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WAVE PROPAGATION IN WATER-SATURATED SOIL

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SUMMARY

Since the fundamental formulation for wave propagation in the water-saturated porous media was constituted by M.A.Biot, many researches have been executed and the fruitful achievements have been obtained. But the investigation of the effect of the soil nonlinearity, which is also significant factor for the soft soil deposit, was not carried out yet sufficiently. In this research, the dynamic analysis of the water-saturated soil is performed in consideration with the soil nonlinearity, and the effect of the soil nonlinearity on the wave propagation characteristics in the water-saturated soil is investigated analytically.

INTRODUCTION

Because the severe earthquake damaged areas locate almost on the soft soil deposit, the wave propagation characteristics in such site should be investigated more precisely to evaluate the input motion to the structures. When the soft soil sites are analyzed, it may be insufficient to deal with them as the linear homogeneous media(1-phase model), according to the disregard of the existence of underground water and the effect of soil nonlinearity. It is necessary to treat them as 2-phase model which consists of the pore-water and the nonlinear soil skeleton.

As is well known, the equations governing the dynamic behaviour of the water-saturated soil were first constituted by M.A.Biot1), and by which the propagation of plane progressive waves in the porous medium was analyzed. Later, the approximate expression on the phase velocity of harmonic waves in the water-saturated soil was introduced and calculated by Atkin2). Moreover, the phenomena of the water-saturated porous media are analyzed by many researchers. Especially, the dynamic behaviour of the water-saturated soil, in which the large strain and nonlinear material behaviour are included, is treated by Zienkiewicz and Shiomi3).

In this paper, the earthquake response phenomena of the water-saturated soil are conducted by using the Biot's formulation and the theory of plasticity. The earthquake response analyses are carried out as for the practical soil model, in which the typical geology of the topographic alluvial formation is idealized. Then the characteristics of the wave propagation in the water-saturated soil is investigated and the ground response is discussed from the viewpoint of the effect of soil nonlinearity.

ANALYSIS CONDITION

1 Numerical Procedure The wave propagation equations in the water-saturated porous media established by M.A.Biot are employed. The finite element procedure is applied on making discretized model and the finite difference method is adopted for time progressive integration.

2 Nonlinear Characteristics Nonlinear constitutive equation is applied only to the soil skeleton, that is conducted by the plastic theorem. The soil is assumed to be an isotropical nonlinear material governed by the Drucker-Prager's yield condition. The pore-water is dealt as the compressible linear fluid. It is assumed that the pore-water pressure is induced in proportion to the volumetric strain, and not accumulated with the number of loading cycle. In other words, the liquefaction is out of consideration in this study. The permeability and the porosity are kept in constant value.

ANALYSIS CASE

1 Analytical Model The alluvial soil formation model is analyzed. This model is an idealized typical geology of the topographic valley. The mesh layout is shown in Fig.1. In this study, only the soil deposit in the valley is treated as the water-saturated nonlinear soil. The constants of the other soil property are summarized in Table 1. The boundary of analytical region is treated as the viscous boundary and the correcting vertical force is applied to the both of side boundaries in order to represent the infinite soil medium. The earthquake record Taft (1952,EW) is employed as the input motion, and applied to the bottom of model. Its maximum acceleration is normalized to 100gal.

2 Linear equivalent 1-phase analysis The linear 2-phase material with low permeability can be represented by the equivalent 1-phase material, because the solid-fluid interaction effect is negligible. The constants of equivalent 1-phase materialare also shown in Table-1. The compression wave velocity depends on the elastic modulus of water strongly, it is found that Poisson's ratio is very close to 0.5. The linear 2-phase model which has different permeability(high:1.0cm/sec, low:1.0×10^{-10} cm/sec) is analyzed and the applicability of the equivalent 1-phase analysis is investigated.

3 Nonlinear 2-phase analysis The effective stress analysis is adopted in this study, in which the soil nonlinearity can be applied to the soil skeleton. Its nonlinear skeleton curve is shown in Fig.2. The effect of soil nonlinearity on the ground response is investigated on the soil deposit with high permeability and low permeability.

