ON THE ACCURACY OF NUMERICAL MODELS IN 3-D SOIL-STRUCTURE INTERACTION

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SUMMARY

The accuracy of a 3-D model for structure-soil-structure interaction is analyzed with respect to the major parameters influencing the cost of computation. In particular, the relative influence of the various terms of the foundation stiffness matrix on the structural response is evaluated, together with the possibility of approximating the expression of the stiffness matrix itself.

INTRODUCTION

The inadequacy of two-dimensional models in three-dimensional soil-structure interaction analysis was recognized by many Authors, expecially when building-to-building interaction is of concern [1,2]. However, very few truly three-dimensional models are available and they are always associated with numerical algorithms leading to very expensive computer runs. The main purpose of this paper is to examine the accuracy of one of such models as regarding those parameters most greatly affecting storage and time requirements in order to allow computer economies or to establish approximate procedures.
The model which will be taken into consideration is the one described in [3]. The outlines of the procedure will be briefly described in the following.
In the context of the three-step approach, a first program computes in the frequency domain the stiffness matrix of two rigid rectangular surface foundations, resting on a soil composed by one or more horizontal elastical hysteretic layers, inferiorly bounded by a rigid bedrock. The program is the extension of the code developed by KAUSEL [4] for a single foundation and is based upon axisymmetric finite-element solutions of the steady motion induced in the soil by vertical and horizontal unit harmonic loads. By this way the flexibility matrix of a set of nodes located at the foundation interface is found. The flexibility matrix is inverted and "condensed" to give a 12x12 stiffness matrix of the system composed by the two rigid footings.
This latter matrix is assembled with the stiffness matrices of the structures supported by the foundations and the resulting model is analyzed with reference to the free-field motion when vertical propagating P or S-waves are only taken into account.
Obviously, the presence of two footings has the effect of modifying the terms of the stiffness matrix of each foundation and of introducing off-diagonal coupling terms. This effect vanishes as the distance between the two foundations is increased. The influence of the distance is examined first as the major parameter affecting the stiffness matrix of the system.

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Secondly, with reference to aligned foundations, a critical comparison among the terms of the stiffness matrix is made in order to determine their different *influence on the* structural response when, with reference to S-waves, the direction of the seismic motion coincides with the alignement.
In the evaluation of the structural response it is convenient to take advantage of interpolation techniques in order to reduce the number of frequencies for which the stiffness functions must be computed. The variation in the response is analyzed for different numbers of frequency determination and cubic spline interpolation of the stiffness values.
Finally, the possibility of establishing approximation procedures allowing substantial reductions of the computational effort, is studied.
All the above considerations are carried out on the example illustrated in Fig. 1 with the numerical values contained in TABLE I.

FACTORS AFFECTING THE STIFFNESS MATRIX

The parameter of the model which has the main influence on storage and time requirements is the number of points where the soil flexibility is computed. The spacing between these points also contributes to the definition of the mesh used in the finite element scheme, together with the subdivision of the soil deposit into layers and sublayers. It should be, therefore, convenient to keep these requirements to a minimum.
By the other hand, a reduction in number of both interface points and sublayers induces a poorer accuracy in the computation and lowers the cut-off frequency as it does not allow the propagation of high frequency waves in the soil or on its surface.
Studies are available from the literature [4] about the above mentioned effect in the case of single foundations. From these studies it can be seen that, while the on-diagonal terms are not greatly affected, the off-diagonal ones are quite sensitive to the choice of the mesh.
In the case of the building-to-building interaction, this phenomenon has not yet extensively been studied, due to economical reasons, but it can be stated that all the off-diagonal terms, included the two foundations coupling ones, show a similar, or sometimes slightly more accentuated, behaviour. However, the most relevant parameter, from the physical point of wiew, is the distance between the two foundations. Obviously the terms of the stiffness matrix are not equally influenced by variations of the distance: indeed, the terms representing the mutual couplings of the motions are more sensitive than the ones related to the motions of each foundation.
If the generical stiffness coefficient is written as

$$K + i\,C = K_0(k + i\,a_0 c)(1 + 2\,i\,\beta) \qquad (1)$$

where K_0 is the static stiffness, a_0 is the dimensionless frequency $\omega H/C_s$, being H the height of the soil deposit and C_s the shear wave velocity, and β the damping constant, the typical behaviour of the dimensionless quantities k and c is plotted in Figs. 2 and 3, versus a_0, with reference to the case of Fig. 1.
In particular, it can be observed that the model seems to loose accuracy increasing the distance, expecially at high frequencies. This fact is more

evident for those coefficients which do not possess a physical relevance (Fig. 3 a and b).

