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ANALYSIS OF GRAVEL DRAIN AGAINST LIQUEFACTION AND ITS APPLICATION TO DESIGN

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SUMMARY

To establish the design technique of the gravel drain method in which the well-resistance of the drain was considered, the authors developed the analysis program where the drain had finite permeability and confirmed the applicability of the program, by vibration model tests. Also from the parametric study by the analysis program, the nomograms on maximum pore water pressure ratio and drainage were proposed. It turned out that the factors of the drain slenderness ratio and the drain-sand permeability ratio were important in predicting the pore pressure during earthquakes by the parametric studies.

INTRODUCTION

The use of the gravel drain method which generates low vibration and noise during construction work is recently drawing attention as a measure against liquefaction of the ground during earthquakes. When designing gravel drains for certain ground conditions, it is necessary to determine the intervals of gravel drains having a certain diameter. This interval is often determined by using the design nomogram proposed by Seed and Booker (Ref.1). However, this nomogram is prepared on the assumption that the excess pore water pressure at the boundary on the gravel drain side is zero (permeability of drain is considered as infinite). Consequently, this seems to evaluate the excess pore water pressure slightly less than that of more realistic models which consider the finite permeability of gravel drains. Because of this, analyses considering the well-resistance of gravel drain are being made of late (Refs.2,3). The authors have developed the analysis program AXPORE considering the permeability of gravel drain and have confirmed its effectiveness by model tests for gravel drains. In addition, parametric studies using the analysis program were conducted, the maximum excess pore water pressure ratio and drainage were rearranged with respect to non-dimensional parameters, and nomograms for practical use were prepared.

BASIC EQUATIONS OF PROGRAM AXPORE AND EXTRACTION OF NON-DIMENSIONAL PARAMETERS

Basic Equation If only one gravel drain is considerd among many gravel drains, then an axisymmetric model as shown in Fig. 1 can be created. We assume that the pore water flow follows Darcy's law without considering the coupling of soil particles with water and sand layers and gravel drains are isotropic and homogeneous. Then the behavior of the pore water can be expressed by the formulae shown below because of the continuity of the pore water.

(Sand layer portion) $a \leqq r \leqq b$,

$$\frac{k_s}{\gamma_w m_{vs}}\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial z^2}\right)=\frac{\partial u}{\partial t}-\frac{\partial u_g}{\partial t} \qquad (1)$$

(Drain portion) $0 \leqq r \leqq a$,

$$\frac{k_d}{\gamma_w m_{vd}}\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial z^2}\right)=\frac{\partial u}{\partial t} \qquad (2)$$

On the other hand, the initial condition and boundary conditions can be given by the following formulae:

(Initial condition) For all r,z at t=0: $u(r,z,0)=0$ (3)

(Boundary conditions) For all r,z at z=0: $u(r,0,t)=0$ (4)
For all r,t at z=H: $\frac{\partial u}{\partial z}(r,H,t)=0$ (5)
For all z,t at r=b: $\frac{\partial u}{\partial r}(b,z,t)=0$ (6)
For all z,t at r=a: $\frac{\partial u}{\partial r}(0,z,t)=0$ (7)

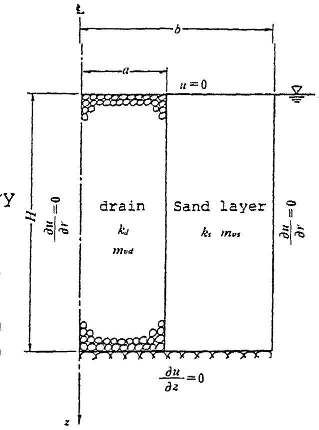


Fig.1 Analytical Model

Where, u:excess pore water pressure, u_g:excess pore water pressure in undrain condition during earthquake, k_s:coefficient of permeability of sand layer, k_d:coefficient of permeability of drain, m_{vs}: volume compressibility of sand layer, m_{vd}: volume compressibility of drain. Generation function u_g of excess pore water pressure is based on the formula given by DeAlba et al. (Ref. 4), and $\partial u_g/\partial t$ is given by the following equation:

$$\frac{\partial u_g}{\partial t}=\frac{\sigma v'}{\alpha\pi}\frac{N_{eq}}{N_l t_d}\left[\sin^{2\alpha-1}\left(\frac{\pi}{2}\frac{u}{\sigma v'}\right)\cdot\cos\left(\frac{\pi}{2}\frac{u}{\sigma v'}\right)\right]^{-1}(t\leqq t_d),\ \frac{\partial u_g}{\partial t}=0(t>t_d) \qquad (8)$$

Where, α:material constant (α=0.7 in the present calculations), N_l:Number of cycles until excess pore water pressure ratio under undrained condition reaches 1.0, N_{eq}: Equivalent number of cycles, t_d: Effective duration time of earthquake, $\sigma v'$: Effective overburden pressure ($\sigma v'=\gamma' z$).

