Hoang Hung Vu was born in 1978 in Hanoi, graduated from Thuy Loi University, received a Doctorate in Marine Structure Engineering from Hohai University - China, Associate Professor of Thuy Loi University. He teaches hydraulic structures, chairs and participates in many scientific research projects at all levels, verifies many large hydropower projects. Main areas of research are simulation of structure and safety of large concrete dam structures, earthquakes and heat effects on water works, large span valve gates.