ANALYSIS OF THE STRUCTURAL RESPONSE

The above considerations suggest that some of the terms of the stiffness matrix could be neglected due to their small numerical influence and that other terms should be cleared as a consequence of the low realiability of their evaluation. Accordingly to this consideration, the elements of the stiffness matrix can be classified into the four categories illustrated in Fig. 4.

By taking the ratio between the acceleration at the base of a structure and the corresponding acceleration at the free-field (herein called amplification function) as a measure of the structural response, the different influence of the various elements is shown in Fig. 5.

The analysis is made for the buildings of Fig. 1, under the circumstances described in the introduction. In this case, the seismic motion taking place along the direction of the alignement, the terms related to in-plane components only are considered. It should be observed that, among the terms to be retained, those of the type B, related to vertical motions, can be neglected in this case only at relatively large distances (D_2), while they are always negligible when the seismic motion is normal to the alignement. This is true, however, for the most sensitive component, that is the base rotation of building 2. Figs. 5a and b show this component for the two distances D_1 and D_2. From Fig. 5 c it can be seen that the B terms are not relevant where the base displacement of building 2 is of concern.

Another parameter which could introduce errors in the response evaluation is the number of frequency determinations of the stiffness matrix. Indeed, the cost of the analysis is approximately proportional to this number and it is, therefore, convenient to minimize the number itself. By using a cubic spline interpolation, of the stiffness coefficients, Fig. 6 shows that, for the case at hand, the number of frequency can be halved without significant loss of accuracy. This conclusion is true also for the other components of the motion of the buildings.

APPROXIMATE EVALUATION OF THE STIFFNESS MATRIX

From the above analysis it can be affirmed that some reductions in the computational effort can be obtained, still working on accurate models. First of all the number of frequency solutions can be minimized in all the cases. Secondly, when the conditions are such that the motion is plane, the out-of-plane components can be eliminated from the beginning in the evaluation of the soil flexibility.

However, in most practical cases, expecially during preliminary design phases, it would be useful to take advantage of even simpler and more economical approaches.

A very crude approximation technique can be established as follows:

a) the foundation stiffness of the two buildings are separately computed in the frequency range of interest,
b) the stiffness of the coupled foundations is determined only at zero fre-

quency,

c) the final stiffnes matrix of the system is obtained by taking the A terms computed in step a) and scaling them to the corresponding zero frequency values given by step b), while the remaining A terms and all the B terms are kept constant at the values of step b).

It should be observed that this technique is similar to the processes in which the mutual interaction is evaluated only in the static case. Figs. 7 a) b) and c) show the degree of approximation reached in the present example. It can be seen that the results are quite satisfactory at low frequencies while, above a certain frequency, the response follows the behaviour of the isolated building. Therefore, if the interaction takes place in the first range, a "good" analysis will be performed (Figs. 7b) and c)) but, in all the other cases the approximation will be very poor (Fig. 7 a)).

However, better models can be realized by expressing the coupling terms of the stiffness matrix as approximate functions of the frequency. This improvement is possible by carrying out extensive parametrical studies. Nevertheless, these studies are feasible only if computational economies are introduced by the above mentioned simplifications in the computation of the soil flexibility.

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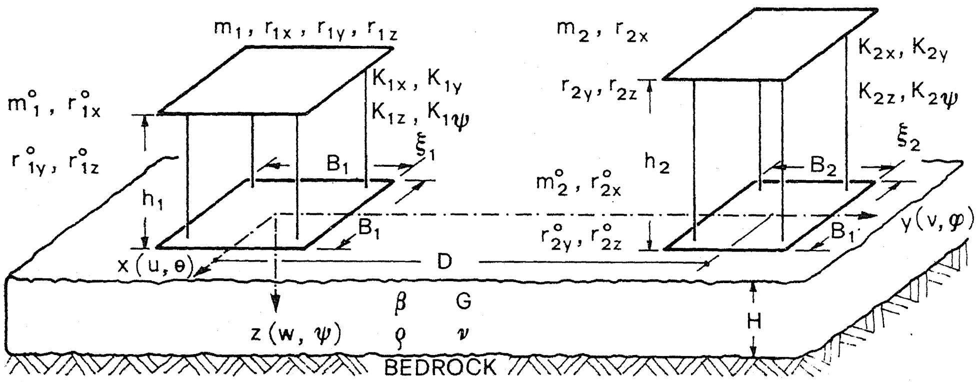