<u>EXTRACTION OF NON-DIMENSIONAL PARAMETERS</u> Now, coordinate transformation of $\eta=r/a$, $\zeta=z/H$, $\theta=t/t_d$ and $\xi=u/\sigma v'$ are made for Eq. (1) to (8) for making them non-dimensional. For the sand layer portion, the folloing formula at $1 \leqq \eta \leqq b/a$ is obtained from Eqs.(1),(3)and (5).

$$\frac{t_d}{a^2}\frac{k_s}{\gamma_w m_{vs}}\left[\frac{\partial^2\xi}{\partial\eta^2}+\frac{1}{\eta}\frac{\partial\xi}{\partial\eta}+\frac{a^2}{H^2}\left(\frac{2}{\zeta}\frac{\partial\xi}{\partial\zeta}+\frac{\partial^2\xi}{\partial\zeta^2}\right)\right]=\frac{\partial\xi}{\partial\theta}-\frac{N_{eq}}{\alpha\pi N_l}\left[\sin^{2\alpha-1}\left(\frac{\pi}{2}\xi\right)\cdot\cos\left(\frac{\pi}{2}\xi\right)\right]^{-1} \qquad (9)$$

$$\left.\begin{aligned}&\xi(\eta,\zeta,0)=0 \text{ for all } \eta,\ \zeta, \text{ and } \xi(\eta,1,\theta)+\frac{\partial\xi}{\partial\zeta}(\eta,1,\theta)=0 \text{ for all } \eta,\ \theta\\&\frac{\partial\xi}{\partial\eta}\left(\frac{b}{a},\zeta,\theta\right)=0 \text{ for all } \zeta,\ \theta\end{aligned}\right\} \qquad (10)$$

On the other hand, for the drain portion, the formula below is obtained at $0 \leqq \eta \leqq 1$ from Eqs.(2),(3),(5) and(7).

$$\frac{t_d}{a^2}\frac{k_d}{\gamma_w m_{vd}}\left[\frac{\partial^2\xi}{\partial\eta^2}+\frac{1}{\eta}\frac{\partial\xi}{\partial\eta}+\frac{a^2}{H^2}\left(\frac{2}{\zeta}\frac{\partial\xi}{\partial\zeta}+\frac{\partial^2\xi}{\partial\zeta^2}\right)\right]=\frac{\partial\xi}{\partial\theta} \qquad (11)$$

$$\left.\begin{aligned}&\xi(\eta,\zeta,0)=0 \text{ for all } \eta,\ \zeta, \text{ and } \xi(\eta,1,\theta)+\frac{\partial\xi}{\partial\zeta}(\eta,1,\theta)=0 \text{ for all } \eta,\ \theta\\&\frac{\partial\xi}{\partial\eta}(0,\zeta,\theta)=0 \text{ for all } \zeta,\ \theta\end{aligned}\right\} \qquad (12)$$

Also, the following formula is held as the boundary condition between drain portion and sand layer portion:

$$\frac{k_d}{k_s}\frac{\partial\xi}{\partial\eta}(1,\zeta,\theta)=\frac{\partial\xi}{\partial\eta}(1,\zeta,\theta) \qquad (13)$$

From the above Eqs.(9) to (13), the following six non-dimensional parameters will affect the solutions of this boundary value problem:

$$\frac{t_d}{a^2}\frac{k_s}{\gamma_w m_{vs}},\ \frac{t_d}{a^2}\frac{k_d}{\gamma_w m_{vd}},\ \frac{H}{a},\ \frac{k_d}{k_s},\ \frac{N_{eq}}{N_l},\ \frac{b}{a} \tag{14}$$

However, these forms will be slightly changed here and the following six parameters will be adopted as final non-dimensinal parameters:

That is, $Td=(t_d/a^2)(k_s/\gamma_w m_{vs})$: time factor; $M=m_{vd}/m_{vs}$: volume compressibility ratio; $K=k_d/k_s$: ratio of coefficient of permeability; $N=H/2a$: slenderness ratio of drain; $m=a/b$: drain diameter to effective diameter ratio; N_{eq}/N_1 : ratio between equivalent cycle number and the number of cycles untill excess pore pressure ratio reaches 1.

