

Fig. 5 –Pile model and maximum responses

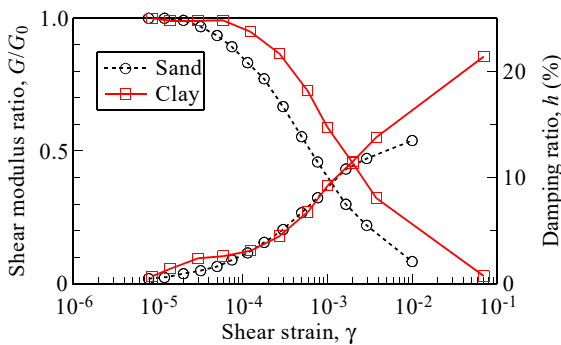


Fig. 6 – Cyclic shear deformation characteristics

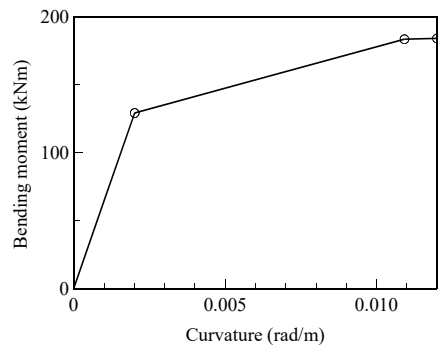


Fig. 7 – Moment-curvature relationships

Result of the analyses is summarized in Fig. 5(c). The whole analysis (whole in Fig. 5(c)) and ① the case to consider all terms (Disp. & Vel. in Fig. 5(c)) are identical. There is very small difference between the whole analysis and ③ (No inertia in Fig. 5(c)). There are, however, significant differences between the whole analysis and ② (Disp. in Fig. 5(c)).

In the engineering practice to analyze a pile during earthquake, seismic deformation method is frequently used. In this method, deformation of the ground is applied through the interaction spring statically. Compared with the multiple support excitation analysis, there are two key points, except that seismic deformation analysis uses displacement of the ground at a particular time or a maximum displacement whereas multiple support excitation analysis conducts time marching analysis. The one is that inertial force of the pile is not considered although inertial force from superstructure is frequently considered. The second is that velocity is not considered. Looking at the result shown in Fig. 5(c), neglecting inertia force of the pile is justified, but velocity term is important.



and that friction coefficient is about 0.5. Ultimate strength increases 1.2 to 1.4 times larger under fast loading. Kobayashi et al. [13] conducted cyclic loading test on polyethylene coated steel pipelines and showed that hysteretic characteristics can be modeled by a bi-linear model whose ultimate stress is 5 to 9kN/m². These two researches shows harmonic conclusions. Therefore, coefficient of subgrade reaction is set 6 MN/m³, and ultimate shear stress is set 5 kN/m². No velocity proportional characteristics is considered.

Since applicability of the multi exciting formulation is proved in the previous chapters, the whole analysis is not conducted here. Same as previous example, shear wave velocity of the ground is 150 m/s; apparent wave velocity is 106 m/s. One sinusoidal wave with maximum amplitude 0.5 m/s and with frequencies 5, 1, and 0.5 Hz is applied. Since whole analysis is not conducted, reflected wave at the ground surface is not considered.

Maximum bending moment of the pipeline is shown in Fig. 15. Fig. 15(a) is the result when interaction spring is elastic. It is zero at the end because boundary condition at the end of the pipeline is set rotation free. It is nearly constant along linear part, and changes at the connection. It is the largest when frequency of the sinusoidal wave, f , is 5 Hz, possibly because curvature of the ground is largest as it is proportional with frequency.

Fig. 15(b) compares maximum bending moment under nonlinear behavior when $f=1$ Hz. Here, nonlinear 1 in the figure is the result when static nonlinear stress-displacement relationships is used, and nonlinear 2 uses ultimate stress 1.4 times larger than the one of static case. Maximum bending moment under nonlinear behavior is much smaller than that under the elastic behavior.

Fig. 16 shows stress-strain relationships in the nonlinear 1 case (ultimate stress = 5 kN/m²). Amplitude of the velocity is set same in this case study, which means displacement amplitude is larger as input frequency becomes smaller. Therefore, displacement of the interaction spring is largest when $f=0.2$ Hz.