Fig. 1

BUILDING 1	BUILDING 2	DISTANCES
$m^o_1 = 8.88\times10^6$ kg	$m^o_2 = 5.40\times10^6$ kg	$D_1 = 1.645\ B_2$
$r^o_{1x} = 10.16$ m	$r^o_{2x} = 6.33$ m	$D_2 = 2.341\ B_2$
$r^o_{1y} = 10.16$ m	$r^o_{2y} = 10.28$ m	$D_3 = 3.425\ B_2$
$r^o_{1z} = 14.15$ m	$r^o_{2z} = 11.81$ m	SOIL PROPERTIES
$m_1 = 2.92\times10^7$ kg	$m_2 = 7.4\times10^6$ kg	
$r_{1x} = 19.05$ m	$r_{2x} = 12.11$ m	$H = 30.5$ m
$r_{1y} = 19.05$ m	$r_{2y} = 14.49$ m	$\beta = 8\%$
$r_{1z} = 14.23$ m	$r_{2z} = 12.70$ m	$\rho = 1900$ kg/m^3
$K_{1x} = 1.41\times10^{10}$ N/m	$K_{2x} = 4.67\times10^9$ N/m	$G = 1.10\times10^8$ N/m^2
$K_{1y} = 1.41\times10^{10}$ N/m	$K_{2y} = 5.15\times10^9$ N/m	$\nu = 0.333$
$K_{1z} = 2.26\times10^{11}$ N/m	$K_{2z} = 8.44\times10^{10}$ N/m	
$K_{1\psi} = 7.05\times10^{12}$ Nm	$K_{2\psi} = 2.00\times10^{12}$ Nm	
$\xi_1 = 2\%$	$\xi_2 = 2\%$	
$B_1 = 35$ m	$B_2 = 21$ m	
$h_1 = 9$ m	$h_2 = 12.5$ m	

