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NON-LINEAR SEISMIC RESPONSE ANALYSIS OF A THREE DIMENSIONAL SOIL-STRUCTURE SYSTEM

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SUMMARY

A three dimensional(3D) model of the stress redistribution of soil is presented. A 3D, full non-linear analysis was used to examine the validity and accuracy of results obtained by 2D analysis by combining the model of redistributed stresses proposed here with the joint element model. We concluded that both the 3D and 2D models of stress redistribution work well and reflect the yielding pattern of soil during excitation, but the former is more realistic. Except for the regions near interfaces, the basic dynamic behaviour of the structure can be reflected by 2D analysis.

INTRODUCTION

During recent decades, interest in dynamic soil-structure interactions with discontinuous contact surface between the soil and the structure has been increasing for the potential and wide application. In analysis of such systems, a full non-linear analysis should be conducted that considers not only the non-linearity of the interface, but the material non-linearity of soil as well, because the separation and sliding along the interface cause the stress concentration, thus making it easier for the soil to yield. On the basis of the fundamentals of the finite element method, Toki et al established a computer program, 7S-II (Seismic Stability of Soil-Structure System against Sliding and Separation, Version-II) to analyse soil-structure interaction phenomena during earthquake (Refs. 1,2). In the program a 3D soil-structure system is treated as a planar strain problem. By using it, the dynamic non-linear behaviour of both the interface and soil, and their effects on the responses of a partially embedded structure, could be analysed in detail (Ref. 3).

Clearly, as an extension of this method to the actual 3D system, a general 3D model that is closer to the actual conditions is needed for greater accuracy when checking the validity and accuracy of the results obtained by 2D analysis. We here present a 3D model of the stress redistribution of soil and use it to represent the non-linear behaviour of soil. A full non-linear analysis was conducted in order to make a detailed comparison of the results obtained from the 3D and 2D analyses.

3D MODEL OF THE STRESS REDISTRIBUTION OF SOIL

Yield criteria As an extension of 2D model of the stress redistribution of soil presented in Ref. 2, the Mohr–Coulomb failure law was adopted here as the yield criterion and the constitutive relation of the soil is assumed to be elasto-perfect plastic.

Shear failure If the following equations are satisfied, shear failure of the soil will result;

$$\sigma_m \leqslant C\cot\phi \tag{1}$$

$$\tau_{max}=(\sigma_1-\sigma_3)/2 \geqslant \tau_y \tag{2}$$

We assume that σ_m and the directions of the principal stresses remain unaltered during the redistribution of stresses after yielding. In doing so, Circle A is reduced to Circle B which has the same centre as Circle A, for evaluation of the unbalanced tensor. The stresses to be transferred, $\Delta\sigma_1$ and $\Delta\sigma_3$, are found geometrically (Fig. 1).

In the 3D analysis, however, it is necessary for determining the transferred tensor to know the change of σ_2 along with the change of σ_1 and σ_3. Having noted that the yield shearing stress, τ_y, is not changed during the redistribution of stresses, provided that $\sigma_1+\sigma_3$ does not alter (as assumed above), a diagram that is like that for Tresca's yield criterion (Fig. 2) can be plotted for every iteration; in other words, with respect to each value of $\sigma_1+\sigma_3$, such a diagram can be drawn. Moreover, because σ_2 has the same redistribution rate as σ_1, when they are equal, Point Q will approach Point Q′ on the yield line, Mohr's Circle A being reduced to Circle B. This also applies to the case of $\sigma_2=\sigma_3$, except that Point Q now lies on the abscissa. Therefore, Point P in the stress space of Figure 2 can be assumed to approach Point P′ as Mohr's circle reduces for the transfer of the unbalanced tensor. Consequently, the following relations can be obtained from Figs. 1 and 2:

$$\Delta\sigma_2=\Delta\sigma_1\tan\alpha+(1-\tan\alpha)\Delta\sigma_3 \tag{3}$$

in which

$$\tan\alpha=\frac{\sigma_2-\sigma_3}{\sigma_1-\sigma_3} \tag{4}$$

The transferred tensor can be written in the principal stress coordinates as

$$\Delta\underline{T}_{123}=\begin{bmatrix}\Delta\sigma_1 & 0 & 0\\ 0 & \Delta\sigma_2 & 0\\ 0 & 0 & \Delta\sigma_3\end{bmatrix} \tag{5}$$

Tensile failure Tensile failure is defined by the equation (6):

$$\sigma_m > C\cot\phi \tag{6}$$

In this case, Mohr's Circle A must be reduced to Point P as shown in Fig. 3. The tensor changes are given by equation (7):

$$\Delta\underline{T}_{123}=\begin{bmatrix}C\cot\phi-\sigma_1 & 0 & 0\\ 0 & C\cot\phi-\sigma_2 & 0\\ 0 & 0 & C\cot\phi-\sigma_3\end{bmatrix} \tag{7}$$

Obviously, the 3D model of the redistribution of stress is more realistic than the 2D model, because now σ_2, together with σ_1 and σ_3, joins the redistribution of stresses after soil yielding.

