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VISCO-PLASTIC DYNAMIC FINITE ELEMENT ANALYSIS OF A DEFORMATION OF LIQUEFIED GROUND

Kazuhito KOMIYA[1]

SUMMARY

The deformation of liquefied ground is modelled by introducing new visco-plastic finite element flow analysis. Visco-plastic finite element analysis is used for the liquefied elements, and the presence of these elements aims to represent the flow deformation the ground caused by the liquefaction.

The visco-plastic flow of the liquefied soil is modeled by i) ascertaining the liquefied element the elasto-plastic dynamic transient response finite element analyses, ii) the visco-plastic finite element flow analysis for the liquefied elements using Generalized Bingham flow model, iii) reevaluating the overstress of the liquefied elements.

In order to verify the effect of the proposed visco-plastic technique, two dimensional elast-plastic dynamic transient response finite element analyses of earthquake motion of simple column with and without the visco-plastic technique were performed. The result shows that using the analysis with the visco-plastic technique is able to simulate the visco-flow failure of structure by the earthquake motion.

A two dimensional elast-plastic dynamic transient response finite element analysis with proposed visco-plastic technique was conducted to simulate the deformation of inclined ground (10 m deep, and 100 m long and inclination of 1/100) due to liquefaction. The long term displacement due to liquefaction obtained from the proposed visco-plastic modelling technique.

INTRODUCTION

The Hyogo-ken Nanbu Earthquake of 1995 caused serious damage to many port facilities in the Kobe harbor. Since these facilities were constructed on a soft sandy ground or a reclaimed ground in the Kobe harbor area, many facilities damaged by sliding, tipping over or subsidence due to the liquefaction of ground that occurs during an earthquake. For example, at the 25m high embankment of the landing stage of Kobe harbor, the ground flow which occurs with liquefaction displaced the ground around the

[1] Dr. Eng., Professor, Department of Civil Engineering, Chiba Institute of Technology, Chiba, Japan. Email: komiya@pf.it-chiba.ac.jp

embankment and serious damage was done to the landing stage. Over 0.7m ground displacement was observed at the ground surface of the landing stage.

The ground displacement in this type tends to take place more than several minute after the earthquake, i.e., the ground displacement was not only generated by the seismic forces but also the viscotic flow of the liquefied ground around the embankment. Because of the complex boundary conditions of such problem, the use of the finite element method is one of the rational methods to investigate the ground deformation behaviour.

In this study, the ground flow which occurs with liquefaction were modelled using the finite element method. The deformation of liquefied soil was simulated using the visco-plastic flow analysing technique which was integrated into the elasto-plastic dynamic transient response finite element analyses. The proposed modelling techniques are applied to simulate the simple column failure and the lateral displacement of liquefied ground due to the earthquake motion.

VISCO-PLASTIC ANALYSIS

The liquefied soil is extremely disturbed by dynamic share deformation. The exact mechanical process of liquefied ground is very difficult to model in the finite element method, because the movement of soil particles and pore water during liquefaction itself violates the assumption of continuum mechanics used in the finite element formulation. In the past, this liquefaction process was commonly modelled by the soil-water coupled finite element method. Although this modelling technique satisfies the force boundary conditions between effective stress and pore water pressure, the sum of the computed nodal displacements at the liquefied element may not necessarily match the actual large movement of the liquefied ground which is given as visco-plastic flow.

In this study, the deformation of liquefied ground is modelled by introducing new visco-plastic finite element flow analysis. Visco-plastic finite element analysis is used for the liquefied elements, and the presence of these elements aims to represent the flow deformation the ground caused by the liquefaction. The visco-plastic finite element analysis procedure is summarised in the flow-chart shown in Fig. 1.

The first step of the analysis is ascertaining the liquefied element. The elasto-plastic dynamic transient response finite element analysis is used in this study to find the liquefied elements. The two dimensional Mohr-Coulomb elasto-plastic model was used for convenience. During the time interval of t_0 to t_0+dt, the effective stress is computed at each element and the elements in which the effective stresses at the Gauss-Lagendre integration points is reached Mohr-Coulomb criteria are estimated the liquefied elements. The liquefied elements need to be estimated from the effective stress and excess pore water pressure in the element. However, this calculation will result in large computing time, and it was considered to be uneconomical.