TABLE I

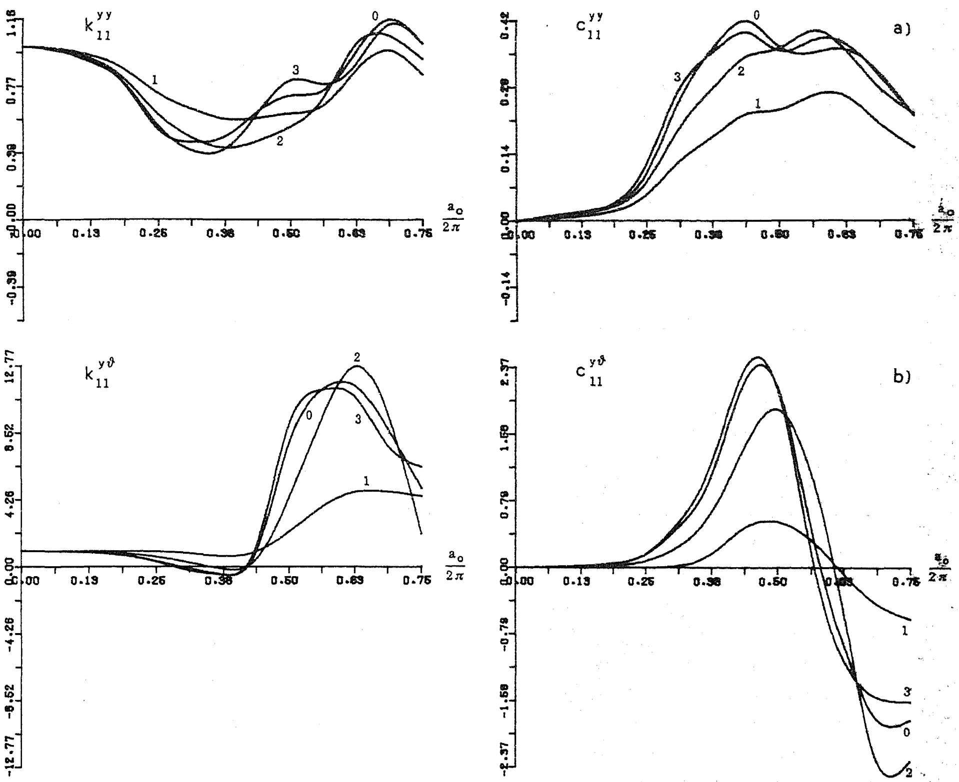

Fig. 2 – 0: bldg. 1 alone; 1: bldgs. 1 & 2 at distance D_1; 2: bldgs. 1 & 2 at distance D_2; 3: bldgs. 1 & 2 at distance D_3.

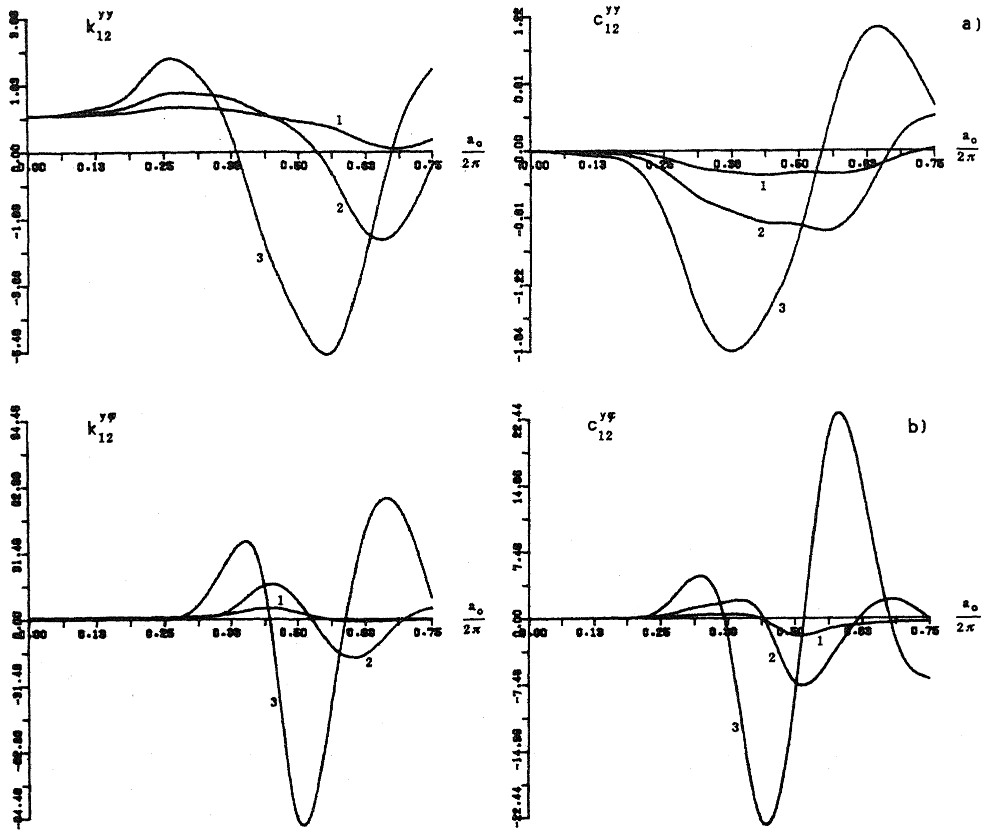

Fig. 3 - 1: bldgs. 1 & 2 at distance D_1; 2: bldgs. 1 & 2 at distance D_2; 3: bldgs. 1 & 2 at distance D_3.