SEISMIC RESPONSE ANALYSIS

Model and excitation The model analysed is shown in Fig. 4, in which 48 3D joint elements (Ref. 4) are arranged along the contact surfaces between the structure and the surrounding soil. The total degrees of freedom of the model amount to 3547. The parameters of the model are given in Table 1; with these parameters the system has a fundamental period of 0.84 sec. In contrast, the mass of the superstructure in the 2D model has been adjusted so as to have the same fundamental period as the 3D model.

The model was excited simultaneously with the NS and UD components of the El Centro accelerograms (1940) through the bedrock, adjusted so that the maximum peak acceleration equalled 0.3g. The model also was analysed step by step in the time domain with unequal intervals for speeding up computations. The time interval, 0.01 and 0.001, was controlled by whether or not separation takes place at the soil-structure interface.

Response analysis The definition of the time history of the dynamic safety factor is

$$\begin{aligned} &SF=\tau_Y/\tau \\ &SF=1.0 \text{ for shearing failure} \\ &SF=0.0 \text{ for tensile failure} \end{aligned} \tag{8}$$

with respect to every time interval, and this value is set equal to 10 when greater than 10. From these values the failure time can be pinpointed during the entire period.

The hysteresis loops for soil element S3 are shown in Fig. 5. Clearly, both the 3D and 2D models of the redistribution stress of soil work well after soil yielding; the loops have similar shapes and the same order of magnitude. In Fig. 5, capitals S and E denote the starting and end points of the curve, and the lower case letters the yield points during excitation. The yielding times that correspond to these points are given in Fig. 6. The yielding pattern of the soil element is reflected whichever model (2D or 3D) is used.

In the 3D model, there are not only X-side wall interfaces, but y-side wall interfaces as well. For the latter, the main dynamic property is sliding, and the interfaces frequently do so. The hysteresis loops for one interface are shown in Fig. 7. Shearing stresses are transmitted through the y-side interface to nearby soil elements, causing them to yield. As the distance from the interface increases, the numbers of yielding elements of the soil are rapidly reduced, almost all the soil elements in the front and back zones remaining elastic under the 0.3g input. This differs from the 2D analysis.

Because of the y-side wall interfaces, the energy that overcomes friction along these interfaces is dispersed and produces soil yielding in the front and back zones; therefore, the safety factors for the X-side wall and the base interfaces are higher than in the 2D analysis. Consequently, the maximum separation values in 2D analysis at these interfaces become one to two orders larger than those for the corresponding elements in the 3D analysis. In contrast, non-linear time ratio, β_J, defined as the ratio of the summation of the opening times for the joint element to the whole duration of the excitation, shows an opposite separation pattern for X-side wall interfaces in the two analyses; values from the 2D analysis are larger for the lower joint elements and smaller for the upper ones, the reverse being the case for the 3D analysis. This is another difference between 2D and 3D analyses.

The instructure response spectra are compared for our 3D and 2D analyses. A substantial variation is found between 2D and 3D analyses in the instructure response spectra for the region near the interface, especially in the short period range. In contrast, there is no substantial difference for the points away from the interface. The instructure response spectra for Point A (Fig. 8), in which we are most interested, obtained by 2D analysis, agree well with those obtained by 3D analysis. The more details were given in Reference 5.

CONCLUSIONS

We have presented a generalized method for a full, non-linear earthquake analysis of 3D soil-structure interaction that uses a 3D model of stress redistribution with the joint element. We compared the responses for 3D and 2D analyses in detail and concluded the following.

1. Both the 3D and 2D models for the redistribution of soil stress work well after soil yielding and reflect the yielding patterns of the soil during excitation.

2. The maximum separation values obtained with 3D model are much smaller than the corresponding 2D values and the separation patterns of the two analyses for the X-side wall interface are opposite. However, these affect only responses in the short period range and in the region close to the contact surface.

3. The general tendencies in the dynamic analysis of structure interacting with soil reported here are in good agreement with those obtained by 2D analysis. The basic dynamic behaviour of the structure can be reflected by 2D analysis.

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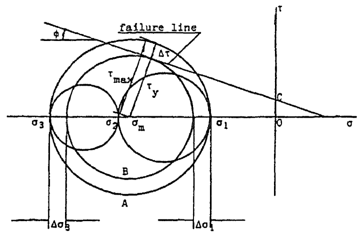


