A DIRECT METHOD FOR SOIL-STRUCTURE INTERACTION ANALYSIS BASED ON FREQUENCY-DEPENDENT SOIL MASSES

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SUMMARY

In a soil-structure interaction analysis, the soil, as a subsystem of the global vibrating system, exerts a strong influence on the response of the nuclear reactor building to the earthquake excitation. The volume of resources required for dealing with the soil have led to a number of different types of frequency-domain solutions, most of them based on the impedance function approach. These procedures require coupling the soil to the lumped-mass finite-element model of the reactor building. In most practical cases, the global vibrating system is analysed in the time domain (i.e. modal time history, linear or non-linear direct time-integration). Hence, it follows that the frequency domain solution for soil must be converted to an "equivalent" soil model in the time domain.

Over the past three decades, different approaches have been developed and used for earthquake analysis of nuclear power plants. In some cases, difficulties experienced in modelling the soil have affected the methods of global analysis, thus leading to approaches like the substructuring technique, e.g. 3-step method. In the practical applications, the limitations of each specific method must be taken into account in order to avoid unrealistic results.

The aim of this paper is to present the recent development on an equivalent SDOF system for soil including frequency-dependent soil masses. The method will be compared with the classical 3-step method.

1 INTRODUCTION

The classical 3-step method for seismic soil-structure analysis consists of the following steps (Idriss et al., 1979): (I) the determination of a motion of a massless foundation with the same shape as the actual foundation when subjected to the seismic input, (II) the determination of the foundation springs and dashpots using impedance functions, accounting for embedment and soil layering, and (III) the determination of the dynamic response of the structure when excited at the base of the springs with the acceleration time histories obtained in the first step. The step (I) is called "kinematic interaction" and (III) - "inertial interaction". The analysis is mostly performed in the time domain, e.g. modal time history analysis or response spectrum modal analysis. In the asymptotic case of a rigid soil, the 3-step method is practically exact from the mathematical point of view, i.e. the response of the nuclear reactor building is not very much affected by the approximate procedure of partitioning the total soil-structure system into soil and upper structure. On the other hand, it is obvious, that the softer the soil,
the worse the approximation, due to the fact, that the kinematic interaction is estimated by neglecting the presence of structural masses.

For the first study (Section 2), using a simplified soil having the impedance function of a specific single-degree-of-freedom (abbr. SDOF) system the interaction effects are demonstrated. Based on this impedance function, the standard 3-step method procedure is strictly followed and the structural response of the model of a nuclear reactor building is estimated. The result of this analysis is then compared with the exact solution of the uncoupled total system consisting of the upper structure resting on the SDOF system chosen above. The SDOF system we selected gives the best least square approximation of the impedance function of a natural soil profile within the range of frequencies from 0 to 8 Hz. This SDOF system is called "ground equivalent model" (abbr. GEM).

For the second study (Section 3), using the curve fitting approach (i.e. the least square method for impedance functions, Danisch et al. 1989/1), we then determine the frequency-dependent soil masses corresponding to the same soil profile. Because the seismic forces in the system come from the masses activated by the support acceleration at the bedrock, the frequency-dependent soil masses enable the effective solution of the equation of motion in the frequency domain. Again, this solution is compared with the classical 3-step method, too.

The curve fitting approach presented here is the further development of the method which is first time introduced and presented in (Danisch et al., 1989/1) and later applied in (Danisch et al., 1991). It is also used in (Danisch et al., 1989/2) for solution of the non-linear uplift problem for a nuclear reactor building.

The method can be applied to any impedance function, no matter if it is corresponding to the flat- or pile-foundation, or if it is calculated or measured. Therefore, it is similar to the method newly presented in (Wolf et al. 1992), which however makes use of specific soil layering properties as well as simple one-dimensional wave pattern in order to define a lumped mass equivalents for the foundation.

2 ANALYSIS USING GROUND EQUIVALENT MODEL

The interaction effects of coupling the soil and upper structure can effectively be demonstrated using GEM of the soil profile given in Table 1 instead of the soil itself. Because GEM is, in fact, a natural mechanical SDOF system, it allows the exact solution by the direct uncoupled procedure of the total system. Therefore the straightforward comparison with the 3-step method is possible. The parameters of the GEM, Table 2, are chosen using the impedance function in Fig.2. The finite-element model of the nuclear reactor building is given in Fig. 1. It is founded on the circular flat foundation of diameter 55,20 m.