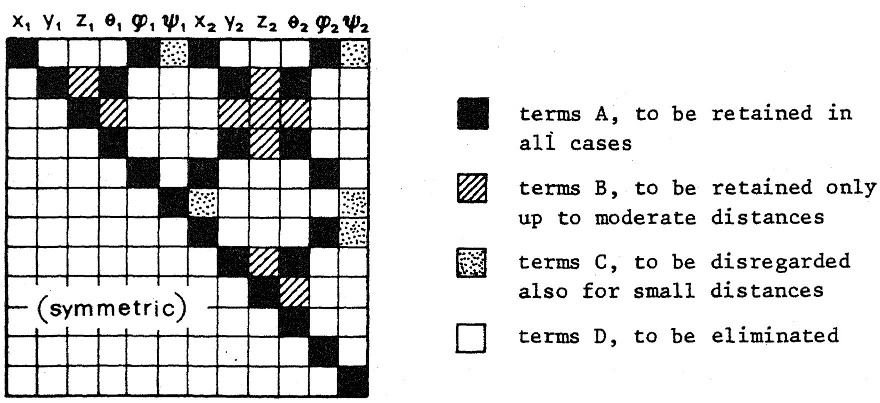

Fig. 4

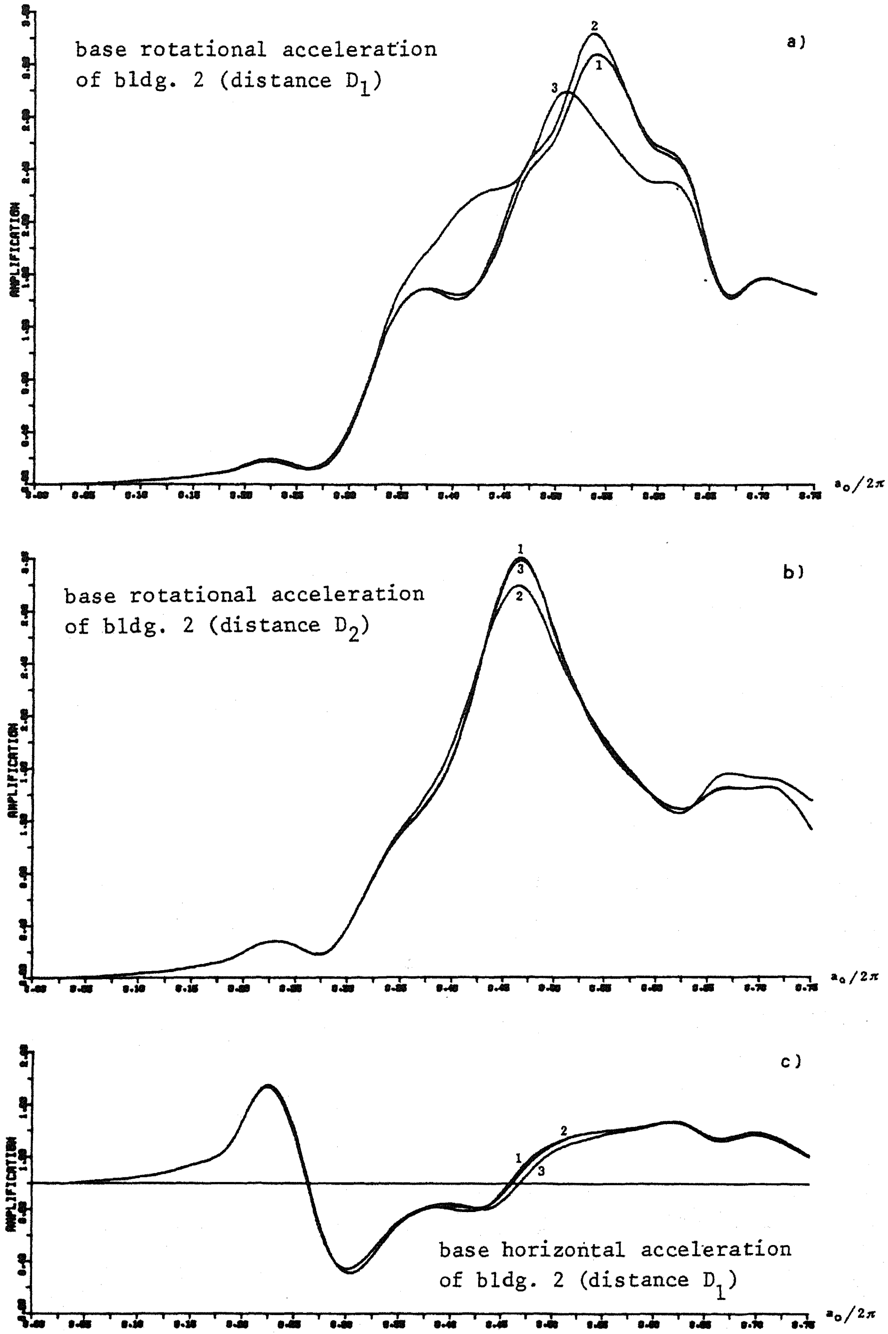

Fig. 5 - 1: full matrix; 2: without C & D terms; 3: A terms only.

