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SETTELEMENT ANALYSIS OF CLAY DEPOSIT INDUCED BY EARTHQUAKE MOTION

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ABSTRACT

A series of undrained cyclic torsional simple shear tests were carried out on clay specimen consolidated under anisotropic stress conditions. An empirical equation has been derived to estimate the accumulation of excess pore pressure and volume change due to its dissipation. By using the proposed empirical equations, three types of analytical methods were presented and applied to calculate the settlement of a clay deposit due to different earthquake motions on a model ground. The effects of earthquake motions, intensities and analytical methods on the settlement of ground has been discussed.

KEYWORDS

Clay deposit, Torsional simple shear tests, Excess pore pressure prediction, Earthquake motion, Earthquake records, Ground settlement, SHAKE, Accumulative damage concept, Response spectrum

INTRODUCTION

Many damages to the earth structures, architectural structures and infrastructures has been reported due to the settlement of ground induced by cyclic loadings such as due to earthquakes, traffic loads, wave loads etc. Many researches have been focused mostly on the liquefaction of sandy grounds and subsequent lateral flows since cohesionless soil ground exhibit catastrophic phenomena like liquefaction due to earthquakes etc. However, a very few researches on the settlement behavior of clay deposits due to earthquake could be found (Hyodo *et al.*, 1988, Matsuda *et al.*, 1991 among others). Concerning the prediction of excess pore pressure induced by undrained cyclic loading, triaxial tests has mostly been used. However, in order to simulate more precisely the in-situ condition, it is necessary to perform anisotropically consolidated undrained cyclic simple shear tests.

In the present study, a series of undrained cyclic torsional simple shear tests were carried out on anisotropically consolidated (normally consolidation condition) clay specimens under uniform stress cycle condition. Empirical equations to predict the pore pressure accumulated during cyclic loading as well as volume change of specimen due to the dissipation of excess pore pressure has been presented. Next, one dimensional earthquake response analysis was performed on a model ground using SHAKE program. Based on the pore pressure model proposed, three methods to calculate the accumulated excess pore pressure induced by irregular stress waves were presented. The methods presented are: (a) Modified accumulative damage concept, (b) Dynamic pore pressure method, and (c) Modified dynamic pore pressure method. The settlement analysis of the model ground has been carried out based on the three methods under three different types of earthquake waves.

UNDRAINED TORSIONAL SIMPLE SHEAR TESTS

Hollow cylindrical specimen (height 5cm, outer and inner diameter 10, 6cm respectively) of remolded clay (Tokyo Bay clay, Plasticity Index 40, Clay fraction content 45%) were anisotropically consolidated under K_0 condition and then subjected to undrained cyclic torsional shear under simple shear conditions. The simple shear condition was achieved mechanically by keeping the inner and outer diameter constant during shearing (Tatsuoka *et al.*, 1988). A series of tests has been carried out under different consolidation level and applied stress ratios SR (Dam, 1995). The cyclic loading frequency was 0.1Hz. Cyclic loading was carried out for a specified number of cycles and then left for curing for 30 minutes. The equilibrium excess pore pressure was measured and then dissipation test was performed for 24 hours.

Excess Pore Pressure Accumulation and Dissipation Model

The normalized averaged excess pore pressure EPP ($=\Delta u/\sigma_v'$) is best fitted by power function of logarithm of loading cycles for different stress ratios SR ($= \tau/\sigma_v'$; τ: cyclic shear stress in horizontal direction and σ_v': vertical consolidation effective stress). The empirical equation is expressed by eq. (1).

$$\Delta u/\sigma_v' = \Delta u/\sigma_v'(N{=}1) + A_u \ (\log N)^{\alpha} \ (SR)^{\beta} \ ; \quad (SR = \tau/\sigma_v') \qquad (1)$$

Here, $\Delta u/\sigma_v'$ (N=1) is EPP generated at the first loading cycle as expressed by eq. (2) and A_u, α, β are experimental parameters. For the clay used, Au=11, α=1.5, β=3.

$$\Delta u/\sigma_v'(N{=}1) = 0.062\,SR \quad (SR \leqq 0.16)\,; \quad \Delta u/\sigma_v'(N{=}1) = -0.045 + 0.33SR \ (SR > 0.16) \qquad (2)$$

From the application of eqs (1) and (2) to other clays, it was found that $\Delta u/\sigma_v'$ (N=1) is slightly larger for higher plastic clay. However, the parameters A_u, α, β are less sensitive to clay properties if the static strength is taken into account while calculating an equivalent stress ratio SR to be used in eq. (1).

