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SYNOPSIS: This paper develops an analytical method for the calculation of the erathquake-induced settlement of foundation by using Biot's type consolidation equation. In order to investigate the effectiveness of the proposed method, a comparison of the numerical result with the observed earthquake-induced settlement on the site at Sendai in Japan caused by the miyagioki earthquake in 1987 will be pressented.

INTRODUCTION

Seismically induced permanent settlement of foundation is a major cause of damage during most large earthquakes. The earthquake at Mexico in 1957 and the earthquake at Miyagioki in 1986 is a typical example per-taining to this category.

The settlements caused by earthquake can be divided into two categories: the residual settlement during undrained dynamic loading and post-earthquake settlement due to dissipation of excess pore pressure generated during the earthquake.

Hyodo et al. (1988) and Yasuhara et al. (1991) have proposed an analytical method for evaluating the settlement of saturated clay ground subjected to earthquake. In these methods the Terzaghi's type consolidation equation was used to calculated the volume change due to partial dissipation of seismic pore water pressure and the undrained cyclic shear deformation was not considered.

In this paper, an analydical method for the calculation of the settlement of foundation by using Biot's type consolidation equation is developed and a model for predicting the excess pore water pressure of peat under dynamic loading is formulated on the basis of the results from un-drained cyclic triaxial tests. In the analysis, both of the volume change due to partial drainage of pore water pressure and the undrained cyclic shear deformation will be calculated by means of finite element analysis.

In order to investigate the effectiveness of the proposed method, a comparison of the numerical result with the observed earthquake-induced settlement on the site at Sendai in Japan caused by the miyagioki earthquake in 1987 will be pressented.

ANALYSIS METHOD

Governing Equation

In 1962, Biot established the basic equation of a saturatedsolid, porous, medium under dynamic condi-tions. A version of his governing equations extended to nonlinear behavior is represented as following (the pore water acceleration has been neglected):

$$[L]^T[D][L]\{u\}-[L]^T\{m\}p$$

$$=-[L]^T[D]\{e_p\}-[L]^T\{m\}U_g-\rho\{g\}+\rho(\{\ddot{u}\}+\{\ddot{u}_g\}) \quad (1)$$

$$\{\nabla\}^T\{k\}\{\nabla\}p-\{m\}^T[L]\{u\}=\{\bar{f}\} \quad (2)$$

where $[L]$ = Appropriate differential operator defining strains in terms of displacements
$[L]^T$ = Transposed matrix of $[L]$
$[D]$ = Tangent modulus
$\{u\}$ = Displacement vector
$\{m\}^T$ = [1,1,1,0,0,0]
p = Pore water pressure
e_p = Seismic residual strain under undrained condition
U_p = Seismic pore water pressure
ρ = Density of soil
$\{g\}$ = Gravity acceleration vector
$\{\ddot{u}\}$ = Inputearthquake acceleration vector
$\{\ddot{u}_g\}$ = Relative acceleration vector
$\{\nabla\}^T$ = Transposed matrix of Laplacian vector
$[k]$ = $[k]/(\rho g)$
$[k]$ = Permeability matrix
$\{\bar{f}\}$ = Seepage discharge vector

Formula of Pore Water Pressure of Peat under Cyclic Loading

In order to predict the earthquake-induced settlements, a model for predicting the excess pore water pressure is formulated on the basis of the results from undrained cyclic triaxial tests on the peat as follow(Fig. 1):

$$U/U_f = a + b \ln N \quad (3)$$

$$U_f = P-(q_s+q_d)/2/\sin\phi+C'/tg\phi' \quad (4)$$

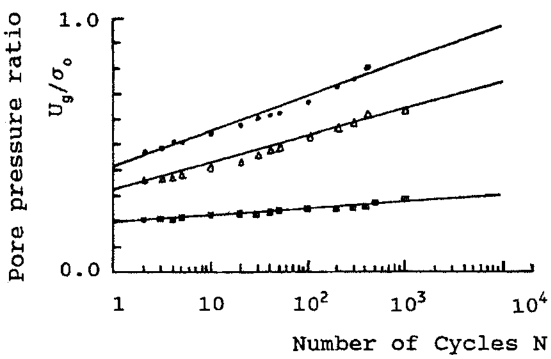

Fig.1 Variation of Excess Pore Pressure with Number of Load Cycles

where: U = Cyclic-induced pore water pressure
U_f = Maximum residual pore water pressure while 5% amplitude of shear strain reached
N = Number of loading cycles
N_f = Number of loading cycles tocause 5% amplitude of shear strain
C_1, C_2 = Experimental parameters by cyclic triaxial test, C_1 =0.82, C_2 = 0.78 for clay
P = Total mean stress
q_s = Difference of static principal stress
q_d = Difference of dynamic principal stress
C' = Effective cohesion
ϕ' = Angle of internal friction
a,b = Experimental parameter (see Fig.2 and Fig.3)