For the first analysis, the standard 3-step method is strictly performed using the GEM impedance function, only. To this aim, the kinematic interaction due to step (I) of the 3-step method, cf. Section 1, is calculated for the bedrock acceleration time history corresponding to the input spectrum 0.2g, cf. Fig. 3(a). For the second step (II), the real part of the impedance function is regarded as a spring stiffness, and the frequency-independent soil spring constant $Re_0$ is read at the frequency $f_0=1.60$ Hz. This frequency has been found by the standard iteration on the real impedance curve, involving the eigenvalue solution of the upper structure at each iteration step. Also, denoting by $Im_0$ the value of the imaginary part of the impedance function at the frequency $f_0$, the decimal value of radiation damping is calculated by $D_0=Im_0/2*Re_0$, as usual. Now, for the third step (III), the model in Fig. 1 is set on the spring with stiffness $Re_0$ having the element damping $D_0$ and excited by the kinematic interaction from the step (I), cf. dotted line in Fig. 3.
For the second analysis, remember that the reactor building is resting on the GEM which is in fact a SDOF system. This enables the direct calculation of the coupled lumped mass system consisting of the model shown in Fig. 1 put on the GEM. The excitation is the original input time history, see full line, Fig. 3(a). Obviously, this solution is mathematically exact. Comparison of both analyses is given in Fig. 4.

3 ANALYSIS USING NATURAL SOIL PROFILE AND FREQUENCY-DEPENDENT SOIL MASSES

In this Section the natural soil profile given in Tab. 1 is considered, only. Again, two analyses are compared - (1) the 3-step method for natural soil and (2) the direct coupling of soil impedances to the upper structure in the frequency domain, including frequency-dependent soil masses to account for proper seismic load forces.

For the first analysis, the analogue steps are performed as in Section 2 above, except that the natural soil instead of GEM is used. The impedance function, Fig. 2, of the circular flat foundation resting on the natural soil profile, (Table 1), are calculated using the approach from (Luko et al. 1983). The basic frequency coming from the iteration process of the step (II) is again \( f_1 = 1.60 \text{ Hz} \). This is due to the fact that the GEM produces a rather good approximation of the natural soil impedances. The kinematic interaction is calculated due to the bedrock acceleration time history - the same one as in Section 2, cf. Fig. 3(a) (the same as Fig. 6(a)).

Denoting by \( R\ell_1 \) and \( I\ell_1 \) the values of the real and imaginary part of the impedance function at the frequency \( f_1 \), the decimal value of radiation damping is calculated by \( D_1 = I\ell_1 / 2 \times R\ell_1 \), as before. Now, the system in Fig. 1 is put on the spring having stiffness \( R\ell_1 \) and element damping \( D_1 \) and is excited by the kinematic interaction given by dotted line in Fig. 6(b).

For the second analysis, the notion of the frequency-dependent soil masses is introduced. To this aim, at each driving frequency, the real impedance curve is locally approximated by a SDOF impedance curve, leading to the "local" mass at this frequency. The frequency-dependent soil mass is drawn in Fig. 5. The subsequent analysis is made in the frequency domain: At each driving frequency, the complex stiffness matrix of the upper structure and the impedance of the soil are assembled giving the left-hand side of the equation of motion in frequency domain. For the right-hand side, the adjoin frequency-dependent masses are used.

Comparison of both analyses is given in Fig. 7.

4 CONCLUSION

The example in Section 2 is, in fact, the justification for the new method presented in Section 3. It shows that decoupling of the mechanical system into subsystems, e.g. into soil and structure, can cause problems in adjusting the mechanical parameters at the interface of the subsystems. The analysis in Section 2 shows the differences in the response at the typical node in the nuclear reactor building. In the specific case considered in this paper, the 3-step method applied on GEM produces 40% more peak response than the direct uncoupled procedure which is exact.

The same difference (40%) is found also in the case of the natural soil, Section 3, where the new method based on the frequency-dependent soil masses is used, Fig. 7. As it can be seen, this approach enables the coupled analysis of the earthquake excited structures avoiding the need for substructuring technique.
References:


Danisch, R., Delinic, K., Trbojevic, V.M. (1989/2) GINTER - a computer program for efficient soil-structure interaction analysis including support non-linearities, SMiRT 10 Transactions, Vol. K, Anaheim, California, USA


Idriss, I.M. Chairman et al. (1979) Analyses for soil-structure interaction effects for nuclear power plants, Report Structural div. ASCE, New York


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Table 1. Layered soil profile for analysis

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Table 2. Parameter of the Ground Equivalent Model (GEM)
Fig. 2. Soil impedance function

Fig. 3. (a) Input excitation (full line) (b) Kinematic interaction using GEM (dotted line)

Fig. 4. Response spectra at node 21 for structure on GEM (a) exact, by the direct uncoupled method (full line) (b) approximate, by the 3-step method (dotted line)
Fig. 5. Frequency-dependent soil masses

Fig. 6. (a) Input excitation (full line)  
           (b) Kinematic interaction for natural soil (dotted line)

Fig. 7. Response spectra at node 21 for structure on natural soil  
           (a) by the direct method including frequency-dependent soil masses (full line)  
           (b) approximate, by the 3-step method (dotted line)