Volumetric strain (ε_v) due to the dissipation of the accumulated excess pore pressure (Δu) is expressed by using recompression index C_r* as in eq. (3).

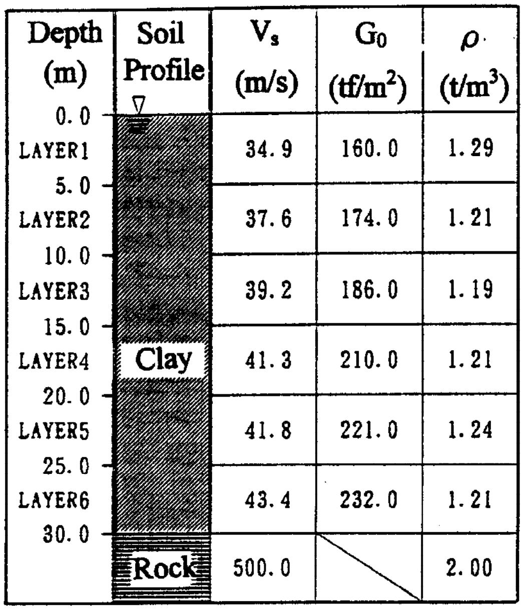
$$\varepsilon_v = [C_r^*/(1+e_c)] \log [1/\{1-\Delta u/\sigma_v'\}] \qquad (3)$$

Here e_c is the void ratio after consolidation and recompression index is considered as a function of $\Delta u/\sigma_v'$ as expressed by eq. (4), where A_{CR} and λ are experimental parameters and equal to 0.12 and 1.9 for the clay used.

$$C_r^* = A_{CR} \ [1/\{1-\Delta u/\sigma_v'\}]^{\lambda} \qquad (4)$$

MODEL GROUND AND EARTHQUAKE MOTIONS

The ground selected for settlement analysis is Mexico city clay deposit (for example by Morita *et al.*, 1986) and is represented by model as shown in Fig.1. Very soft clay deposit of thickness about 30m lies on a stiff rock and the ground water table was considered at the surface. Since the water content was more than 200%, the maximum shear modulus (G_0) of each layer was estimated by using formula for void ratio less or equal to 4, as given by eq. (5) (Kokusho *et al.*, 1982).



Depth (m)	Soil Profile	V_s (m/s)	G_0 (tf/m^2)	ρ (t/m^3)
0.0	∇			
LAYER1		34.9	160.0	1.29
5.0				
LAYER2		37.6	174.0	1.21
10.0				
LAYER3		39.2	186.0	1.19
15.0				
LAYER4	Clay	41.3	210.0	1.21
20.0				
LAYER5		41.8	221.0	1.24
25.0				
LAYER6		43.4	232.0	1.21
30.0				
	Rock	500.0		2.00

Fig.1 Model ground (Mexico city)

$$G_0 = 9(7.32-e_c)^2/(1+e_c) \cdot \sigma_v'^{0.6} \tag{5}$$

Here e_c is the void ratio and σ_v' (in kgf/cm^2 = 98 kPa) is the effective overburden pressure. From G_0, shear wave velocity Vs $\{=\sqrt{(G_0/\rho)}\}$ is calculated and the parameters used for one dimensional earthquake response analysis is shown in Fig.1. The nonlinearity of the shear modulus and damping ratio with respect to strain level has been taken into account in a hyperbolic form to run the program SHAKE.

Three types of recorded earthquake waves were used for input at the 30m down bedrock of the model ground. They are: ① Mexico earthquake of 1985 with recorded maximum acceleration of 96gal, ② Elcentro earthquake of 1940 with recorded maximum acceleration of 330gal and ③ Tokachi-oki earthquake of 1968 with recorded maximum acceleration of 221gal. The time history of acceleration records are shown in Figs2 to 4. The response spectrums of acceleration of each earthquake wave for damping ratios of 0, 5, 10% are shown in Figs 5 to 7. From Figs 5 to 7, it can be observed that the resonant period T_{res} of each earthquake motion is different and is equal to 2.0, 0.5 and 0.4 sec for Mexico, Elcentro and Tokachi-oki earthquakes respectively. Another point to be noticed is that the duration of earthquake is longer in case of Mexico earthquake as compared to others.