RESULTS

1 Linear equivalent 1-phase analysis Fig.3 shows the maximum acceleration distribution on the ground surface, and the acceleration response spectra at point-A are shown in Fig.4. The results of the equivalent 1-phase model coincide with the low permeable soil. The smaller response is obtained from the high permeable soil, because there is the energy dissipation due to solid-fluid interaction. It is understood that the linear dynamic characteristics of the low permeable soil can be represented by the equivalent 1-phase model sufficiently, but the 2-phase analysis is necessary to evaluate the ground response in the high permeable soil.

2 Nonlinear 2-phase analysis The maximum accelerations of the ground surface obtained by the linear and nonlinear analysis are compared in Fig.5. Nonlinear results are smaller than linear results independent of the permeability. Fig.6

shows the ratio of nonlinear to linear maximum acceleration in each case. It is found that the both of them decrease to 80 - 90% from linear results, the decreasing ratio in the low permeable case tends to varied spatially, and it decreases uniformly in the high permeable case. This result means that the effect of soil nonlinearity appears strongly and locally in the low permeable case, because the soil skeleton and the pore-water move together in the low permeable case, and the effective stress is coupled with the pore-water motion which is governed by the local compression vibration. Fig.7 shows acceleration response spectra. As same as the maximum acceleration, the effect of soil nonlinearity can be recognized strongly in the low permeable case. And the spectrum value decreases in the both case, but the zero period acceleration decreases more remarkably in the low permeable soil case. The time histories of effective stress, the pore-water pressure and the yield order(the order of yield surface on which the stress contacts) are shown in Fig.8. The stronger influence of the soil nonlinearity also can be recognized in the low permeable soil case. It is understood that the effective stress and the pore-water pressure decrease significantly, and the soil yields more frequently in the low permeable soil case. Fig.9 shows the ratio of nonlinear to linear response spectra for different input maximum accelerations. When the input acceleration increases, the ground response derceases due to the stronger soil nonlinearity. But, there are some period ranges in which the almost same ratio is obtained independently of the input maximum acceleration and the permeability.

CONCLUSION

In order to evaluate the input motion to the structures located onthe soft soil site, the wave propagation analyses are carried out for the 2-phase nonlinear model based on the Biot's theorem and the Drucker-Prager's yield condition. The concluding remarks obtained in this research are as follows.

a)In the linear analysis, the dynamic characteristics of the soil with low permeabilty can be represented by the equivalent 1-phase model. But the 2-phase model should be employed when the soil with high permeability is analyzed.
b)The ground response decreases in the high permeable soil case. This is caused by the energy dissipation due to the solid-fluid interaction effect.
c)The effect of the soil nonlinearity appears strongly in the low permeable soil case, because the pore-water and the soil skeleton move together and the effective stress is governed by the compression vibration of the water.
d)When the soil nonlinearity is taking into account, the 2-phase analysis(e.g. effective stress analysis) is necessary to evaluate the ground response even for the low permeable soil deposit.
e)The ground response in the water-saturated soil decreases due to the soil nonlinearity and the solid-fluid interaction effect in the soil with high permeability.
f)It can be expected that the ground response dereases more, when the stronger input motion is adopted, there are some period ranges in which the response decreasing ratio is kept in almost constant in spite of the input amplitude.