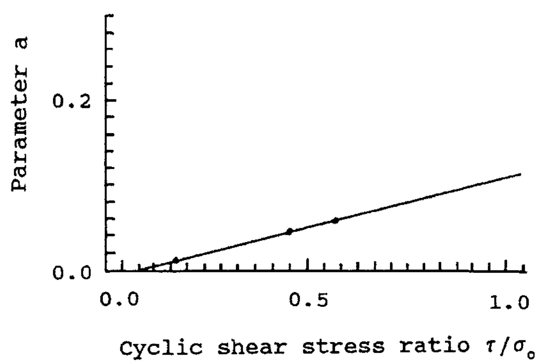

Fig.2 Variatio of Parameter a with cyclic shear stress ratio

Formula of undrained residual strain under Cyclic Loading

A form of undrained residual strain model (Zhou et al., 1992) is used for analysis as follow:

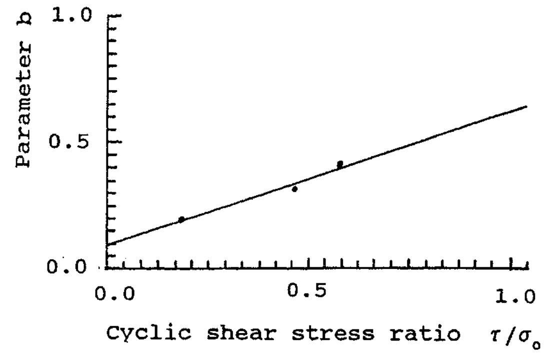

Fig.3 Variatio of Parameter b with cyclic shear stress ratio

$$e_p = \frac{U/U_f}{C_3 + (20-C_3)U/U_f} \quad (6)$$

where C_3 = 60.0, if U_f is defined as the residual pore water pressure while e_p reaches to 5%.

ANALYTICAL PROCEDURES

Equations (1) and (2) can be solved numerically under given boundary and initial conditions by the finite element method. The weighted residual method and 2-D isoparametic element with 4 nodes are used to formulate the following set of finite equations:

$$[K]\{u\} + [Q]\{p\} + [M]\{\ddot{u}\} = \{F\} \quad (7)$$

$$[Q]^T\{u\} + [H]\{p\} = \{\bar{F}\} \quad (8)$$

where [K] = Stiffness matrix
[Q] = Couple matrix
[M] = Mass matrix
[H] = Permeability matrix
{F} = Nodal earthquake load vector
$\{\bar{F}\}$ = Nodal seepage discharge vector
{u} = Nodal displacement vector
$\{\ddot{u}\}$ = Acceleration vector
{p} = Nodal pore water pressure vector

Equations (7) and (8) are solved by the front solution method (Cheung, Y. K. and Yeo, M. Y. 1982). The main steps are as follows:

1. Pre-front, form the identification vector for assembly and elimination of dynammic equation.

2. Compute the element matrices of dynamic equation and the loading vector.

3. Front solution, calculate nodal displacements, velocities, acceleration and pore water pressure at each time step.

4. Compute strain and stress field from nodal displacements.

5. Calculate seismic pore water pressure increment and undrained residual strain , convert them into equivalent nodal forces and add it into the

loading terms of Eq. (7).

6. Repeat step 2-5 until the earthquake motion ends.

7. Continue post-earthquake static analysis using the equation (1) and (2) without input motion until no further dissipation of pore water pressure is taking place.

CASE STUDY FOR EVALUATING EARTHQUAKE INDUCED SETTLEMENT OF PEAT

In the area in Sendai in Japan, there is a layer of 2-3m thick of peat beneath about 0.8m thick of surface soil. The maximum settlement measured near the centre of Nigatake in Sendai three Months after the Miyagioki Earthquake in 1987 is about 80mm, and the maximum settlement reached about 120mm four years after.

The computational analysys of seismic settlements of the ground and a 2 story building in near the centre of Niga-take in Sendai Caused by the Miyagioki Earthquake in 1987 is presented by the analytical procedure mentioned above.

An accelerogram recorded on rock at Sendai during the Miyagioki Earthquake was used as input motion. The input scaled peak acceleration was rivised to 0.2g and the shock duration was rivised to 20 second(Fig. 4).