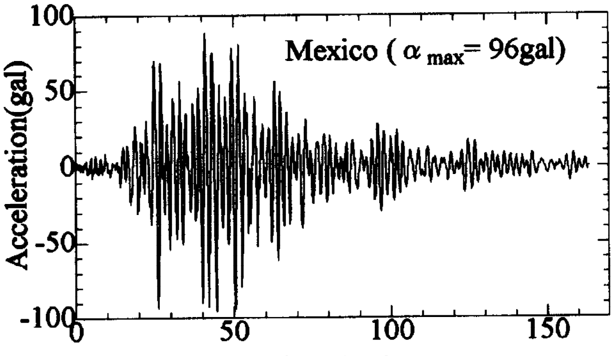


Fig.2 Acceleration record of Mexico Earthquake

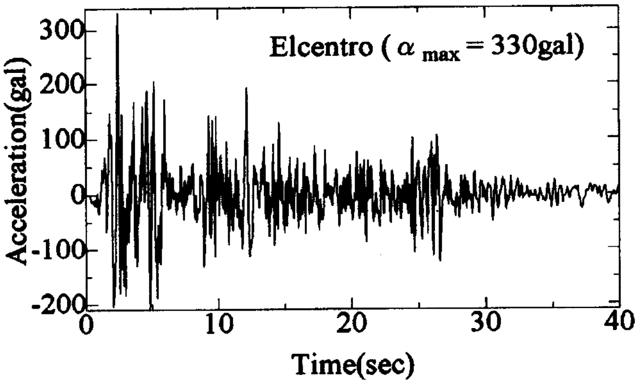


Fig.3 Acceleration record of Elcentro Earthquake

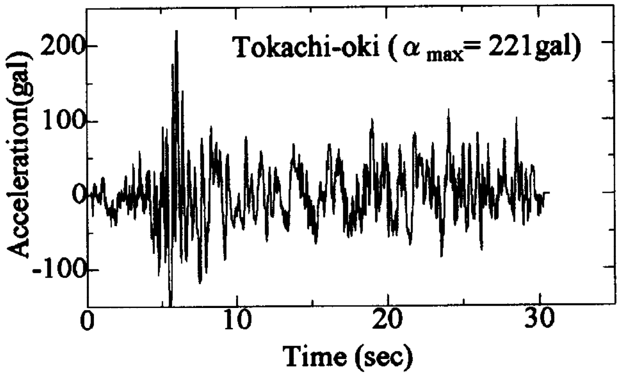


Fig.4 Acceleration record of Tokachi-oki Earthquake

ANALYTICAL METHODS

Three different methods to calculate the accumulation of excess pore pressure due to irregular earthquake stress waves by using the proposed empirical pore pressure model established for uniform stress cycles, are presented.

Modified Accumulative Damage Concept (ACCUM)

The basic premise of this method is the assumption that the energy applied during any stress cycle has an accumulative damage effect on the material. Annaki *et al.* (1977) extended this method and named as equivalent uniform cycle concept and has been widely used to estimate cyclic strengths of soils subjected to irregular loadings. Here the same concept is used to estimate the excess pore pressure due to irregular loading cycles based on the proposed empirical formula. Uniform stress ratio cycle (SR_e) is calculated as 65% of the peak stress ratio in the irregular stress wave. SR-N curve corresponding to $\Delta u/\sigma_v'$ of 0.4 from the empirical equation was used for calculation since this pore pressure level can be considered to be high enough for NC clays. The number of uniform stress cycle (N_e) corresponding to SR_e