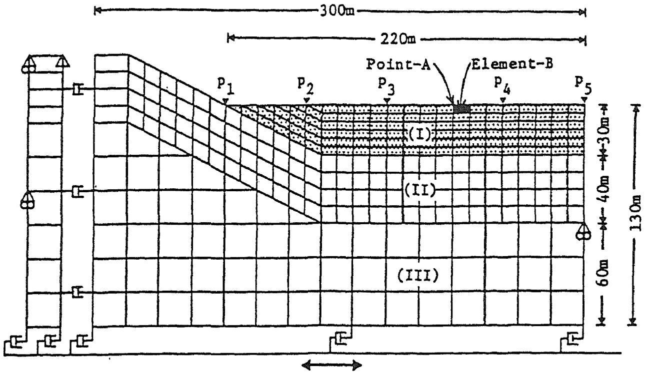

Fig.1 Mesh Layout of Alluvial Deposit Model

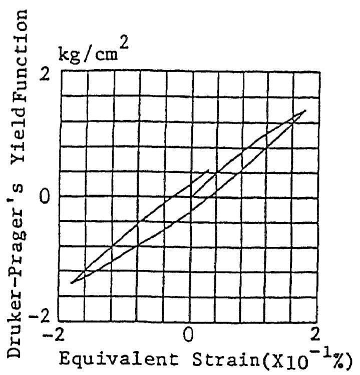

Fig.2 Nonlinear Soil Skeleton

Table 1 Material Properties of Soil Skeleton

Regions / Material Parameter	(I)		(II)	(III)
	1-Phase	2-Phase		
Velocity of Shear Wave (m/sec.)	91.1	100.0	500.0	2000.0
Unit Weight (t/m^3)	2.4	2.0	2.0	1.8
Poisson's Ratio	0.49793	0.4	0.4	0.4

Bulk Modulus of Solid
= 370t/cm^2
Bulk Modulus of Fluid
= 20.8t/cm^2
Permeability
= 10^{-10},1.0cm/sec
Porosity
= 0.4

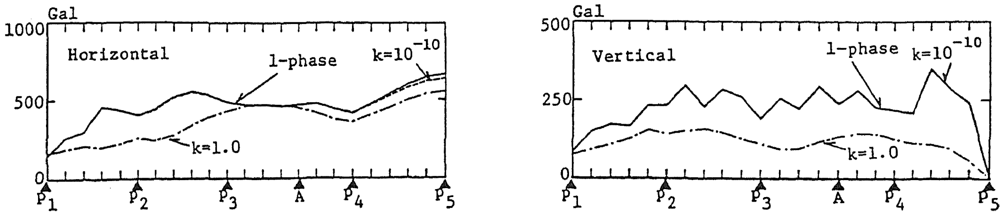

Fig.3 Distribution of Maximum Response Acceleration on The Ground Surface

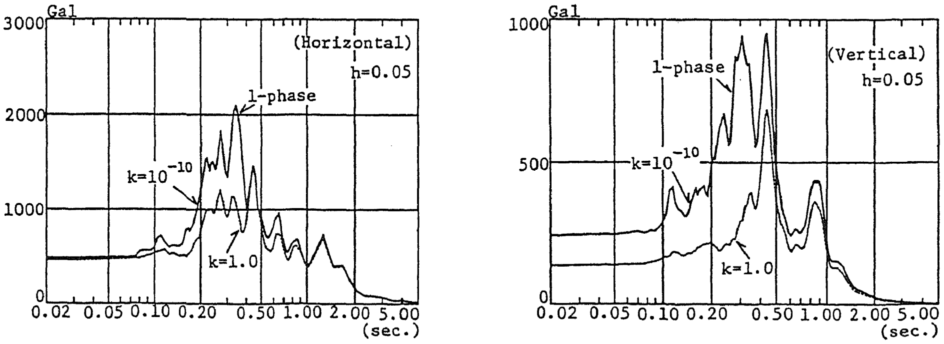

Fig.4 Soil Acceleration Response Spectrum (Point-A)