Fig. 1

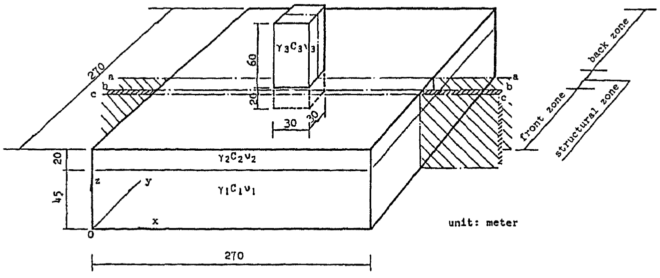


Fig. 4

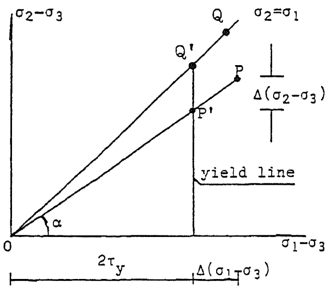
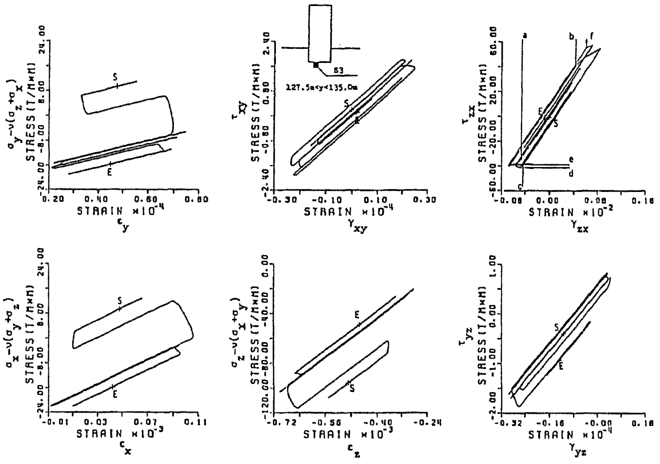


Fig. 2



(a) 3D analysis

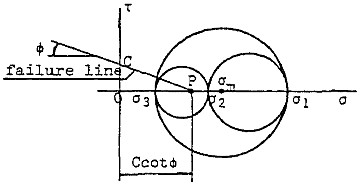
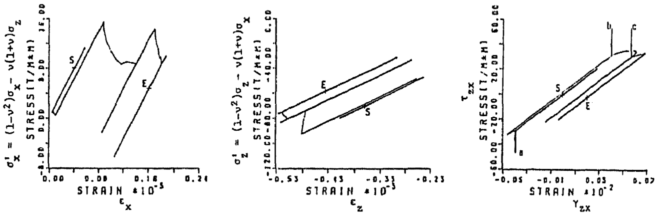
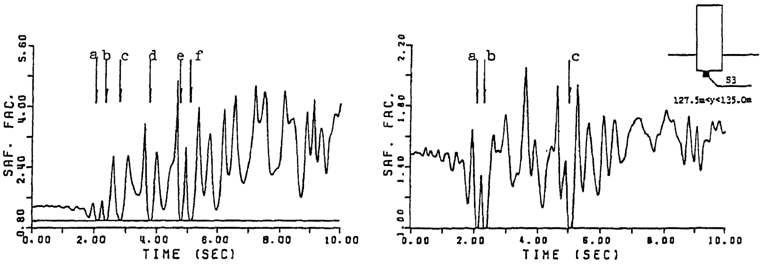


Fig. 3



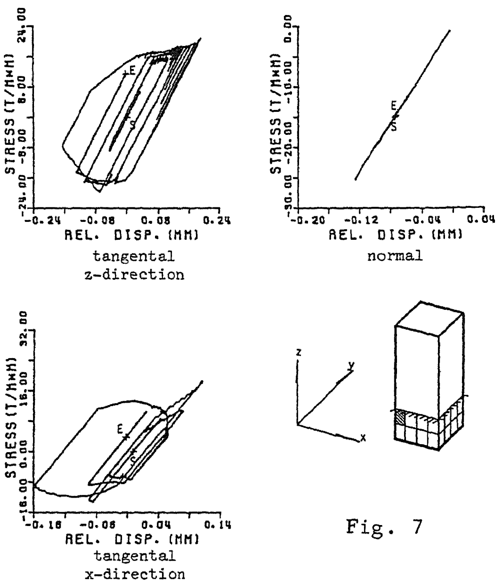
(b) 2D analysis

Fig. 5



(a) 3D analysis (b) 2D analysis

Fig. 6

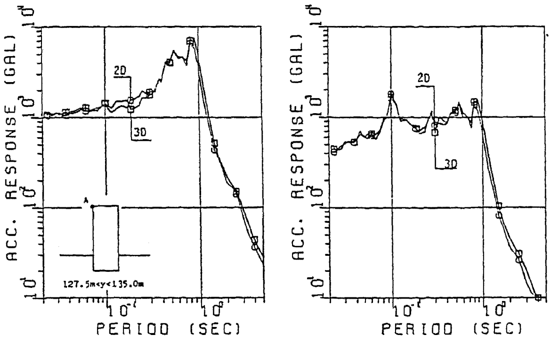


tangental
z-direction

normal

tangental
x-direction

Fig. 7



(a) horizontal (b) vertical

Fig. 8

Table 1. Physical Parameters of the Model

	unit weight (t/m^3)	shear wave velocity (m/s)	poisson's ratio	damping factor	cohesion (t/m^2)	friction angle (o)
ground	2.0 1.8	600 200	0.333 0.450	0.1 0.1	10 10	30 30
structure	2.4	1600	0.167	0.05		
joint	shear spring const. k_r=200000t/m^3 normal spring const. k_t=200000t/m^3				10	30