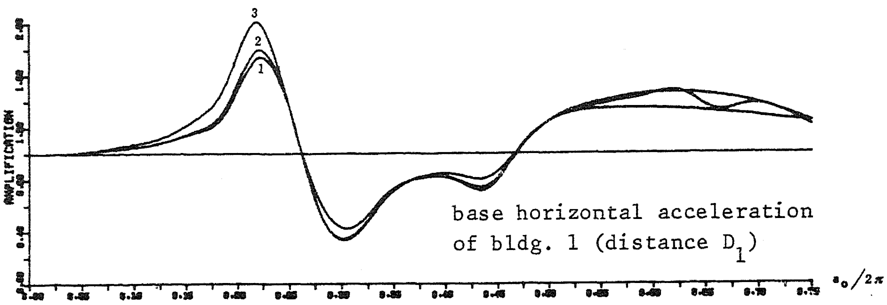

Fig. 6 - frequency steps: 1: 0.5 Hz; 2: 1 Hz; 3: 2 Hz.

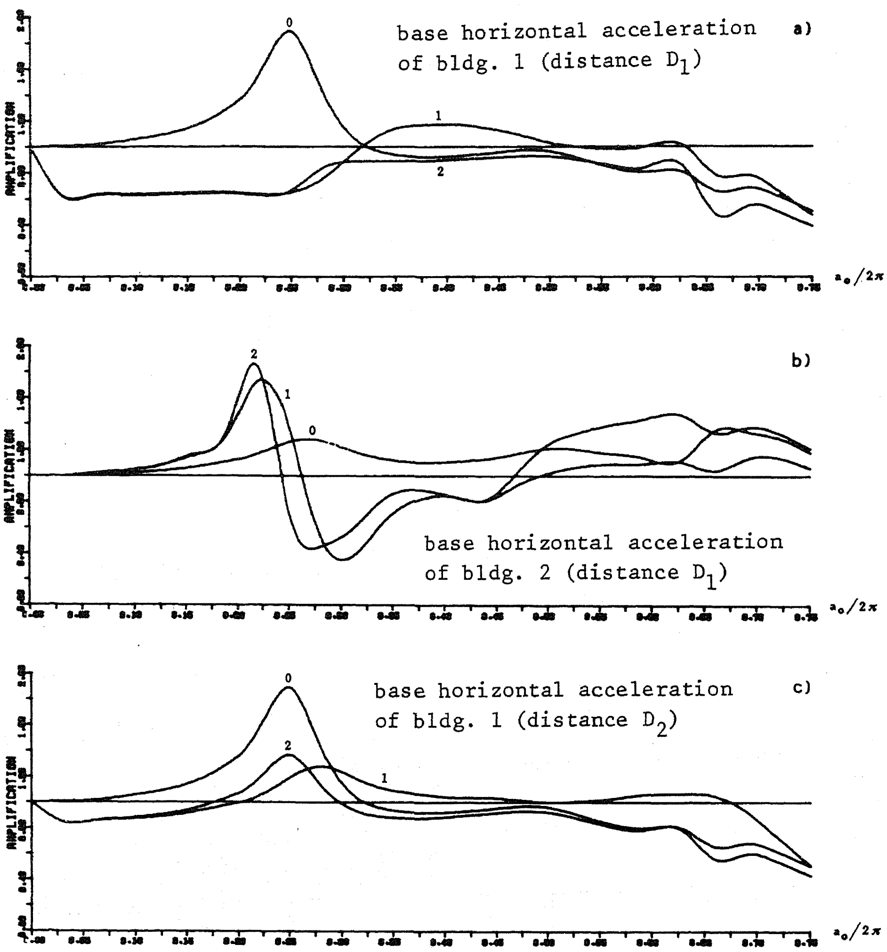

Fig. 7 - 0: bldg. 1 or 2 alone; 1: exact analysis; 2: approximate analysis.