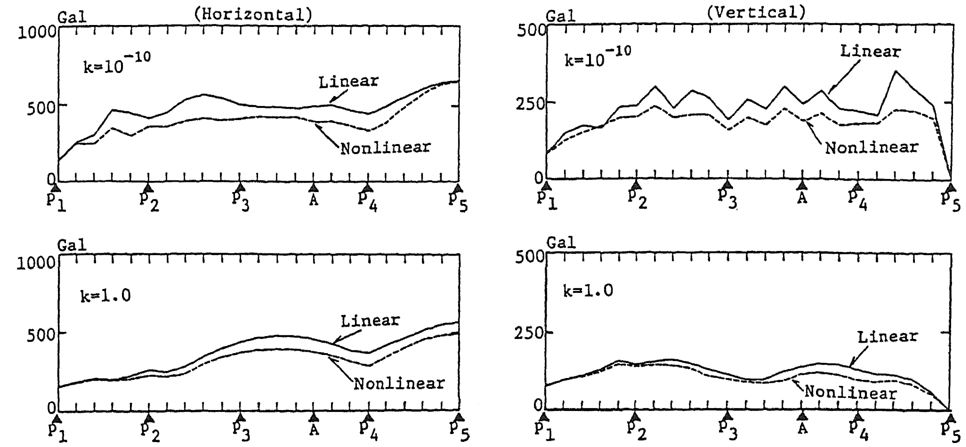

Fig.5 Distribution of Maximum Response Acceleration

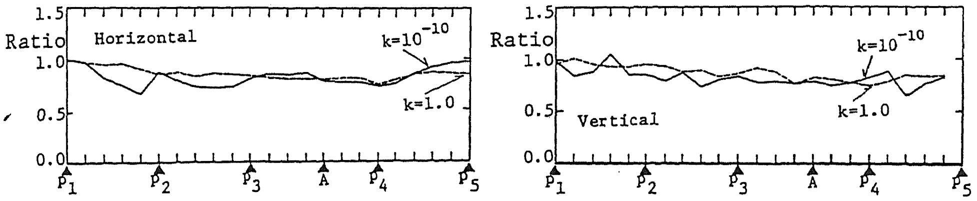

Fig.6 Decreasing Ratio of Maximum Acceleration

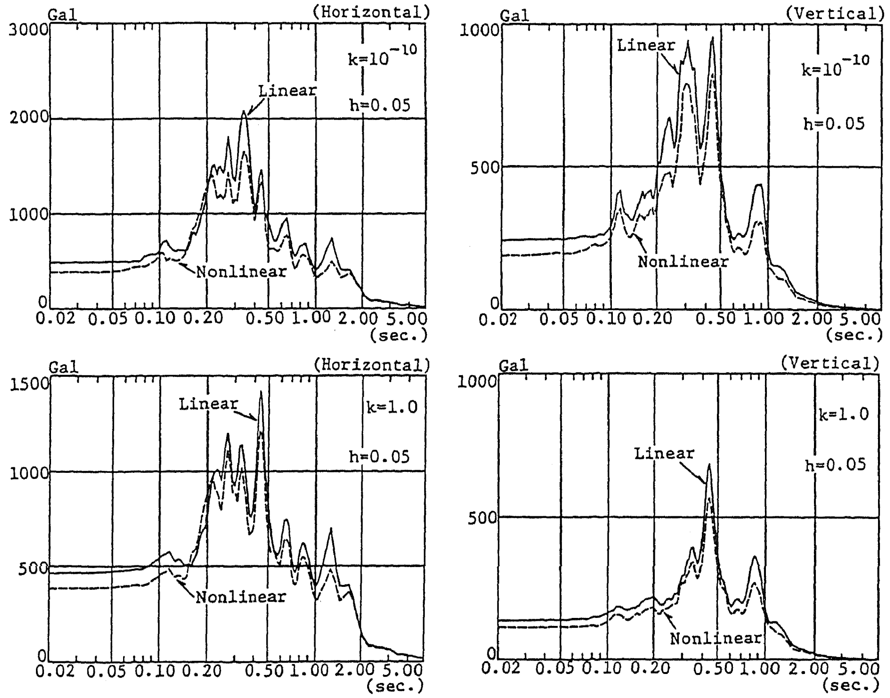

Fig.7 Soil Acceleration Response Spectrum (Point-A)

