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PROPOSAL OF ANALYTICAL METHOD ON FOUNDATION UPLIFT CONSIDERING THE DAMPING EFFECT

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SUMMARY

The purpose of this study is to propose the analytical method which can estimate the damping effect due to foundation uplift. The authors framed the nonlinear S-R model based on the data from the shaking table test on soil-structure interaction model and confirmed the validity of proposed method comparing to the experimental and the dynamic FEM analytical results. Through this study, it is concluded that the proposed model is much practical use for estimation of foundation uplift considering the damping effect.

INTRODUCTION

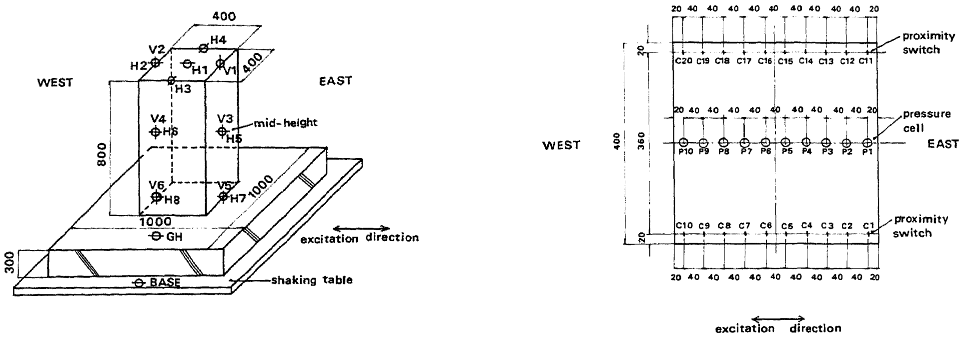
During a strong earthquake, foundation may be lifted partially by response overturning moment. And it causes the damping effect to interaction between foundation and ground, because it should be appeared interruption of wave propagation from ground and energy loss by collision between foundation and ground. For example, the authors already confirmed these uplift phenomena experimentally (Ref.1). Therefore, in the case of performing numerical analysis considering geometrical nonlinear interaction between foundation and ground due to foundation uplift, it must be estimated quantitatively the magnitudes of damping constants during uplift. And it is necessary to take them into the numerical procedure.

In this paper, the nonlinear S-R model which can estimate the damping effect due to foundation uplift based on the data from the shaking table test on soil-structure interaction model is proposed and it is confirmed the validity of proposed analytical method comparing to the experimental and the dynamic FEM analytical results.

SHAKING TABLE TEST AND RESULTS

The authors would like to mention simply the contents of the shaking table test of foundation uplift.

The soil-structure interaction model was placed on the shaking table shown in Fig.1. In this experiment, the authors intended to grasp uplift phenomena simply.



(a) Accelerometers

(b) Pressure Cells and Proximity Switches

Fig.1 Soil-Structure Interaction Model and Arrangement of Measured Points

The ground model used in this experiment is made of silicone rubber which is regarded as elastic media, with 100cm x 100cm x 30cm in size. 2 type of the ground model on rigidity, that is hard type and soft type, were prepared within the condition of easiness for vibration measurement. The elastic properties of the both ground model were determined from supersonic wave test.

The foundation model is a rigid box framed by acryl plates to prevent its own elastic deformation. The dimensions of it are 40cm x 40cm in plane, 80cm in height. The height was designed so as to uplift easily by rocking motion during excitation. And the weight of model foundation is 100 kgf.

Fourteen accelerometers were arranged on the foundation model shown in Fig.1(a). Ten pressure cells and twenty (multiply two row by ten) proximity switches were embedded shallowly in the ground model to measure contact ratio, which is defined as the ratio of compression stress zone area of foundation for total area of foundation, more precisely shown in Fig.1(b).

As to excitation with shaking table, sinusoidal wave excitation under constant frequency to confirm the response characteristics on foundation uplift, sweep excitation to estimate the damping characteristics during uplift, random wave excitation (EL CENTRO motion in the time scale one to five) to be applied proposed to the analytical method, were performed, respectively. In each excitation cases, input acceleration level was set up from smaller level to larger level.