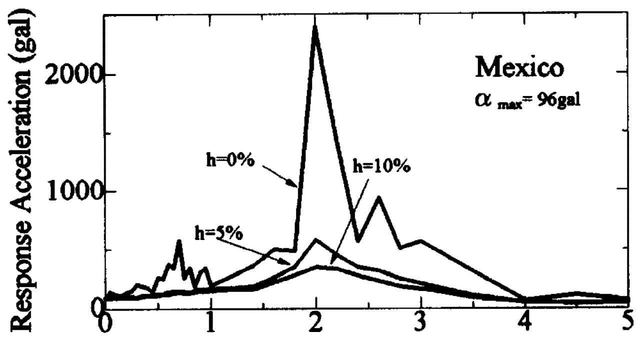


Fig.5 Response Spectrum of Mexico Earthquake

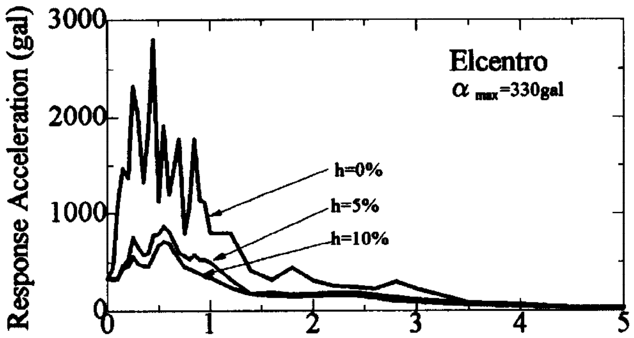


Fig.6 Response Spectrum of Elcentro Earthquake

can be calculated by eq. (6).

$$(\log N_e)^{\alpha} = 0.4 - \Delta u/\sigma_v'(N=1,\ SR_e) + A_u\ (SR_e)^{\beta}] \tag{6}$$

In the same way, number of stress cycle N_i corresponding to each half pulse of stress ratio time history for each layer is calculated by eq. (6').

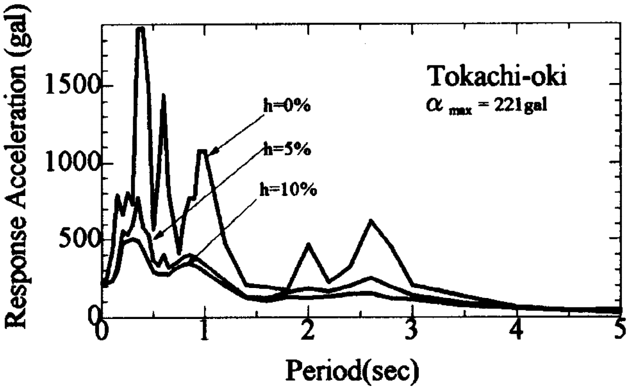


Fig.7 Response Spectrum of Tokachi-oki Earthquake

$$(\log N_i)^{\alpha} = [0.4 - \Delta u/\sigma_v'(N=1, SR_i) + A_u (SR_i)^{\beta}] \tag{6'}$$

Then the equivalent number of cycles N_{eq} is calculated by eq. (7).

$$N_{eq} = N_e \ \Sigma\ [1/(2N_i)] \tag{7}$$

The accumulated pore pressure due to the whole irregular stress waves is then calculated by eq. (1) by substituting $N= N_{eq}$ and $SR = SR_e$. This method is quite simple, however there are some demerits as: (1) cannot calculate the time history of pore pressure, (2) cannot take into account the sequence of the stress waves. Also it is confirmed that there is a tendency of estimating higher pore pressure when compared to experimental data under irregular stress cycles.

Dynamic Pore Pressure Method (DYN)

Sarma *et al.* (1980) proposed a method for treating irregular cyclic stress history called 'concept of a dynamic pore pressure parameter'. The method is based on the assumption that the pore pressure response to a cycle of loading depends on the amount of excess pore pressure already present and also on the level of shear stress applied. In their method, the pore pressure is assumed to be linearly proportional to the stress applied related by a dynamic pore pressure parameter. However in the present method, the proposed empirical pore pressure model (eq.1) is used directly and the procedure to calculate the pore pressure due to each irregular stress wave is basically the same. The procedure is to calculate the equivalent number of cycles (N_{eq}) of uniform stress ratio history SR_i which would have been responsible for developing the pore pressure currently accumulated. Hence the next accumulated pore pressure can be calculated by substituting $N= N_{eq}+1$ and $SR= SR_i$ in eq. (1). These steps are repeated for each averaged stress ratio cycle and hence a time history of pore pressure can be calculated for a given irregular stress waves. The path ① in the flow chart shown in Fig.8 gives the procedure of this method.

