Analysis of Pile-Soil-Structure Interaction for Aircraft Impact

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SUMMARY

A computer program for soil-pile-structure interaction analysis (PINTER) was developed and reported elsewhere[3]. This program has been developed further to include multiple basemat structures on piles, non-linearities at soil-pile interface and the capability of considering impact loading on the superstructure. This paper describes these recent developments and demonstrates the capability of the computer program for an aircraft impact on a protective structure around a reactor building. The analysis is performed in the frequency domain. The soil is treated as a horizontally layered media with isotropic viscoelastic material properties with hysteretic damping. Soil properties may vary from layer to layer but are constant within each layer. The piles are modelled as beam elements of linear viscoelastic material, the properties of which may vary also from layer to layer. Piles may be vertical, battered or floating. There may be several discontinuous basemats each of which may have its own superstructure. The pile-soil-pile interaction and the radiation damping is fully taken into account. Any complex flexible structures may also be connected to piles. There is also a provision to account for slippage, loss of bond and non-linearities between the pile and the soil. The aircraft impact is represented by a force time history applied to specific points on the superstructure model.

1. INTRODUCTION

Soil-structure interaction analysis for a foundation consisting of a group of piles should, ideally, be approached as a three-dimensional non-linear problem. Determination of the response of such a system to an earthquake input motion would require great computational effort, firstly because the idealisations used in such analysis would result in a large number of degrees-of-freedom and secondly, tbe solution would have to be evaluated successively at many different times. This may be possible with a powerful computer and no constraints on computing time. However, in practice, some simplifying approximations must be made.

The state-of-the-art opens two major possibilities:

- The non-linearity of the pile-soil interaction is taken into account, but the interaction between the piles neglected[1].
- Pile-soil-pile interaction is accounted for, but the non-linearity of soil behaviour is neglected[2],[3].

However, as pile spacing under nuclear facilities and particularly under the reactor building are usually very small, the pile-soil-pile interaction should be taken into account. In this light a computer program, PINTER[3], was developed in which pile-soil-pile interaction and radiation damping are properly modelled at the price of a linearly viscoelastic soil with hysteretic damping. Such a procedure allows carrying out the analysis by the complex response method in frequency domain. The further developments of the computer code PINTER and its application to the aircraft impact problem and structure-to-structure interaction is presented in this article.

2. METHOD OF ANALYSIS

The analysis is performed in frequency domain. The procedure involves three main steps:

- Transformation of loading time function to frequency domain. This is performed with pre- and post-processor code PINTER-X.
- Calculation of the impedance and transfer functions for the pile-structure-soil system. This is the main part of the analysis and is performed by PINTER. The soil is idealised as an axisymmetric horizontally layered media with isotropic viscoelastic material properties and hysteretic damping. Soil medium is modelled by four-noded torsoidal finite elements. Applying unit forces at the centre of the axisymmetric mesh displacement amplitudes are calculated for all nodal circles. These displacement amplitudes represent soil flexibility coefficients. Soil flexibility matrix which relates forces and displacements for all pile nodes is calculated from the flexibility coefficients by geometric transformation and interpolation. This soil flexibility is

three-dimensional and is utilised to obtain the soil stiffness matrix. The pile stiffnesses are superimposed to obtain the stiffness of the complete pile-soil system. Rigid basemat constraints are introduced to pile heads and/or the superstructure is directly coupled to pile heads and the transfer functions are calculated for a complete system. This is repeated for each frequency determined in the first step. The dynamic response is then calculated in the frequency domain.

Transformation from frequency to time domain and calculation of the dynamic response. This task is also performed by pre- and post-processor code PINTER-X.

These three steps complete the dynamic analysis.

3. PROGRAM CAPABILITIES

One of the developments incorporated in the computer code PINTER is a capability to treat structure-to-structure interaction. In other words there may be several disconnected basemats each of which may support its own superstructure. Since the interaction between all piles is taken into account, in the case of more than one basemat this leads to structure-to-structure interaction.

Two types of basemats are considered in PINTER. The rigid basemat may support a simple beam-type superstructure with lumped masses. The flexible basemat and/or superstructure is modelled by the finite element program SAP4[4] and may be directly attached to pile heads. Piles may be vertical, battered or floating. Any superstructure attached to the pile heads can be modelled separately and coupled to the soil-pile stiffness and mass matrices for treating the soil-pile-structure problem.