The second step is the visco-plastic finite element flow analysis for the liquefied elements. Generalized Bingham flow model which was obtained by Hohenemser and Prager[1] was used to model the deformation behaviour of the liquefied soil.

$$2\eta v_{ij} = \begin{cases} 0 & (F < 0) \\ F \cdot S_{ij} & (F \geq 0) \end{cases} \qquad (1)$$

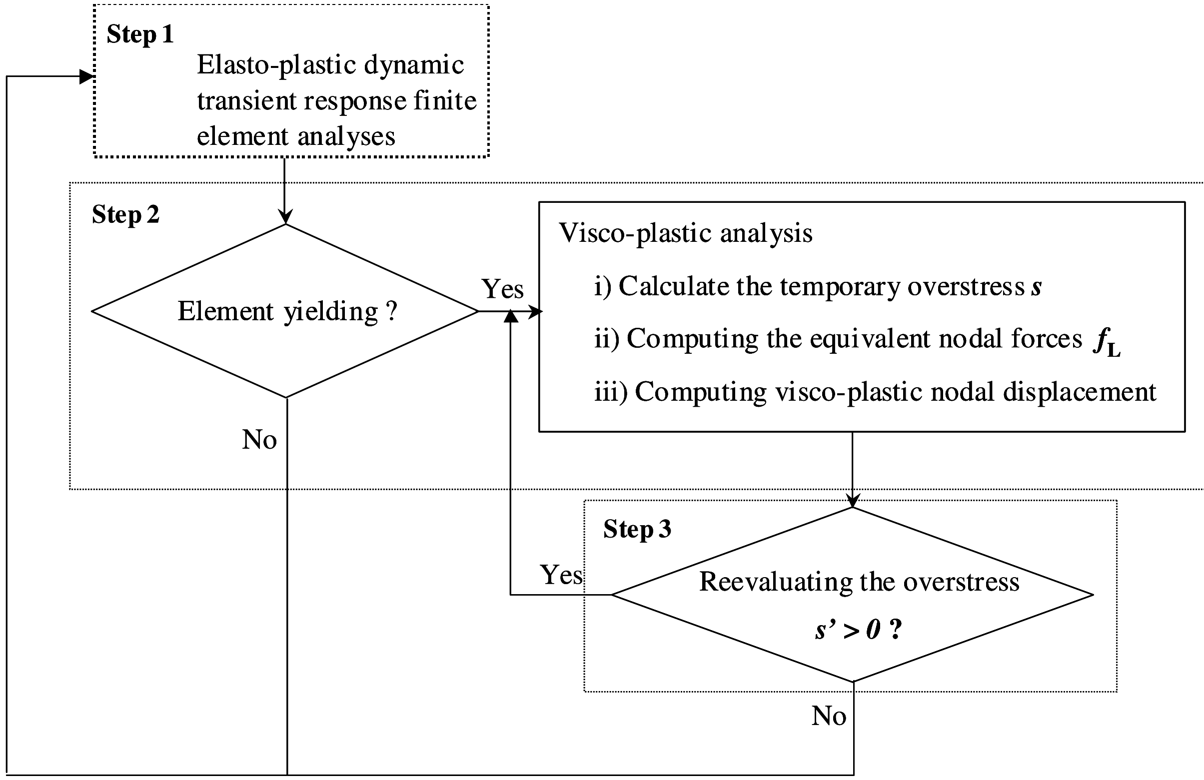

Fig.1 Flow-chart of the visco-plastic analysis

where η is coefficient of viscosity, v_{ij} is stretching tensor of element, S_{ij} is deviation stress tensor of element, τ_y is adhesive strength, J_2 is the second invariant of deviation stress tensor, F is the yield function which is obtained by following equation..

$$F = 1 - \frac{\tau_y}{\sqrt{J_2}} \qquad (2)$$

In this study, S_{ij} is simply assumed as deviation stress computed elasto-plastic dynamic finite element analysis (first step).