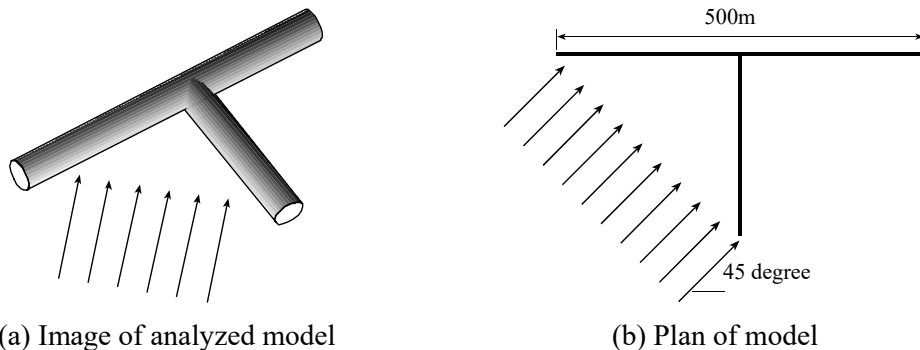


Fig. 14 – Analyzed model

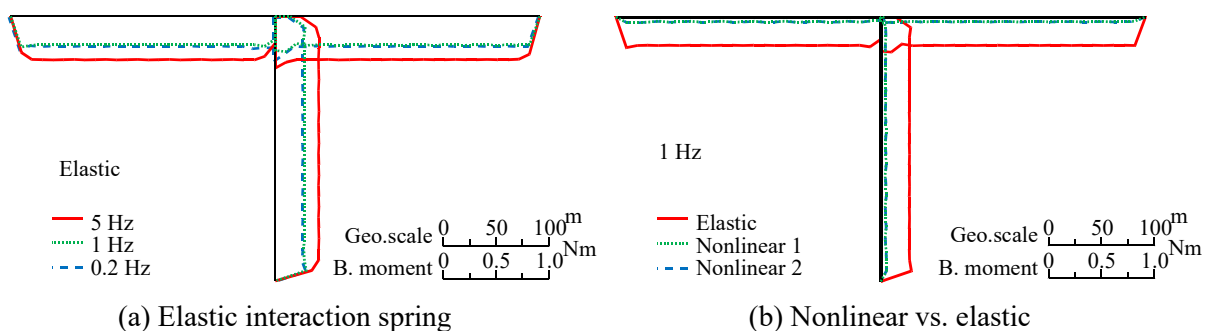


Fig. 15 – Maximum bending moment



Then both velocity and acceleration increments are calculated from specified displacement increment. Result of calculation is shown in Fig. 17(b)(c). Velocity response vibrates around the analytical response and acceleration increase monotonically. It is noted that value of abscissa is very large; analytical line looks horizontal line. This indicates that Newmark's β method is not relevant in this kind of calculation.

They are also calculated by the Euler backward difference method from the displacement increment as

$$\dot{u} = du / dt, \quad \ddot{u} = d\dot{u} / dt \quad (17)$$

Result of calculation is shown in Fig. 17(d)(e). Both velocity and acceleration responses are well simulated except that acceleration at the beginning and at the end of the sinusoidal wave. Acceleration response shows pulse peak (35.3 m/s^2). The reason of this pulse is clear; as shown in Fig. 17(a), slope of displacement is not continuous at these points. This means that input displacement time history is better to be natural one, i.e., that does not have discontinuous slope.

6. Concluding remarks

Applicability of the multiple support excitation formulation for underground structures is examined. Obtained conclusions and notes to use the formulation are as follows.

Multiple support excitation analysis gives results same with the whole analysis in which structures and grounds are solved simultaneously. The conventional computer program need to add function to consider velocity and displacement input. However, it is shown that inertia force hardly affects the response, and can be negligible. Therefore if there is no velocity dependent characteristics in the interaction spring, only displacement is required as input.

Velocity is not negligible in the first case study in chapter 3. Rayleigh damping (stiffness proportional damping) is used with coefficient $\beta=0.005$, which is not an extraordinary value but frequently used value. On the other hand, in the second case study in chapter 4, velocity dependent property does not affect the seismic response when $\beta=0.0005$, and velocity dependent property of the interaction spring is shown to affect the seismic response. It is noted that Rayleigh damping is the most frequently used damping in the seismic response analysis partly because it helps stability of numerical integration. It is usually evaluated from global mass and stiffness matrix. Therefore, special care is required in order to consider velocity dependent property relevantly because velocity dependent damping is automatically considered in the interaction spring.

In the third case study in chapter 5, ultimate strength is affective in the seismic response.

Considering these findings, mechanical property of the interaction spring is very important factor. Number of research is not many, and conclusions are different to each other. A research shows velocity dependent and another is not. A research shows ultimate strength and another is not. It may depend on materials. Actually, as shown in Fig. 11, mechanical properties are different between different sand. Therefore, research on this field is encouraged.

Acknowledgement

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