Modified Dynamic Pore Pressure Method (MDYN)

The validity of Dynamic pore pressure method (DYN) is first checked by using irregular stress cycles data in Torsional simple shear test. It was found that this method DYN seems to underestimate the measured pore pressure. The reason for this is surmised to be that the pore pressure increment due to a stress cycle following a higher stress cycle is estimated to be very small since the equivalent number of cycle is largely increased. However, from the experimental data it seems that pore pressure increment induced by stress cycle followed by a higher stress cycle is not negligible. Hence, only in this case this method is modified. The main point is that N_{eq} is kept constant if a stress cycle is followed by higher stress cycle and the pore pressure increment is calculated for $SR = SR_i$ and N from N_{eq} to $(N_{eq}+1)$. The path ② in the flow chart shown in Fig.8 gives the procedure of this modified method.

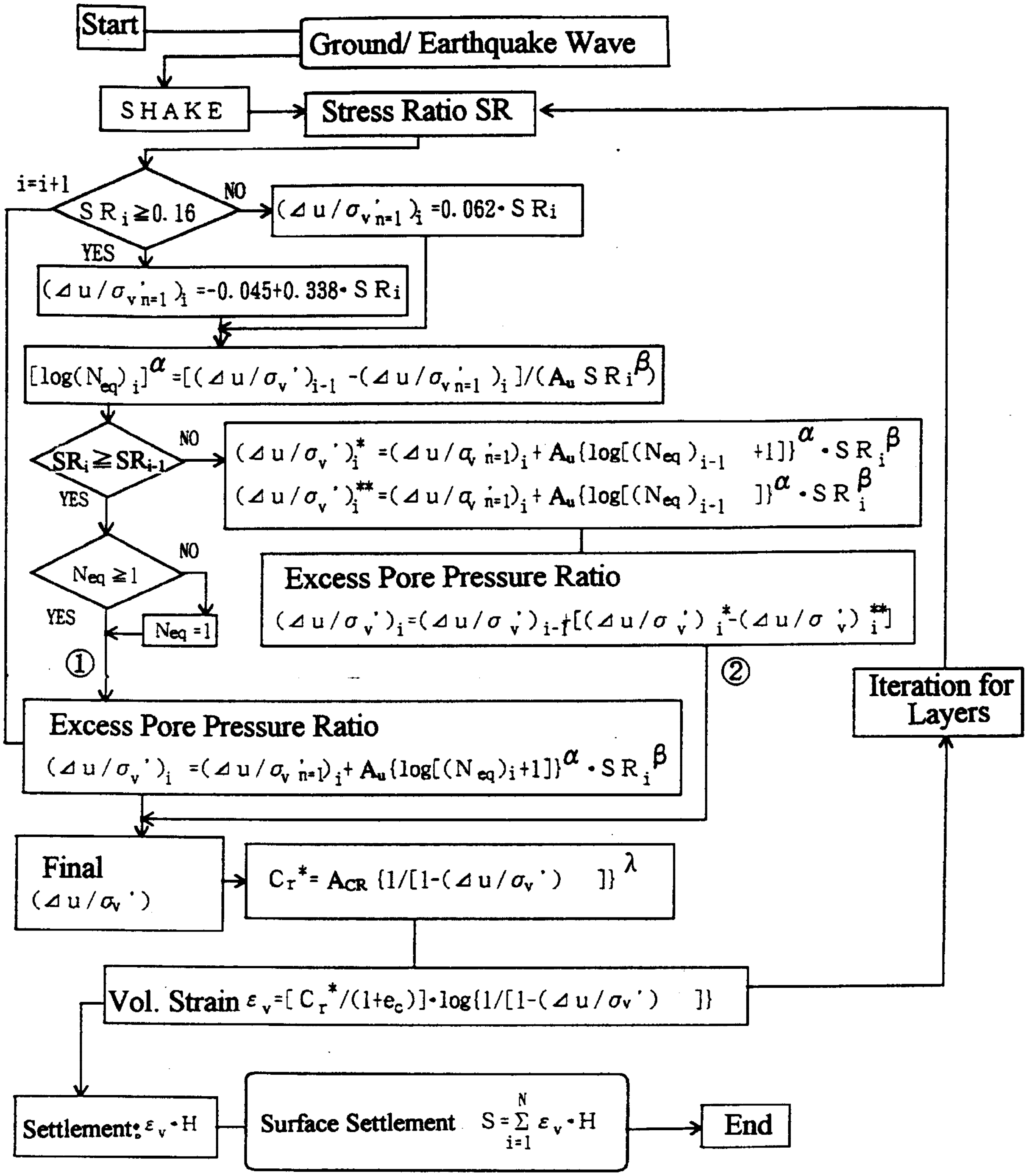


Fig.8 Flow chart of Dynamic Pore Pressure Method (DYN and MDYN Methods)