Once the stretching vector of all liquefied element is computed by equation (1), the temporary overstress ***s*** at the Gauss-Legendre integration points of the liquefied finite elements are estimated using the following equation.

$$\boldsymbol{s} = \int \boldsymbol{D} \, v_{ij} \qquad (3)$$

where ***D*** is the stress-strain relationship of the liquefied element at the Gauss-Legendre integration points. The selection of ***D*** depends on the flow elasticity of the liquefied soil.

After overstress computing, the equivalent nodal forces of the liquefied element $\boldsymbol{f}_L$ are computed using the following equation and the visco-plastic nodal displacement are calculated using $\boldsymbol{D}$ and $\boldsymbol{f}_L$ during the given time interval dt.

$$\boldsymbol{f}_L = \int \boldsymbol{B}\boldsymbol{s}dV \qquad (4)$$

where $\boldsymbol{B}$ is the strain-displacement matrix and V is the volume of the element.

The third step of the analysis is the calculation of overstress dissipation. In this study, it is assumed that the dissipation of the overstresses are equal to the stress increment at the liquefied element during the time interval of t_0 to t_0+dt. With this assumption, once the incremental visco-plastic displacement vector of all nodal points is computed, the overstress given for the next time step $\boldsymbol{s}'$ at the Gauss-Legendre integration points of the liquefied finite elements are estimated using the following equation.

$$\boldsymbol{s}' = \boldsymbol{s}_0 - \int \boldsymbol{D}\boldsymbol{B}d\boldsymbol{u} \qquad (5)$$

where $\boldsymbol{s}_0$ is the overstress at t=t0 and $d\boldsymbol{u}$ is the incremental displacement vector at nodal point of the liquefied element during time interval dt.

SIMULATION OF EARTHQUAKE MOTION OF SIMPLE COLUMN USING VISCO-PLASTIC ANALYSIS

In order to verify the effect of the proposed visco-plastic technique, two dimensional elast-plastic dynamic transient response finite element analyses of earthquake motion of simple column with and without the visco-plastic technique were performed.

