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EFFECT OF NONLINEAR BEHAVIOURS ON THE EARTH PRESSURE FOR A DEEPLY EMBEDDED BUILDING

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SUMMARY

Effect of nonlinear behaviours on the earth pressure for a deeply embedded building is studied by comparing analytical results of an equivalent linear analysis and a nonlinear analysis. Material and geometrical nonlinear characteristics are taken into account by using two-dimensional RBSM.

Maximum responses obtained from the two analyses are compared, and it is shown that the nonlinearities have little effect on the earth pressure distribution for this type of building.

INTRODUCTION

In recent years, soil-structure interaction behaviours have been studied extensively from a wide variety of standpoints, especially for the research and design of nuclear power plants against seismic loadings. The equivalent linear analysis is one of an efficient numerical tool to solve such behaviours by replacing nonlinear systems with equivalent linear ones. However, as input motion of earthquakes becomes large, nonlinearities may greatly affect seismic responses. In this paper, effect of nonlinear behaviours on the seismic responses for a deeply embedded building is studied by comparing analytical results of an equivalent linear analysis and a nonlinear analysis. Particularly, attention is focused on the earth pressure during earthquake acting on embedded parts of the building. In the equivalent linear analysis, nonlinearities are considered in terms of reduced shear stiffnesses and equivalent damping ratios. While in the nonlinear analysis, material and geometrical nonlinearities, such as stress-strain relations of soils, soil-structure contact frictions or separations are taken into account through incremental nonlinear algorithm. The analyses are based on two-dimensional RBSM (Rigid Body Spring Model) which has been originally proposed by Prof. Kawai in 1976 (Ref.1).

METHOD

RBSM Model of a Deeply Embedded Building In the RBSM, the objects are divided into rigid elements having three degrees of freedom (two translations and a rotation). The elements are connected by distributed springs which represent displacement and stress field of the structure. Material and geometrical characteristics such as soil-structure contact friction, separation or strain dependency of the soil properties are considered by using nonlinear stress-strain relations and the Mohr-Coulomb criterion with tension cut-off condition.

In the present study, a building embedded 41m in the ground (Fig.1) was analysed. The surrounding soil consists of (i) backfill layer, (ii) surface layer and (iii) rock layer. In order to take into account of the semi-infinite propagation of the wave, the analysis field is connected to the left and right free fields by horizontal viscous dampers at both sides and by out-of plane viscous dampers at each element. The elements in the free fileds have a degree of freedom in the horizontal direction. The bottom of both analysis and free fileds are fixed in all directions.

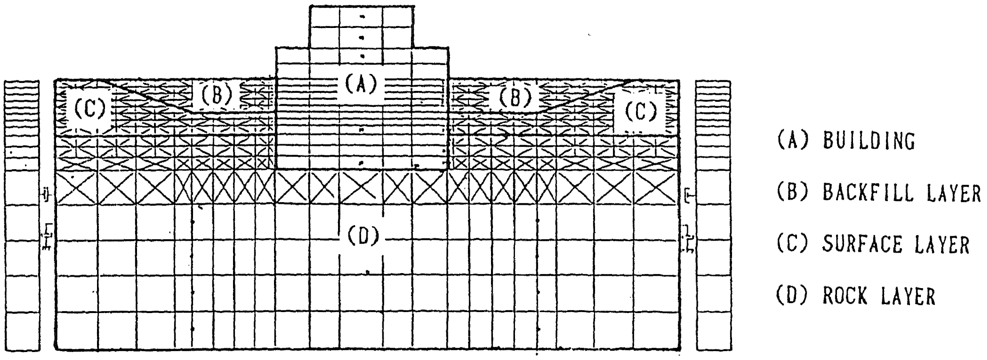


Fig.1 Model of A Deeply Embedded Building

Input Wave of Motion Based on the theory for the propagation of harmonic shear waves in a one-dimensional system, the input motion of the earthquake was decided from a standard design wave (Ref.2). The calculation was based on the equivalent linear analysis. Fig.2 shows the nonlinear material characteristics of the soils. In the figure, the relations between shear stiffnesses and damping ratios to the shear strains are given for each layer. Fig.3 shows the standard design wave and the calculated input wave. In this study, the intensity of the design wave was artificially increased by 50% so that nonlinear behaviours are clearly observed. The calculated wave of the motion was introduced at the bottom of the analysis field.