MODEL TEST OF GRAVEL DRAIN AND ITS ANALYSIS

Outline of Model Test In order to review the effectiveness of the gravel drain measures against liquefaction and the validity of analysis method mentioned above, model tests were conducted on the gravel drain-sand system. Outline of the model used in the test and the location of instruments installed are shown in Fig. 2. As shown in the figure, a cylindrical specimen 375 mm in diameter and 1000 mm high was made in the special soil container for shear mode vibration having a circular section. Quarrying (grain size 2.0-10.0mm) was used as crushed stone for gravel drain, and Toyoura Sand was used for the sand layer portion. Water was first poured to a certain level in the container and sand was then dropped from the top by water-pluviation method. The sand was compacted by tamper every 12.5cm high.

For the drain portion, a vinyl chloride pipe with an inside diameter of 10 cm was installed, crushed stone was placed inside the pipe to a proper height,and then the pipe was raised completely. Instruments used were ten pore pressure meters, five accelerometers and four displacement meters. They were installed for each 25 cm of depth. The tests were conducted for both the case with sand layer only without the drain and the case with the gravel drain installed. The relative density Dr of respective sand layer was 82% without drain and 79% with drain. Also, the submerged unit weight γ' calculated from the specific weight of soil particles of Toyoura Sand and the dry density during compaction was 0.98 tf/m^3 in both the cases.

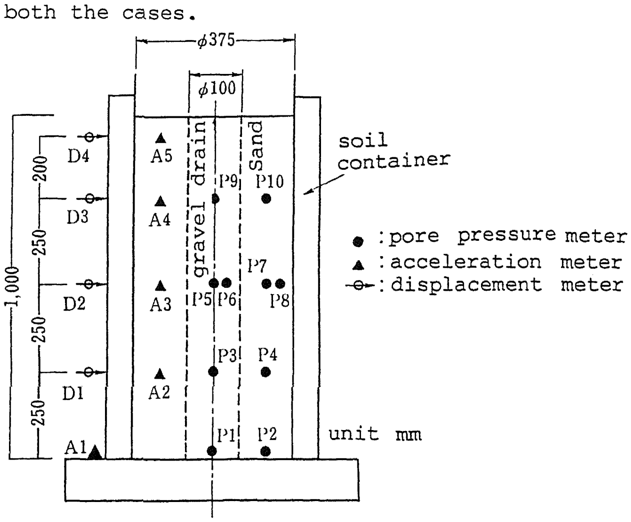


Fig.2 Experimental Model and Location of Instruments

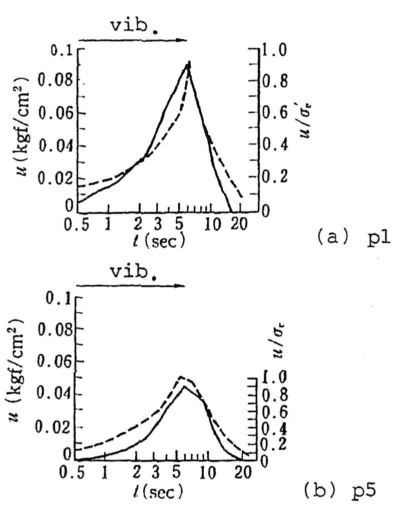
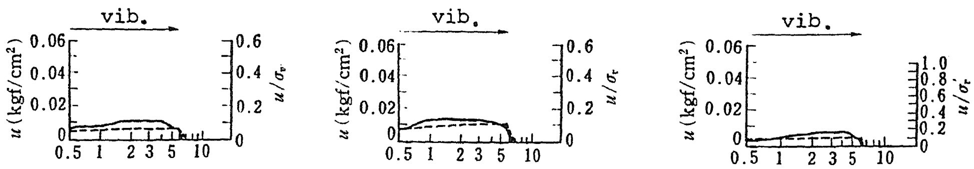
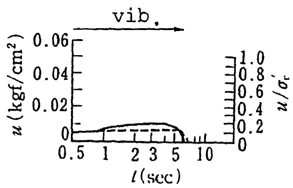


Fig.3 Excess Pore Pressure (without drain)



(a) p1 (b) p2 (c) p5



(d) p7

Solid Line : Experiment
Broken Line : Calculation

Fig.4 Excess Pore Water Pressure (with drain)

The specimen thus producted was placed on a shaking table and shaken in the horizontal direction. The excitation frequency was 2 Hz and duration of excitation was 6 sec. A sine wave was used as the input motion for the excitation, and the value of peak acceleration was 90 gal without drain and 87 gal with drain.