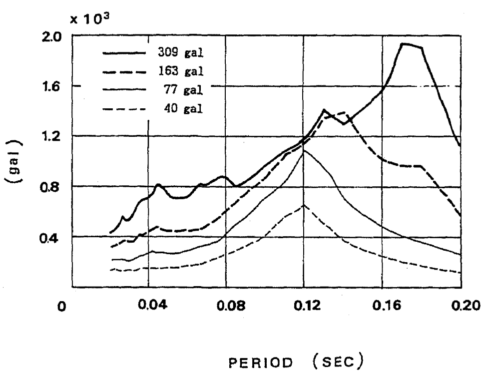


Fig.2 Horizontal Response Spectra

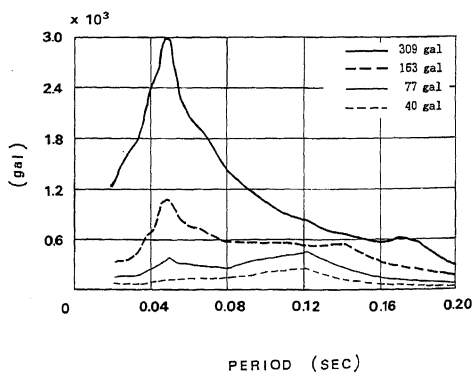


Fig.3 Vertical Response Spectra

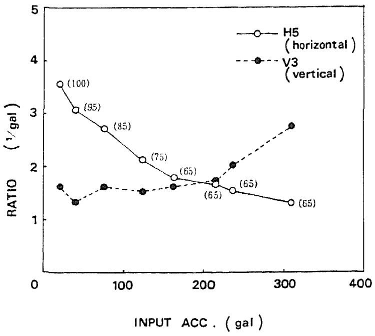


Fig.4 Cange of Amplification Ratio

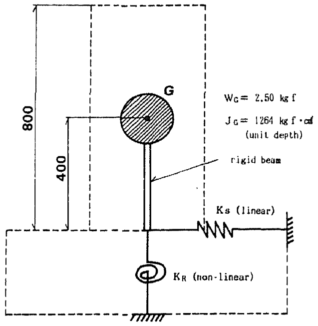


Fig.5 Analytical Model

Acceleration response spectra on horizontal response (measured point at H5) and vertical response (measured point at V3) which are obtained from the random excitation,are shown in Figs.2, 3. It is evident that the predominant period of horizontal response turns to the longer period range and the vertical motion is induced in the shorter period range without input vertical motion with decreasing of contact ratio. And the amplification ratio of horizontal response decreases remarkably shown in Fig.4. It is considered that these phenomena are given by the effect of reduction of rigidity and collision between foundation and ground during uplift.

METHOD OF ANALYSIS

<u>Analytical Model</u> The soil-structure interaction model was converted to the one-lumped mass sway and rocking model(S-R model) shown in Fig.5. In this analytical model, the rocking spring is regarded as nonlinear to express foundation uplift, on the other hand,the sway spring is regarded as linear to simplify the analytical procedure. The magnitudes of these spring constant with linear range are determined using static FEM analysis.

Eigenvalue analysis was performed to confirm the validity of determined spring constant. The calculated eigen frequency was compared with the measured one obtained from the free vibration test. In order to let agree the calculated value with the measured one, the elastic properties were adequately corrected,and then, they were re-taken into the static FEM analysis.

<u>Set Up of M-θ Curve</u> In this analysis, the nonlinear characteristics of rocking spring was given the relation of response overturning moment and rotational angle, that is, M-θ curve, based on the coefficient of subgrade reaction method(Ref.2). The equation of M-θ curve is given, as

$$M / M_0 = 3-2\sqrt{\theta_0 / \theta}, \qquad M_0 / \theta_0 = K_{R0} \tag{1}$$

where M_0 and θ_0 are critical overturning moment and critical rotational angle of uplift, respectively, and K_{R0} is the linear rocking sprin constant. Eq.(1) indicates that the tangent modulus of the rocking spring decreases in portion to cube of contact ratio(Ref.2).