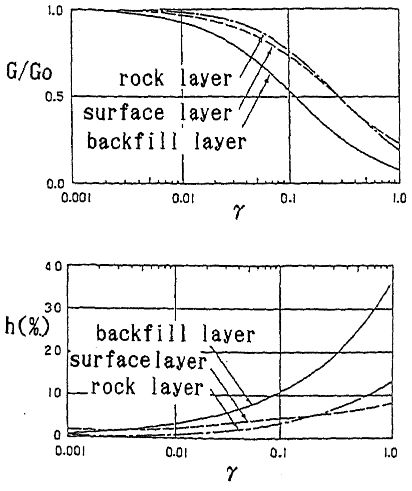
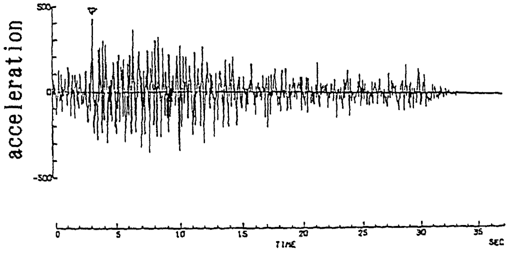


Fig.2 Nonlinear Material Characteristics of Soils

1.5*Standard Design Wave



Input Wave of Motion

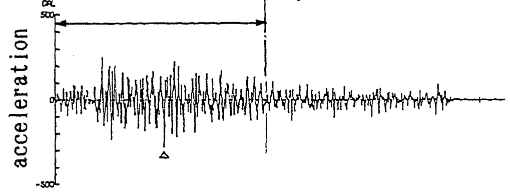


Fig.3 1.5*Standard Design Wave and Input Wave of Motion

Equivalent Linear Analysis In the equivalent linear analysis, the nonlinearity of the shear modulus and damping is accounted for by the use of equivalent linear soil properties using an iterative procedure to obtain values for shear modules and damping compatible with the effective strains in each layer. The material characteristics of the soils given in Fig.2 was employed to determine the equivalent shear stiffness and damping ratios. The initial and the equivalent shear stiffnesses are given in Table 1 together with the other soil properties. The modulus of the building was decided in such a way that the natural frequency coincided with that given by the equivalent spring-mass system.

Nonlinear Analysis The nonlinear properties of the soils were determined from the field measurements and the laboratory experiments. Based on these results, the stress-strain relations were assumed in the following formula.

$$\tau = \frac{Go * 10^{-2}}{1 + a\gamma} \cdot \gamma \qquad (1)$$

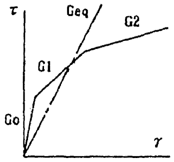
where Go is the initial shear stiffness and a is a material constant. Assuming that shear stress becomes maximum when shear strain reaches 1.0% , the constant a is given by the following formula.

$$a = \frac{Go * 10^{-2}}{\tau y} - 1 \qquad (2)$$

where τy is the maximum shear stress which varies along the depth. In the analysis, the stress-strain curves were modelled by tri-linear relations and the Mohr-Coulomb yield criterion was used to develop nonlinear constitutive equations. The input parameters used in the nonlinear analysis are also given in Table 1. In this study, the sliding and separation between the soils and the building were also considered. The sliding was judged by the Mohr-Coulomb condition with the factors c = 2 t/m² and ϕ = 30° . For separation, the spring constant was reduced to zero when the contact pressure vanished.

Table 1 Material Properties for the Soils

layer	level(GL-) (m)	Go (t/m²)	Geq (t/m²)	G1 (t/m²)	G2 (t/m²)	ν	ρ (t/m³)	c (t/m²)	ϕ (°)
backfill	0 ~ 3	1860	950	690	140	0.33	1.90	2.0	35.0
	3 ~ 6	3880	1770	1400	260				
	6 ~ 9	5450	2560	1980	380				
	9 ~ 15	7450	3810	2760	570				
surface	0 ~ 20	14100	12000	4880	710	0.48	1.78	16.0	7.0
	20 ~ 25	14100	11100	5400	1280			24.0	11.0
rock	25 ~ 35	45500	42600	19200	6220	0.44	1.75	123.	12.4
	35 ~ 41	47000	43800	19700	6290				
	41 ~ 57	49000	45100	20400	6380				
	57 ~ 73	52100	47800	21500	6530				
	73 ~ 90	55400	51000	22600	6680				
	90 ~107	58700	54700	23800	6830				
	107 ~125	62400	58700	25000	7000				



RESULTS

Maximum Responses Fig.4 and Fig.5 show the maximum response accelerations and displacements in horizontal direction. The results from both the equivalent linear analysis and the nonlinear analysis are compared at the center of the building. Although the results obtained from the nonlinear analysis are slightly larger for both the acceleration and the displacement,the discrepancies given by the both analyses are small. Fig.6 shows the maximum earth pressures acted on the side wall of the building. The earth pressures include the initial pressure at rest which is shown by the broken line. As the location goes into deep, the earth pressure becomes large. However, it does not increase linearly along the depth. Qualitatively the both analyses give similar results.

