13 Mar 1991, 1:30 pm - 3:30 pm

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## Recommended Citation

Ghiocel, Dan Mircea; Ghiocel, Dan; and Mauna, Traian, "Evaluation of Seismic Soil-Structure Interaction (SSI) by Different Approaches" (1991). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 17.
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Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,
March 11-15, 1991, St. Louis, Missouri, Paper No. 5.59

# Evaluation of Seismic Soil-Structure Interaction (SSI) by Different Approaches

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SYNOPSIS : The paper investigates the seismic SSI effects for rigid type structures. Structural response is computed by modal synthesis versus frequency complex reponse approach. The main aspects analysed are as follows : a) the seismic SSI effects on structural response ; b) short - comings in the current SSI computational procedure ; c) seismic structure - soil - structure interaction (SSSI) effects on structural response of neighbouring heavy buildings. Two case studies are presented : a shearwall multistory building (SMB) on soft clay and a massive reactor building (RB). Seismic response quantities are accelerations, displacements, stresses, floor response spectra (FRS) and spectral amplification functions (SAF).

## INTRODUCTION

It is known that for rigid type structures,the seismic SSI effects on structural response are favourable if the excitation is described by a smoothed design spectrum and the soil-structure interface behaves as rigid body, i.e. quasistatic stresses due to the displacements of the structure base are neglijible. Two essential aspects are resulted as consequencies of SSI : (i) the drastic reduction of the fundamental frequency of soil-structure system and (ii)the increase of energy disipation in the system,as result of the seismic waves radiation from the structure base into the soil deposit. The latter aspect is difficult to accurately idealised, i.e. inconsistencies are included in different approaches due to the neglection of the frequency dependence and spatial character of seismic waves radiation.
The structure-soil-structure interaction (SSSI) generated by through the soil coupling of the neighbouring buildings may, in some situations as reported herein significantly influence the response of the structures. Energy transfer between coupled structures is greater if the natural frequencies of structures are tunned. Dissipative coupling due to reflected waves from a foundation to the other may play also an important role in special cases, as light structure sitted in the vicinity of massive ones or neighbouring embedded buildings.
The paper presents two cases stuies : (i) a shear wall multistory building (SMB) on a soft clay deposit, (ii) a nuclear reactor building (RB) and other two buildings sitted in its vicinity, i.e. auxiliary building (AB) and heavy turbine building (TB). Special attention is payed to SSSI effects between the nuclear heavy buildings.
The SSI effects are evaluated via 2D and 3D finite element models using two computational procedures. The first procedure consists in the application of modal synthesis for the soil - structure system excited at the base by the seismic design spectrum. The computer code ANSYS and a modified version of computer code SAP V are applied. The ground plays the role of the deformable support of the structure, having null inertial characteristics in order to avoid a supplementary amplification of seismic motion through the soil deposit. The soil damping is considered 10 %. The second computational procedure, representing a more advanced approach is based on frequency complex response method (Fast Fourier transform method). The procedure allows a proper idealization of nonlinear soil behaviour, upward propagation of seismic waves including energy radiation by the reflected waves into soil medium. The computer code FLUSH is applied. The 2D models are used to evaluate the SSI overall effects and compute the base structure motions, while computational 3D detailed models are used to determine the stresses in the structures and respectively the FRS, including the local amplification effects of the response. The computational 3D models are excited by the translation and rocking motions of the structure base obtained by the SSI analysis. Seismic response parameters are accelerations, displacements, stresses, floor response spectra (FRS) and spectral amplification functions (SAF).

## SHEARWALL MULTISTORY BUILDING

A shearwall 9 stories building on soft clay deposit is analysed. For building site the dynamic characteristics of soil foundation are written in Tabel 1. For each soil layer experimental $G/G_o - \gamma$ and $D/D_0 - \gamma$ are determined.The maximum ground acceleration is evaluated by seismic hazard analysis at the value 0.20 g. The design spectrum is characterised by a constant maximum aplification factor in the range 1.2 - 8.0 Hz. This shape of spectrum is particularly convenient, as in such case the structural response is not influenced by the modification of the fundamental frequency of structure-soil system as result of SSI i.e. the other SSI effects are pointed out.
For comparative purposes fixed base (FB) analyses are performed using the above mentioned computa-

tional procedures, i.e. the models SSI1 and FB1 for the modal approach and the models SSI2 and FB2 for the complex frequency approach, respectively.