Pile properties may vary from layer to layer. The original assumption that the pile is bonded to the soil may be relaxed in PINTER in the approximate manner. In reality slippage or even separation may occur in the contact area between pile and the soil. The soil region adjacent to the pile can experience local plastification and behave in a non-linear fashion. A rigorous approach to these phenomena is extremely difficult and approximations have to be made. The approach described in [5] has been adopted in PINTER. It is based on the assumption that a pile is surrounded by a linear viscoelastic medium composed of two parts: an outer region and an inner layer (hollow cylinder) surrounding the pile. Soil non-linearity and slippage are accounted for by a reduced shear modulus and increased material damping of the inner layer.

Further developments include the incorporation of symmetry conditions when computing the flexibility coefficients for the soil-pile system. Imposing symmetry conditions when computing flexibilities is not as straight-forward as when computing stiffness. However, a method has been devised and has resulted in large savings of computational time as the flexibility matrix that has to be invented is much smaller. The alternative would be to impose the symmetry conditions to the stiffness matrix after the inversion of the full flexibility matrix. This would prove to be far more expensive. PINTER distinguishes the following three cases: symmetry about one axis, symmetry about two axes and symmetry about one axis with antisymmetry about the other.

At present PINTER treats piled foundations only. However, further development is envisaged, so that the general embedded foundations may be treated. The intentions are to make PINTER a general tool for the dynamic analysis in the frequency domain.

In many countries, safety assessments of nuclear plant facilities include the possibility of aircraft impact. The computer program PINTER can deal with this problem by specifying a force time history to the model of the superstructure. The overall response of the structure would depend on the interaction between the superstructure and the soil-pile foundation, so the entire problem should be treated together. The next section presents an example to demonstrate the use of PINTER to such a problem.

4. EXAMPLE

The model analysed for a horizontal aircraft impact comprises the concrete box which shields a reactor, Figure 1. The reactor is represented by a beam with lumped masses connected to a flexible basemat. Both structures are modelled by SAP4. Typical dimensions of the protective box are 36x36x40m and of the basemat 30x30m, the material is concrete. Only half of the complete structure is modelled. The protective box is founded on 24 piles and the basemat on 42 piles, Figure 2. All piles are 24m long with diameter of 1.8m and made of concrete. The soil is layered, properties of which are given in Table 1. A horizontal aircraft impact load is considered acting on point A, Figure 1, the time history of which is given in Figure 3. The point of this analysis was to determine the response to the reactor building from an impact on the concrete protective shell. It is obvious that the reactor building response will depend on the energy transmitted in the soil-pile system as there is no direct connection to the concrete box. In such a problem, it becomes important to model the soil-pile flexibility accurately. The maximum acceleration at the point of impact is 2.9g. Table 2 shows the peak acceleration at other positions in the configuration. Since soil is acting as a high frequency filter, 50 frequencies up to 35Hz are accounted for in the analysis. The maximum absolute values of the horizontal displacement, shear force and bending moment along pile axis are presented in Figure 4 for piles no.1 and no.13 (Figure 2).

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TABLE 1 SOIL PROPERTIES

DEPTH [m]	SHEAR MODULUS [MN/m^2]	POISSON'S RATIO	MASS DENSITY [Gg/m^3]	DAMPING %
0				
	30	0.45	0.0018	20
-1				
	80	0.35	0.0018	20
-3				
	150	0.35	0.0019	20
-6				
	300	0.45	0.0019	20
-9				
	400	0.30	0.0022	10
-15				
	900	0.30	0.0022	10
-24				