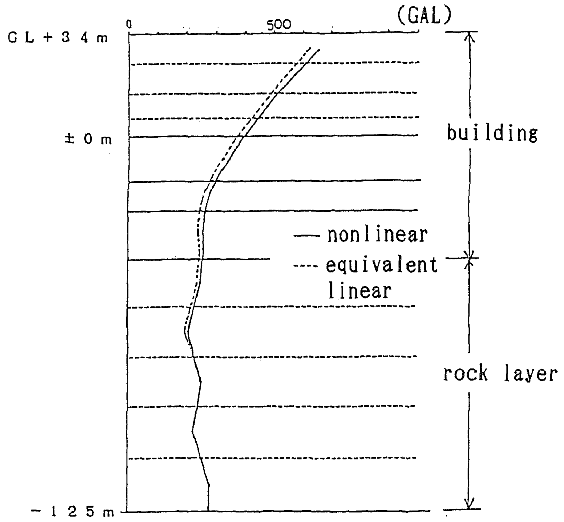


Fig.4 Maximum Response Acceleration

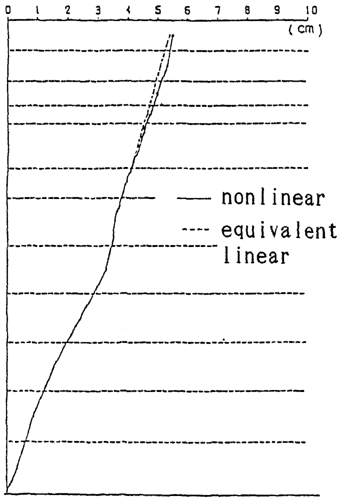


Fig.5 Maximum Response Displacement

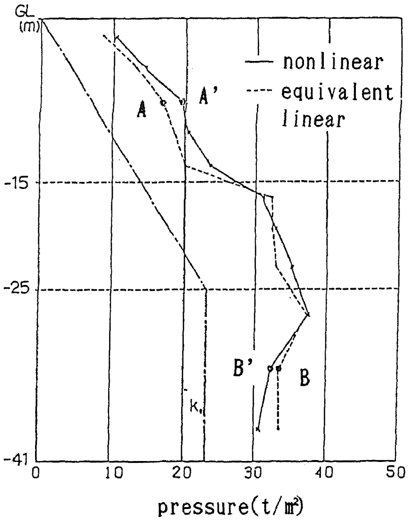


Fig.6 Maximum Earth Pressure Distribution

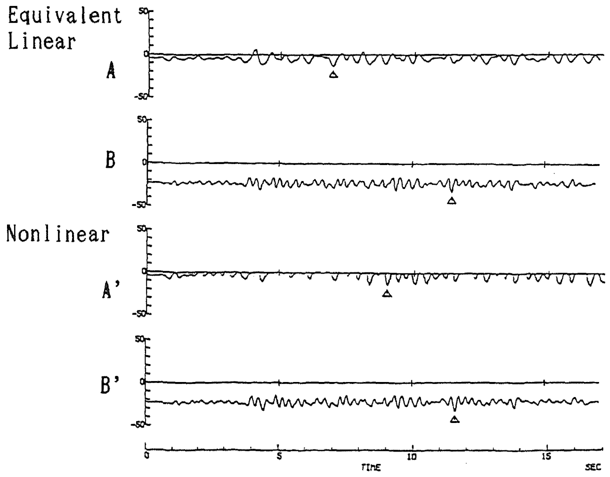


Fig.7 Time History of the Earth Pressure

Nonlinear Responses   Fig.7 shows the time history of the earth pressures at the middle region of backfill layer and the rock layer. From this result, it can be seen that in the nonlinear analysis, the separation took place at the backfill layer, while in the equivalent linear analysis, positive (tensile) pressure was obtained numerically. In the rock layer the two analyses gave almost identical results. Fig.8 shows the state of nonlinearities obtained from the nonlinear analysis. The shaded parts represent the elements whose maximum responses became the nonlinear states. The separation and the sliding parts are also shown. Most of the springs in the backfill layer and the surface layer experienced nonlinear stages while the rock layer remained linear elastic. As far as the maximum responses are concerned, the equivalent linear analysis gave close agreement with the nonlinear analysis. Fig.9 shows comparisons of the maximum strains obtained from the two analyses. From these comparisons, it is observed that as a whole a good agreement was obtained for the maximum shear strains. This is a main reason that the maximum responses (acceleration, displacement and earth pressure) obtained from the two analyses agree well in spite of some local nonlinearities.

Fig.10 shows a horizontal force equilibrium of the building when the maximum separation took place. In the nonlinear analysis, the separation occured at the upper four elements of the left side of the building. While in the equivalent linear analysis, positive earth pressures acted in this region. At the surface and the rock layers, the equivalent linear analysis gave larger earth pressures than the nonlinear analysis. At the right side of the building, the nonlinear analysis gave a slightly larger earth pressure than the equivalent linear analysis, but the differences are small. On the other hand, at the bottom of the building, the sliding did not occur at this time. It could have taken place if the shear stresses became greater than 30 t/m^2. Thus, the shear stress distributions were almost identical for both analyses. At this time step, although the separations took place, the earth pressure distributions obtained from the two analyses did not differ much except in the separated region. As a whole, the geometrical nonlinearities also had little effect on the overall earth pressure distribution.