<u>Experimental Result and its Analysis</u> As test results, the time histories of the excess pore water pressure at p1 and p5 without drain were shown in Fig. 3 . And time histories of the excess pore water pressure at p1, p2, p5 and p7 with drain were shown in Fig. 4. The time histories of the excess pore water pressure indicated actually showed the vibrating characteristics, but the histories were taken from envelope lines of the peak values at each time. Where there was no drain, the excess pore pressure at p1 reached the maximum value at the end of the excitation and its value was 0.088 kgf/cm^2 . Also, maximum value of 0.045 kgf/cm^2 was obtained at the end of the excitation at p5. At both p1 and p5, the excess pore water pressure ratio $u/\sigma v'$, was about 0.9 and this state was close to liquefaction.

On the other hand, where there was a drain, the maximum value of excess pore water pressure was about 0.010 kgf/cm^2 and the excess pore water pressure ratio was about 0.1 to 0.2 at p1, p2, p5, and p7 . According to this, the rise in excess pore water pressure at p1 and p5 in the case with drain was limited to about 14% of that in the case without drain. This means that gravel drains were effective against liquefaction. Also, where there was no drain, more than 10 seconds were needed for the excess pore water pressure dissipation after the elapse of 6 seconds of the excitation . On the other hand, when gravel drain was installed, the excess pore water pressure was quickly dissipated about 6 seconds after the beginning of the excitation. This is considered to be also one of effects of gravel drains.

Next, the test result were compared with calculated results by using the program AXPORE based on the analytical method explained previously. The calculated results are indicated by the broken lines in Figs.3 and 4. The input data used in the calculations were the coefficients of permeability of the sand layer, k_s=0.01 cm/sec, coefficient of permeability of gravel drain, k_d=2.5 cm/sec, volume compressibility of both sand layer and gravel drain, $m_{vs}=m_{vd}$=0.0017 m^2/tf, number of cycles, N_1=8 until the excess pore water pressure ratio reaches 1.0 under undrained condition, equivalent number of cycles of input motion, Neq=12, and effective duration time of earthquake, t_d=6.0 sec. In this case, the values of m_{vs} and N_1 for without the gravel drain were determined in such a manner that the test results agree with calculated results with respect to the time history of excess pore water pressure. Moreover, the values of k_s and k_d were determined by reffering to the results of the permeability test conducted previously.

According to the results of comparison between the calculated values and the experimental values in the case with the gravel drain (Fig.4), the calculated values agree fairly well with the experimental values, thereby indicating good adaptability of the analysis program explained in this report.

PARAMETRIC STUDY USING AXPORE

We excuted parametric studies using AXPORE whose validity was indicated. The excess pore water pressure ratio was determined from the average obtained by weighting excess pore water pressure with area of the sand layer portion at each depth. Also, the maximum value in time history of the ratio averaged in the vertical direction was defined as the maximum excess pore water pressure ratio, and the maximum excess pore pressure ratio $(u_{max}/\sigma v')av$ and drainage Q were non-dimensionized with respect to non-dimensinal parameters previously extracted in order to prepare practical nomograms. The drainage Q which was difined on the diposite surface was arranged by non-dimensinal drainage $Q/(\pi a^2 k_d t_d)$. Of the six independent parameters previously explained, the volume compressibility ratio $m=m_{vd}/m_{vs}$ was found to only slightly affect the results of calculations, and so the remaining five parameters were readjusted.

Some of the results of caluculations are shown in Fig.5(a) to Fig.5(f). When the permeability coefficient ratio $K=k_d/k_s$ is about 1000 and the slenderness ratio N=H/2a is about 10 in the present report, the results of calculations are almost the same as the results obtained by Seed and Booker. The coeffitient of permeability ratio K therefore was fixed to 500, and the calculations were made for the case where N_{eq}/N_1 = 1, 2 and 3 and the slenderness ratio of drain, N=H/2a =10 and 30.