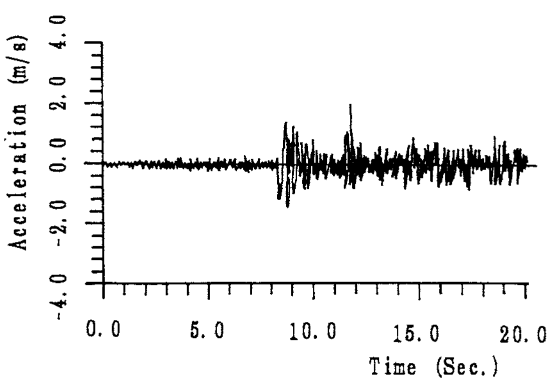

Fig. 4 Input Motion

The finite element mesh of a 2-story building with raft foundation is shown in Fig. 5. the

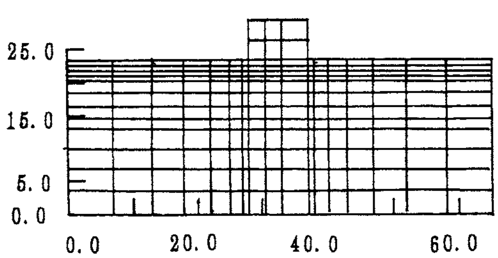

Fig. 5 Finite Element Mesh of 2-Story Building with Raft Foundation

height of the building is 6.0 meter. Six siol layers with the thickness of 23.5 meter and the width of 70 meter was taken in the calculation. The relevant material properties and computation parameters are listed in Table 1.

Table 1 Index Properties of Materials

Layer thickness	Soil type	Unit weight (KN/m3)	Shear velocity (m/s)	Shear modulus (kPa)
0.8	Surface soil	16.0	124	25000
2.4	Orgnic Soil	13.5	95	11000
5.8	Silty fine sand	17.0	142	35000
1.5	Sandy silt	16.5	154	40000
3.5	Clay	16.0	247	100000
21.5	Sandy gravel	20.0	443	400000

Fig. 6 shows the calculated settlement of soil ground (with no buildings on it) during and after the earthquake. Fig. 7 shows the calculated settlement of 2-stored soil foundation at the end of the earthquake and 2 years after the earthquake. The calculated maximum settlement at the end of the earthquake is about 72mm and the calculated maximum settle-ment 4 years after the earth-quake is about 107mm. It shows that there is an agreement between the computed and observed data.

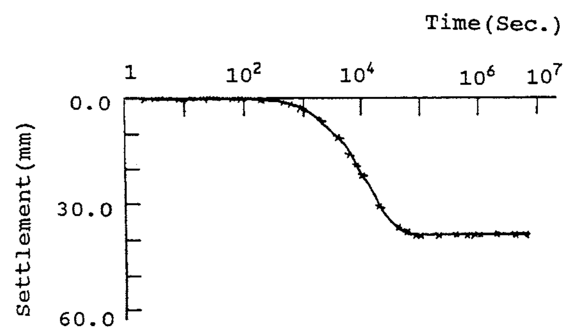

Fig.6 Calculated Settlement of Soil Ground (with no Buildings on It) with Time

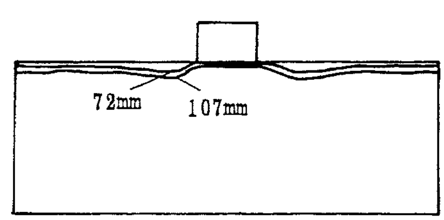

Fig.7 Calculated Settlement contours of Soil Foundation

CONCLUSIONS

An analytical procedure for evaluating the settlement of soil foundation subjected to an earthquake was presented. The principal of calculation and the selection of parameters used in the calculation were described. The computational results show that there is an agreement between the computed and observed results.

The methodology presented in this paper would be applicable to calculate the cyclic-induced settlements of clayey soil foundations.

REFERENCES:

Hyodo, M., Yasuhara, K. and Murata, H.(1988), "Earthquake induced settlements in clays." Proc. 9th World Conference on Earthquake Engineering, 1 (III), 89-94.

Yasuhara K. and Hyodo M.(1991), "Earthquake-induced Settlement in soft grounds", 2nd International Conferece on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Marth 11-15, 1991, St, Louis, Missouri, USA, 365 - 370.

Biot, M. A. (1962), "Mechanics of deformation and acoustic propagation in porous media", J. Appl. Phys., 1484-1498.

Zhou, J. Yasuhara, K. and Hirai, M. (1992), "A model for predicting the cyclic-induced behavior of clay with Initial static shear stress." Proc. of 47th annual meeting of Japanese Society of Civil Eng. in Sendai, Sept. 1992.

Cheung, Y. K. and Yeo, M. Y. (1982), An Introduction to Pratical Use of The Finite Element Method, 1st Edition, Jiangxi Renmin, Jiangxi, China (in Chinese).