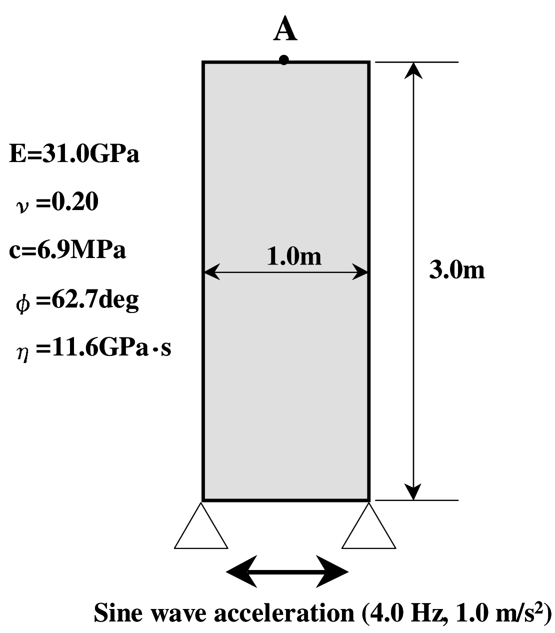

Fig.2 Finite element model used in the simple column problem

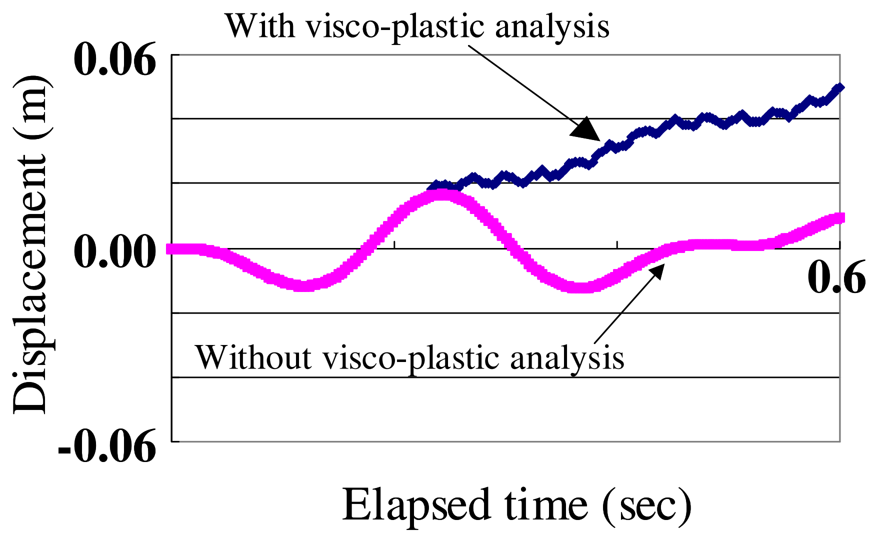

Fig.3 Horizontal displacement at the top of the column

The finite element meshes and the material properties used in these analyses are shown in Fig.2. The applied horizontal acceleration is obtained from the sine wave of 4.0 Hz wave length and of 1.0 m/s^2 amplitude, and it is applied at bottom boundary of the column.
The computed time-displacement curves are shown in Fig.3 for synamic trasient response analysis with visco-plastic technique and for analysis without visco-plastic technique. The vertical axis of the figures is the horizontal displacement at point A of the top of the column, whereas the horizontal axis is elapsed time t. The result of the analysis with visco-plastic technique provides the out-of-plumbness of the column after t=0.22 sec. This is due to the visco-plastic flow deformation in the yielding finite elements and the result shows that using the analysis with the visco-plastic technique is able to simulate the visco-flow failure of structure by the earthquake motion.

SIMULATION OF LIQUEFIED LATERAL FLOW OF INCLINED GROUND

A two dimensional elast-plastic dynamic transient response finite element analysis with proposed visco-plastic technique was conducted to simulate the lateral deformation of inclined ground due to liquefaction. The ground was 10 m deep, and 100 m long and inclination of 1/100.
The finite element meshes and the displacement boundary condition used in these analyses are shown in Fig.4. The shaded area in the figure represents the liquefied elements which is used to visco-plastic analysis after yielding by the elast-plastic dynamic transient response finite element analysis.

Mohr-Coulomb elasto-plastic model was used to model the stress-strain behaviour of the soil. The input parameters used in the analysis are listed in Table 1. The input parameters for visco-plastic analysis were determined from the results provided by laboratory tests[2].
The applied acceleration is obtained from the sine wave which has wave length of 4.0 Hz and amplitude of 4.9 m/s^2, and it is applied horizontally for 90 sec at bottom boundary of the ground.

The computed horizontal displacements at the ground surface (point A) and at 2 m (point B), 4 m (point C), 6 m (point D), 8 m (point D) blow the ground surface are shown in Fig. 5. Points D and E are in the

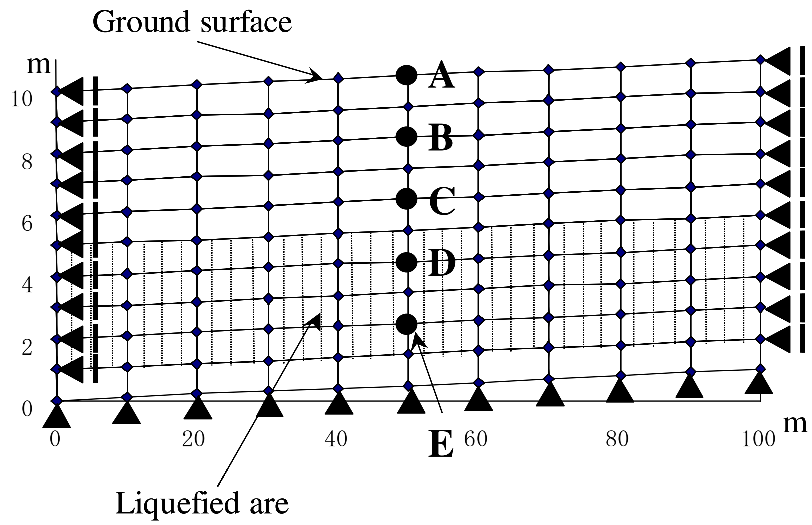

Fig.4 Finite element model used in the Inclined ground problem

Table 1 Input parameters for the visco-plastic analysis

Young's Modulus	1000.0 kPa
Poison's Ratio	0.380 (0.490 in the visco-plastic analysis)
Density of the ground	1.50 g/cm3
Friction angle	30 deg
Cohesion	1.00 kPa
Coefficient of viscosity	1680 kPa sec
Time step	0.001 sec