SETTLEMENT PREDICTION OF MODEL GROUND AND DISCUSSIONS

Surface settlement analysis of the model ground is carried out in the following steps: (a) earthquake wave is induced at the bed rock and the stress ratio (τ / σ_v') induced is calculated at each soil layer based on SHAKE analysis, (b) accumulation of pore pressure is estimated using three different types of methods (ACCUM, DYN and MDYN), (c) volumetric strain (one dimensional settlement is assumed) due to the dissipation of excess pore pressure at each layer is calculated and summed up to get total settlement.

As a typical result, the time history of accumulated pore pressure at each layer is shown in Fig.9 when recorded Mexico earthquake wave is induced. It can be observed that pore pressure is higher at layer 1 and method MDYN gives slightly higher pore pressure as compared to method DYN. On the other hand, method ACCUM gave the final pore pressure about 150% of that given by DYN method. The reason for this overestimation of pore pressure may be due to the assumption of linearity of clay behavior under cyclic loading and neglection of the sequence of the stress wave.

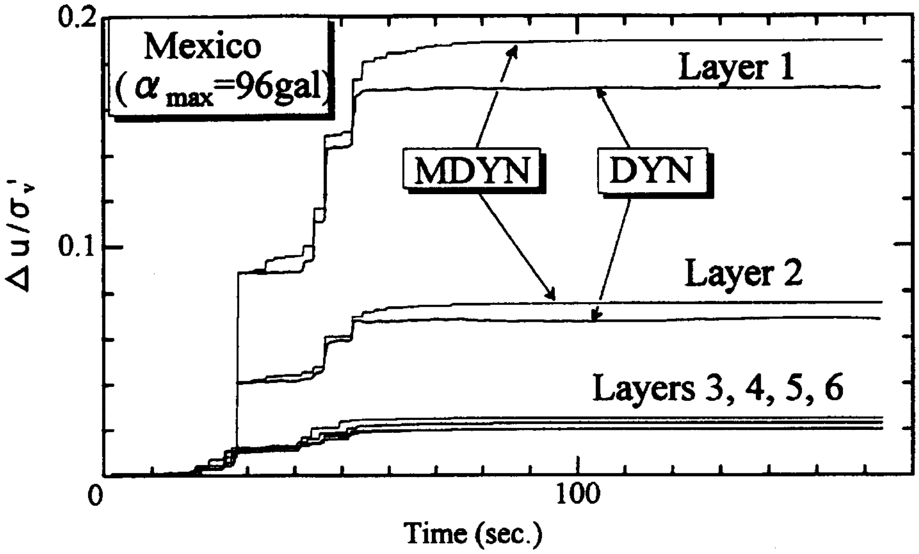


Fig.9 Typical time history of pore pressure (Mexico earthquake)

Comparison of settlements calculated from three methods are shown in Fig.10 for the recorded earthquake waves. Following points could be noticed: (a) Method ACCUM gives very high settlement values as compared to other two methods, (b) Method MDYN gives slightly higher settlement than method DYN, (c) Mexico earthquake induces higher settlement as compared to other two earthquakes eventhough the peak acceleration α_{max} of this wave is the smallest one.

The natural period T_G {$= 4 \Sigma(H_i / V_{Si})$; H_i, V_{Si} are thickness and shear wave velocity of each layer} of the model ground is calculated to be 3 sec. Hence it can be surmised that this model ground is very sensitive to Mexico earthquake type of wave since the resonant period T_{res} of the Mexico wave is 2 sec while T_{res} for other two waves are less than 0.5 sec.