Eq.(1) for the soft ground model is drawn in Fig.6. The experimental values of obtained from the sinusoidal wave excitation and the analytical values obtained from the static FEM analysis having a joint element of which stress-strain relation is shown in Fig.7. are plotted in Fig.6. It can be seen that Eq.(1) agrees well with the experimental and the analytical values. It can be therefore decided that Eq.(1). is enough applicable to the response analysis considering foundation uplift.

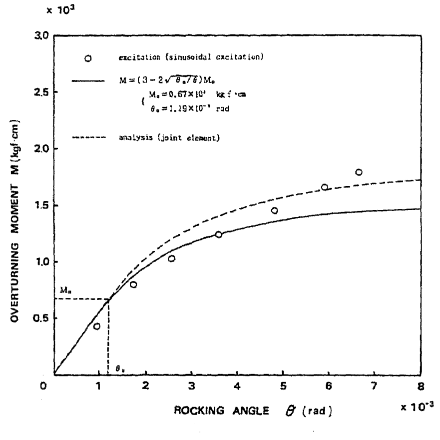
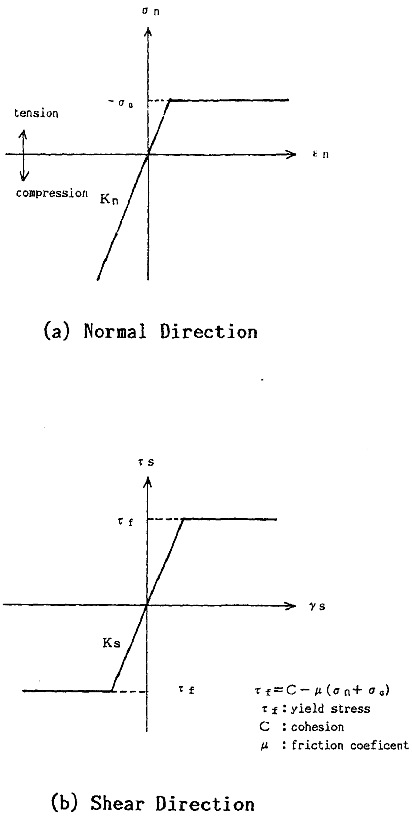


Fig.6 M-θ Curve



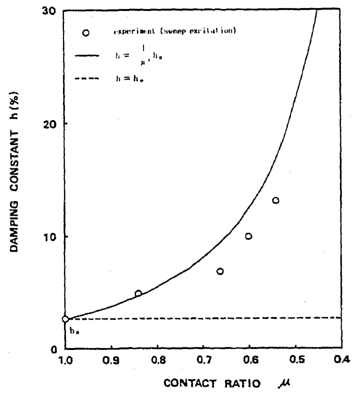


Fig.8 Relation between Contact Ratio and Mode Damping Constant

Fig.7 Relation of Stress and Strain

<u>Set Up of Damping Characteristics</u> In this analysis, the damping characteristics during uplift was taken into the nonlinear rocking spring. Some plots in Fig.8 show the relation of contact ratio μ and the mode damping constant of soil-structure interaction model h , which were obtained from the sweep excitation. It is evident that the damping constant remarkably turns to higher value with decreasing of contact ratio, or extension of uplift.

For this experimental results, the estimated equation under an assumption of the damping constant in portion to a reciprocal of cube of contact ratio is drawn in Fig.8. The estimated equation is given, as

$$h = h_0 \cdot (1/\mu^3) \qquad (2)$$

where h_0 is the damping constant without foundation uplift. It seems that Eq.(2) explains quite all right the tendency of experimental results. Furthermore, it is considered that Eq.(2) has a opposite nature to Eq.(1). The damping characteristics involved in Eq.(2) can positively estimate the increasing damping during uplift, so the authors took it in the response analysis procedure.

Dynamic Analysis As well known, uplift phenomena are nonlinear vibration system, in consequence of it the vibration equation is solved by numerical integral. In this analysis, the damping characteristics shown in Eq.(2) is evaluated analytically, as

$$[C_e] = h_0 \cdot [K_e] / \pi f_0 \tag{3}$$

where h_0 and f_0 are damping constant and eigen frequency without uplift,respectively, $[C_e]$ and $[K_e]$ are damping matrix and stiffness matrix on the element of rocking spring, respectively.