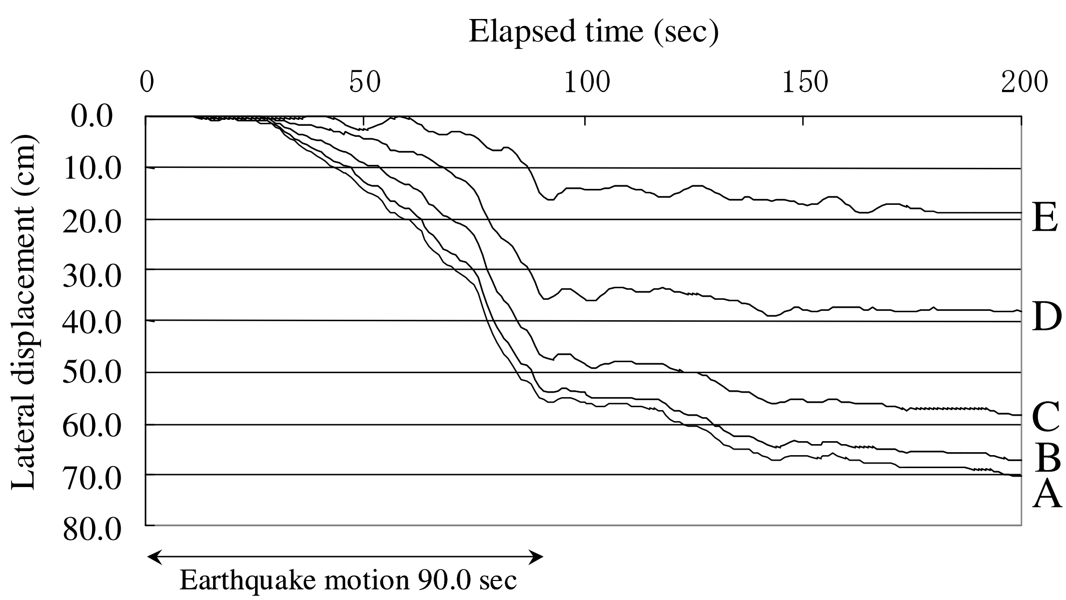

Fig.5 Lateral displacement obtained by the visco-plastic analysis

liquefied elements. The horizontal axis of the figure is the elapsed time from the beginning of the earthquake motion. The horizontal displacements at t=200 sec are 70 cm at point A, 67 cm at point B, 58 cm at point C, 38 cm at point D an 18 cm at point E respectively. At t=200 sec, the difference of displacement are approximately 20 cm between point C and D and between point D and E, whereas difference of displacement between point A and B is 3 cm. The results show that the liquefied elements are in a condition of yielding due to the earthquake motion and that the liquefied elements are deformed large by visco-plastic flow.

It is important to notice here that the horizontal displacement increases after stopping the earthquake motion at t=90 sec. The long term displacement due to liquefaction obtained from the dynamic transient response finite element simulation using the proposed visco-plastic modelling technique, and the results agreed with the field observations.

CONCLUSIONS

In this study, the ground deformation of liquefied soil was simulated using the visco-plastic flow analysing technique which was integrated into the elasto-plastic dynamic transient response finite element analyses.

The two dimensional elast-plastic dynamic transient response finite element analyses of earthquake motion of simple column with and without the visco-plastic technique were performed. The result shows that using the analysis with the visco-plastic technique is able to simulate the visco-flow failure of structure by the earthquake motion.

The two dimensional elast-plastic dynamic transient response finite element analysis with proposed visco-plastic technique was conducted to simulate the deformation of inclined ground (10 m deep, and 100 m long and inclination of 1/100) due to liquefaction. The results show that the liquefied elements are in a condition of yielding due to the earthquake motion and that more than 70 cm lateral flow of the liquefied ground obtained by visco-plastic analysis. And the long term displacement due to liquefaction obtained from the proposed visco-plastic modelling technique.

REFERENCES

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