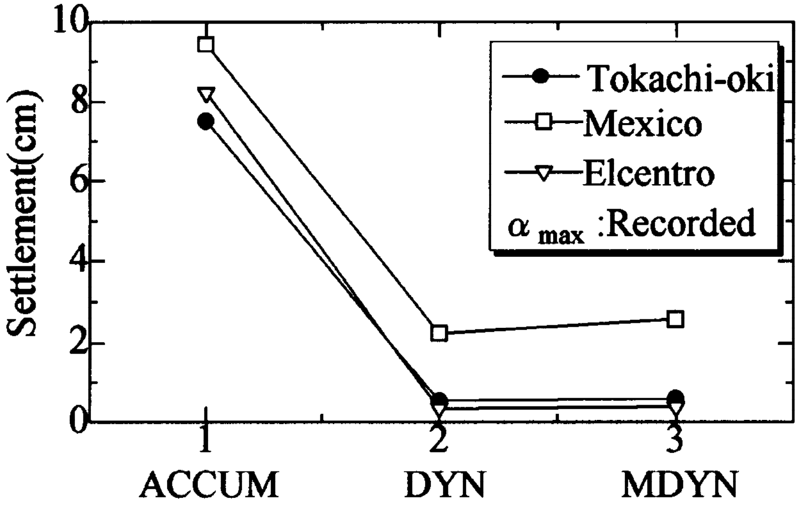


Fig.10 Settlement from different methods

In order to see the effect of maximum peak acceleration α_{max} on settlement for the similar wave forms, calculations are done for α_{max} equal to 50% and 150% of the recorded values and the results are shown in Figs 11 to 13 for different analytical methods. It was confirmed that if $\alpha_{\max}$ is twice, the output stress ratio is also twice, however the absolute value is quite different depending on the stress waves. It can be observed that irrespective of the analytical methods, a small increase in $\alpha_{\max}$ in Mexico earthquake wave, the settlement increases abruptly. Hence the model ground is very sensitive to this kind of stress wave, while the settlement is not so much affected for other two earthquake waves. The reason may be that resonant period of Elcentro and Tokachi-oki earthquakes are quite small as compared to T_G.

In order to see the effect of stress wave forms for a fixed maximum acceleration, settlements are calculated for the same $\alpha_{\max} = 100$gal for all earthquake waves and is shown in Fig.14. It can be noticed that Elcentro and Tokachi-oki stress waves basically give same settlement while Mexico wave gives fairy high settlement. The reason may be the same as has been explained before.

CONCLUSIONS

Following conclusions could be drawn from the present study.

1. Three different types of analytical methods are presented to calculate the accumulation of excess pore pressure induced by irregular stress cycle waves.
2. Modified accumulated damage concept method (ACCUM) gives higher surface settlement as comparedto Dynamic pore pressure method (DYN) and Modified dynamic pore pressure.
3. Mexico earthquake wave induces higher settlement as compared to other two earthquake waves

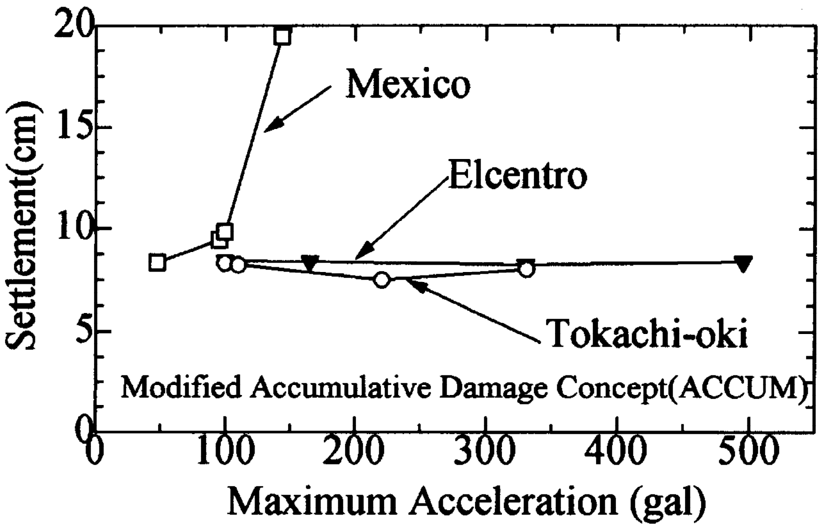


Fig.11 Settlement for different maximum acceleration (ACCUM)