Also, volume compressibility will not be constant when the excess pore water pressure ratio increases and the deformation tends to increase suddenly when the excess pore water pressure ratio is close to 0.6 to 0.7 in liquefaction test. Because of this, only values up to 0.6 were indicated for the maximum excess pore water pressure ratio $(u_{max}/\sigma v')av$.

Finally, it should be noted that the results of the present calculations should not be applied to the case where a structure is located above the ground, and particularly where the permeability resistance of gravel mat and so forth cannot be neglected.

CONCLUSION

The following effective results were recognized from the above-mentioned studies.

1. By non-dimensionizing the basic equations of the program AXPORE, the five parameters that govern the pore pressure of the drain-sand system were extracted. Those parameters were time factor;T_d, ratio of permeability;K, drain slenderness ratio;N, ratio between drain diameter and effective diameter;m, and ratio between equivalent cycle number and cycle number to be necessary for pore pressure ratio to amount to 1.0;N_{eq}/N_1.

2. The results calculated using AXPORE were compared with the experimental results in the pore pressure time histories and good agreement was obtained. It was recognized that the analysis program AXPORE was able to evaluate the excess pore water pressure distribution in gravel drain and surrounding sandy deposits with high accuracy.

3. By comparing Seed and Booker's nomograms with those obtained here by parametric studies, it turned out that difference between Seed and Booker's results and the results of the authors was distinct when the slenderness ratio of

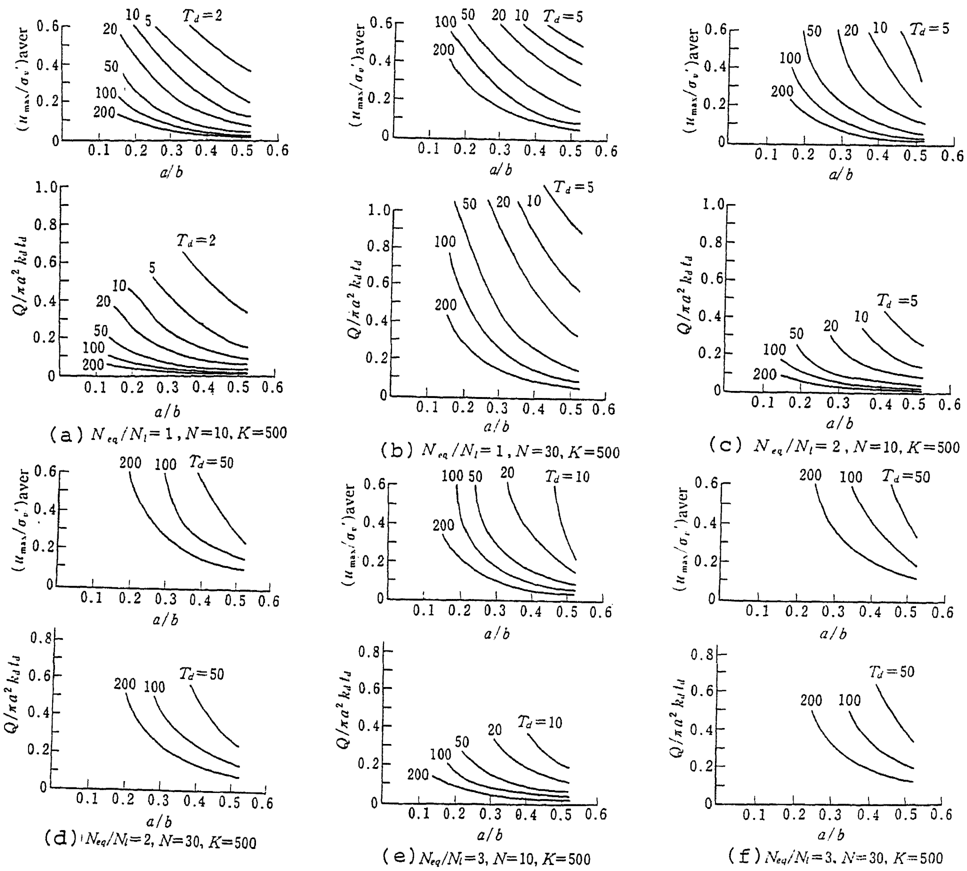


Fig.5 Nomographs of Maximum Pore Pressure Ratio and Drainage

gravel drain was large or the permeability ratio between drain and sand was small.

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