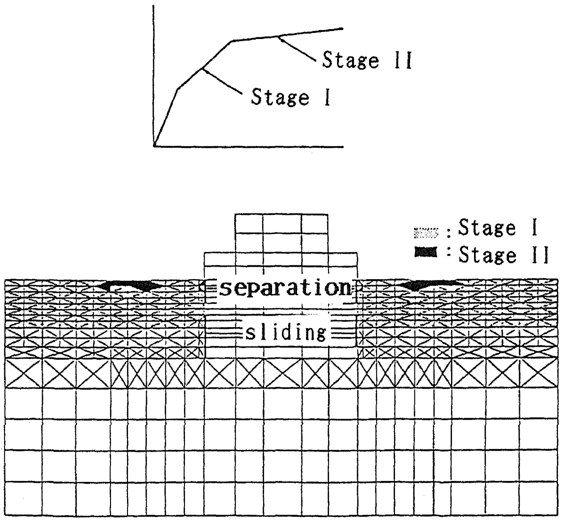


Fig.8 State of Nonlinearities

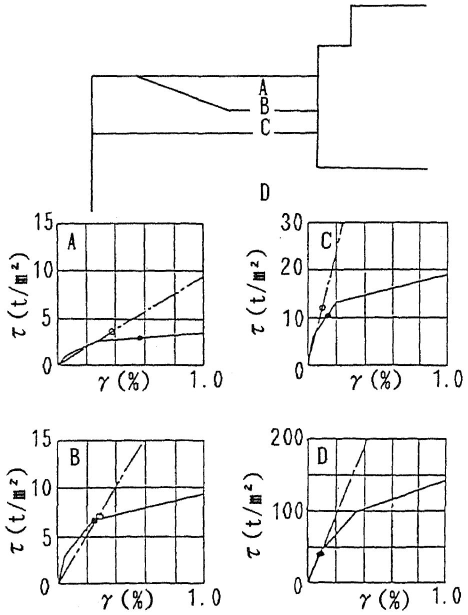


Fig.9 Maximum Shear Strains

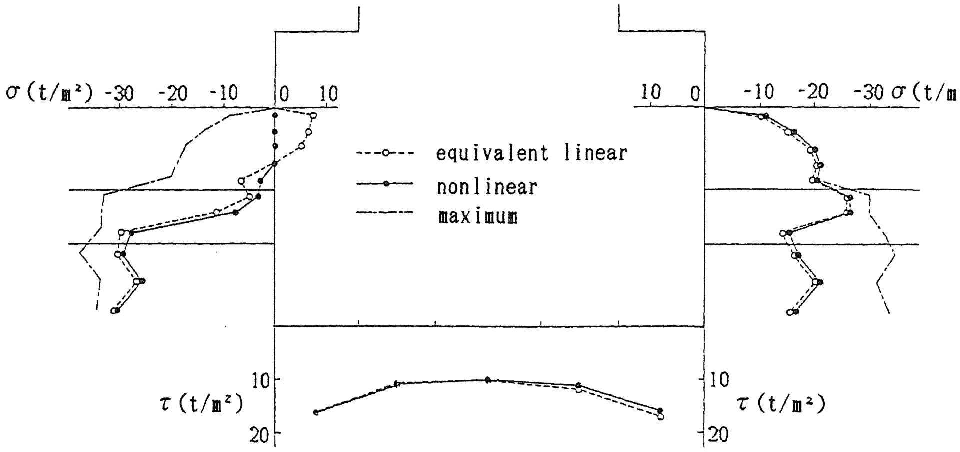


Fig.10 Horizontal Force Equilibrium

CONCLUSION

By comparing analytical results of an equivalent linear analysis and a nonlinear analysis, the effect of nonlinear behaviours on the earth pressure for a deeply embedded building was studied. In the nonlinear analysis, material nonlinearities mainly appeared in the backfill and surface layers. Geometrical nonlinear behaviours, especially the separations, occured at the backfill layer. However, comparing the results of the equivalent linear analysis with the nonlinear analysis, the differences of the overall responses of the building were small and the maximum earth pressure was not much affected by the nonlinear behaviours. Based on the present investigations, it is concluded that the effect of nonlinear behaviours on the maximum earth pressure is small for a building which is deeply embedded in the ground. And this is mainly due to the following reasons : (i) severe nonlinearities took place only in the local regions of the backfill layer and (ii) the rock layer, which dominantly affects the overall seismic behaviours, remain linear elastic in this study.

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