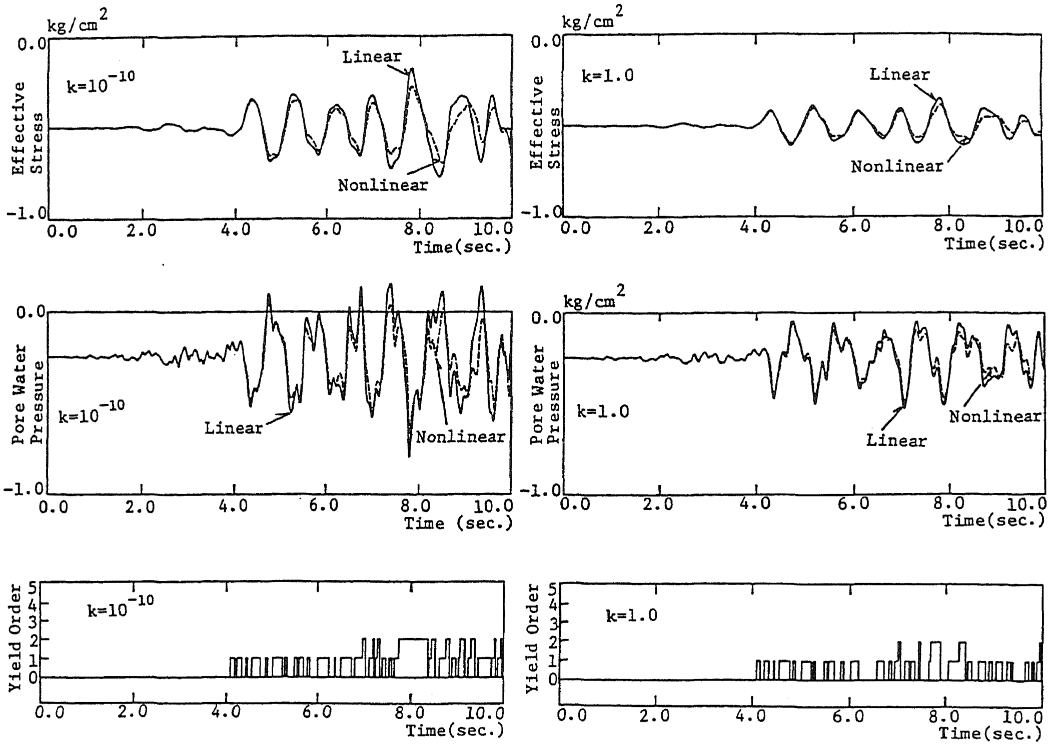

Fig.8 Vertical Effective Stress, Pore Water Pressure and Yield Order (Element-B)

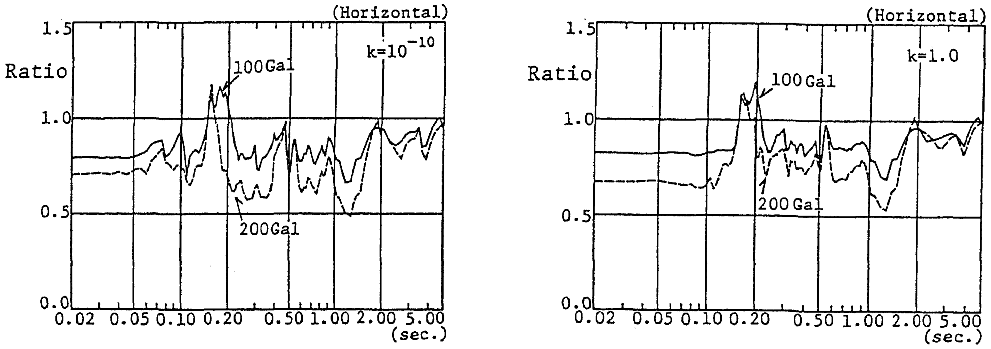

Fig.9 Ratio of Nonlinear to Linear Response Spectrum (Point-A)

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