In order to satisfy the relation between $[C_e]$ and $[K_e]$ shown in Eq.(3), $[C_e]$ is set up to be invariable, so as to h_0 only increases in portion to a reciprocal of cube of contact ratio with decreasing of $[K_e]$ The stiffness matrix $[K_e]$ is arranged at each time step in the numerical integral by the Newton' s method. Numerical integral method used in this analysis is Newmark' s β method, and the time interval of integral is 0.0025 SEC.

COMPUTED AND MEASURED RESPONSES

The authors firstly discuss the results of linear analysis for the experimental response of foundation with uplift. Fig.9 shows computed and measured response spectra(h=5%) on horizontal response of the foundation excited by the random excitation with maximum acceleration is 239gal and 65% of contact ratio. What is evident from Fig.9 is that linear analysis overestimates the experimental response of the foundation with uplift. Consequently, it should be used nonlinear analysis considering the damping effect during uplift instead of linear analysis.

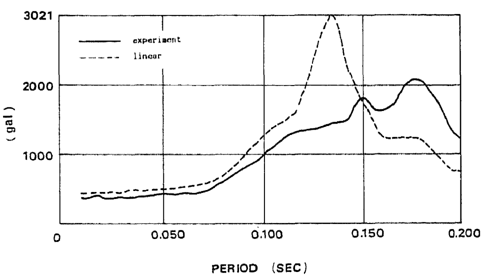


Fig.9 Computed and Measured Horizontal Response (Linear Analysis)

On the other hand, computed acceleration response spectrum(h=5%) on horizontal response obtained by the proposed method is compared with the above mentioned measured response in Fig.10. Computed response agrees well with the peak of measured one, although the position of both predominant period are slightly different.It is considered that the difference of both predominant peak position is caused by that accuracy for the M-θ curve was slightly inferior.

Fig.11 shows the comparison of computed and measured response on vertical response under the same excitation above discussed. The peak appeared at 0.05 SEC. in measured spectrum shown in Fig.11 can be considered the induced vertical motion, however, the proposed method can not solve about it analytically because of the lack of estimation for the induced vertical motion in the analytical model shown in Fig.2.

Furthermore, in order to confirm the validity of the proposed analytical method, dynamic FEM analysis having a joint element which can more strictly express separation of foundation and ground was performed.The nonlinear relations of stress and strain in the joint element are shown in Fig.7. The

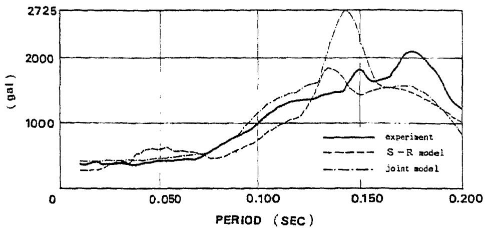


Fig.10 Computed and Measured Horizontal Response (Nonlinear Analysis)

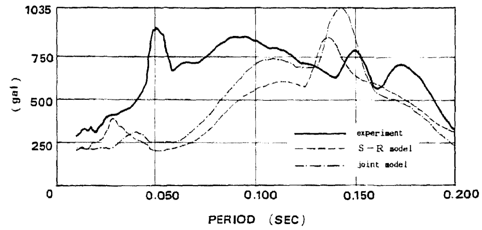


Fig.11 Computed and Measured Vertical Response (Nonlinear Analysis)

results obtained by the dynamic FEM analysis are shown in Figs.10,11. The acceleration response spectra computed by the proposed method generally agree well with the spectra computed by the dynamic FEM analysis. And it goes without saying that both computed acceleration response spectra almost correspond to measured spectra. Consequently, it became evident the validity of proposed nonlinear S-R model.

CONCLUSIONS

In this report, the authors proposed the nonlinear S-R model which can estimates the damping effect due to foundation uplift based on the data from the shaking table test on soil structure interaction model, and confirmed the validity of proposed method comparing to the experimental and the dynamic FEM analytical results. Through this study, it became clear that the proposed S-R model is much practical use for estimation of foundation uplift considering the damping effect.

Moreover, the analytical estimation of the induced vertical motion during uplift is the subject for a future study.

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