TABLE 2 PEAK RESPONSE ACCELERATIONS FOR MODEL USED IN EXAMPLE

RESPONSE POINT	PEAK ACCELERATION RESPONSE (g)
A	2.97
B	1.48
C	0.67
D	0.73
E	0.26
F	0.58

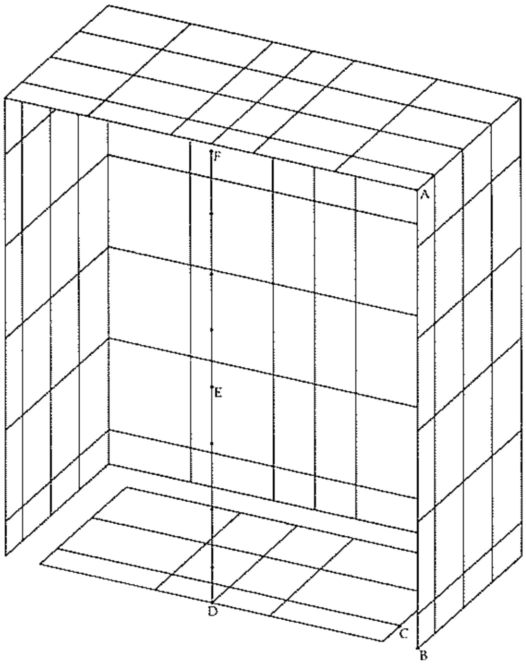

Figure 1 Reactor Building with Protective Shell