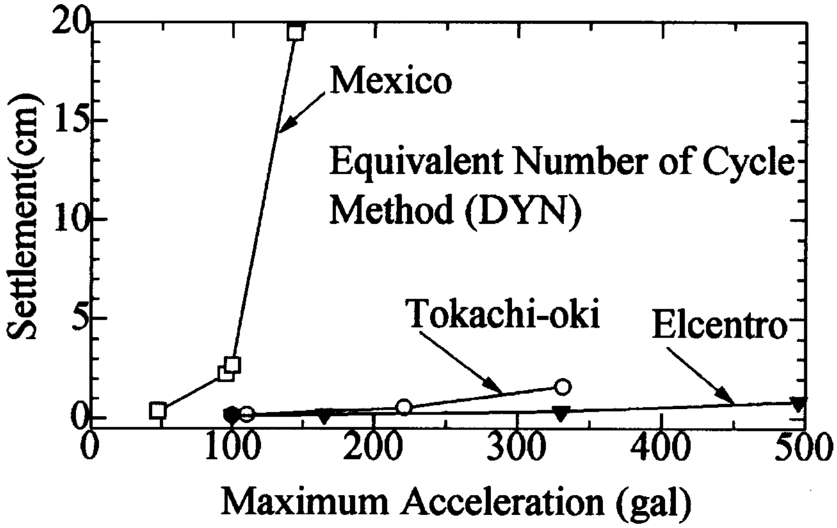


Fig.12 Settlement for different maximum acceleration (DYN)

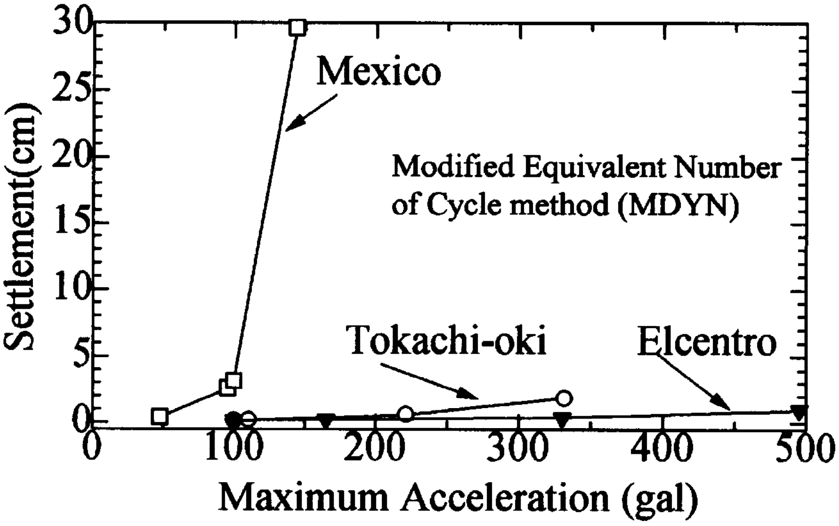


Fig.13 Settlement for different maximum acceleration (MDYN)

eventhough the maximum peak acceleration of this wave is the smallest one.

4. Settlement of the model ground is very sensitive to stress wave like Mexico earthquake of which the resonant period is close to that of the ground, while less sensitive to Elcentro and Tokachi-oki earthquakes.

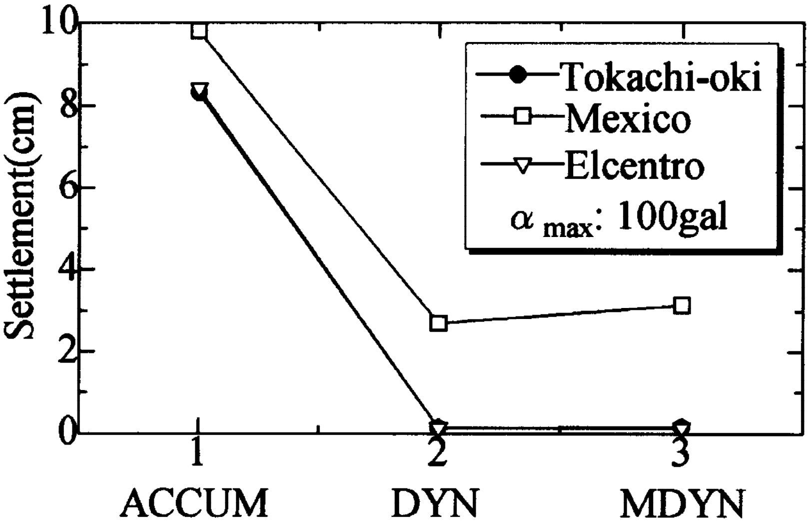


Fig.14 Settlement for same α_{max}

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