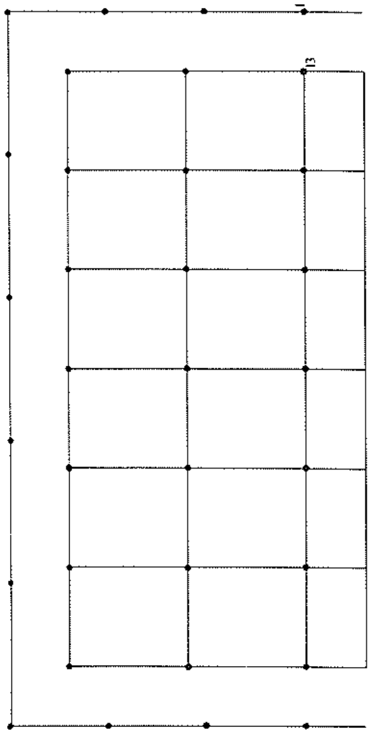

Figure 2 Pile Arrangement

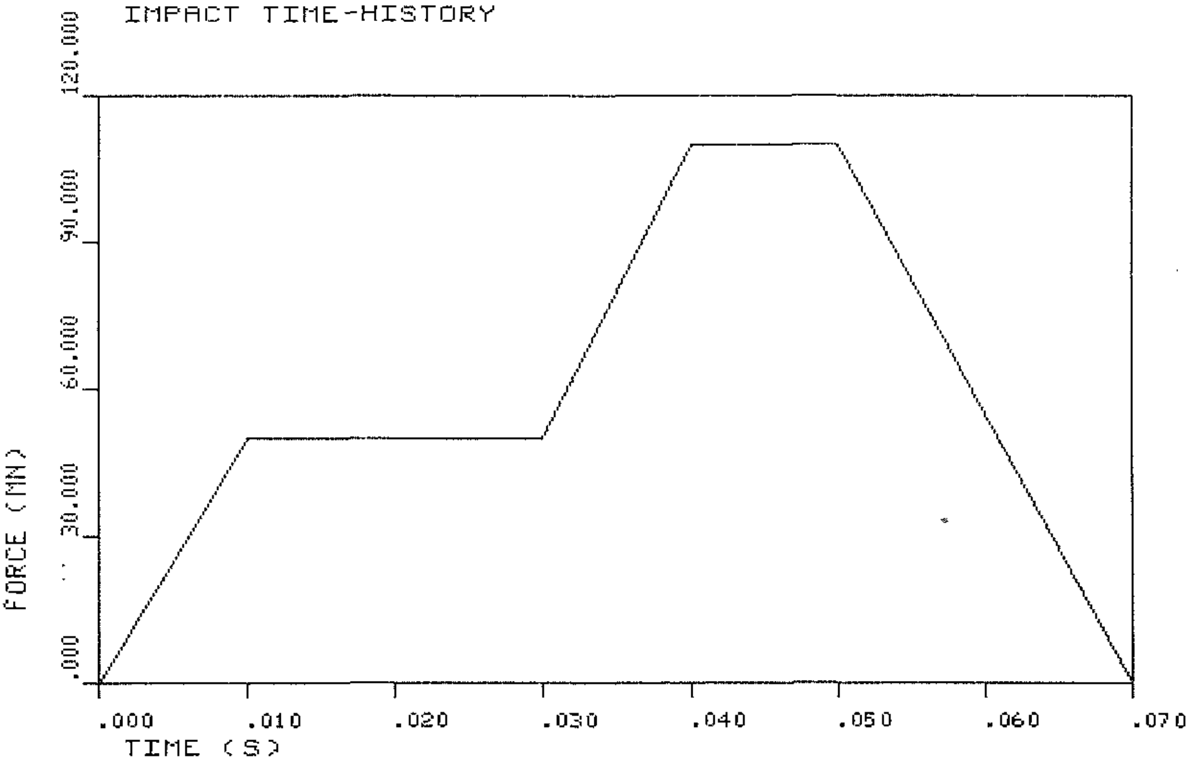

Figure 3 Impact Load Time History

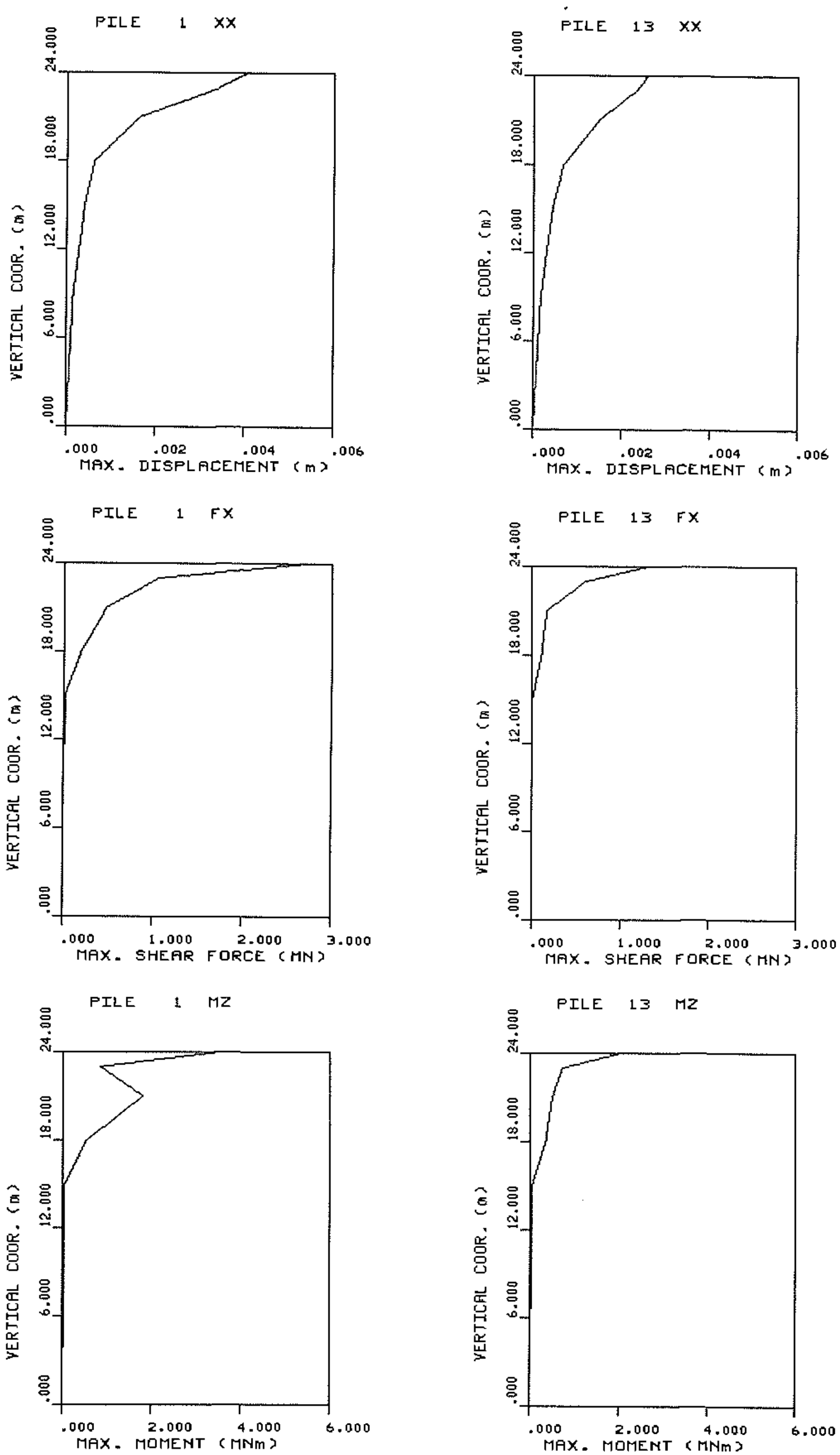

Figure 4 Maximum Absolute Values of Displacement, Shear Force and Bending Moment along Pile Axis.