TABLE 1. Dynamic properties of soil

| Layer | Thickness (m) | $G_o$ (kN/m$^2$) | $D_o$ (%) | (kN/m$^3$) |
|---|---|---|---|---|
| 1 | 10.70 | 75,000 | 3 | 16.20 |
| 2 | 5.70 | 87,000 | 3 | 18.30 |
| 3 | 7.20 | 135,000 | 2.5 | 18,00 |
| 4 | 4.00 | 180,000 | 2.5 | 18.60 |
| 5 | 12.40 | 210,000 | 3 | 19.20 |
| 6 | 23.30 | 305,000 | 3 | 19.20 |

The dominant influence of the SSI is manifested by the considerable "softening" of the fundamental mode of vibration of the shearwall building-soil deposit system ; the natural frequency reduces from 4.0 Hz to 1.62 Hz, while the maximum displacement increase from 1 cm to 7 cm. SSI significant natural mode shapes of the system in transverse direction are represented in the Figures 1 and 2, for the 3D model and the 2D model, respectively. For the 2D model the isostresses of the shear stresses are plotted.

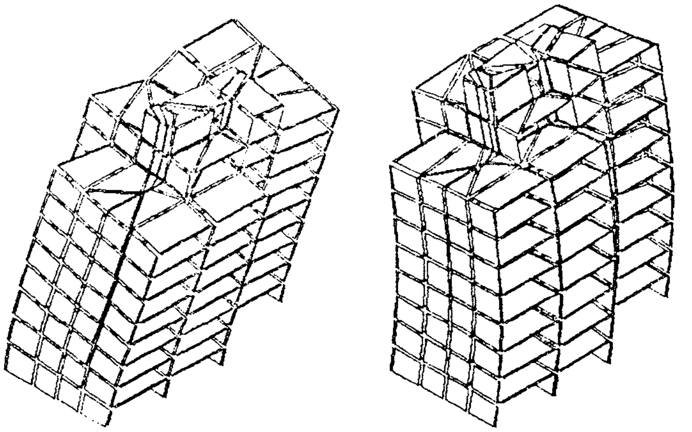


Fig.1 Mode shapes of 3D structural model

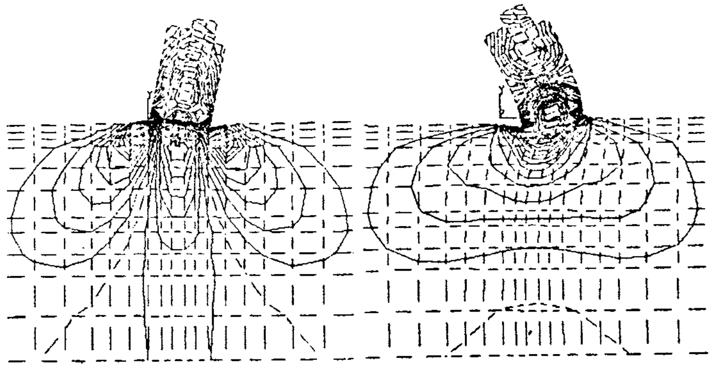


Fig.2 Mode shapes of 2D structure-soil model

The SSI effects computed by the modal approach consists in stress increases by 10-25 % in the lower part of the structure.
The complex frequency approach assumes the definition of seismic input in the time domain by a spectrum compatible accelerogram. The horizontal response spectra computed at the foundation level in the structure versus free field are shown in the Figure 3. It is to be noted the amplification of low frequency components, especially at 1.5 - 2.0 Hz, simultaneously with the decrease of higher frequency components.

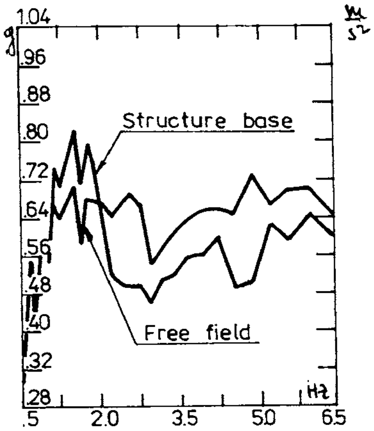


Fig.3 FRS at the foundation level

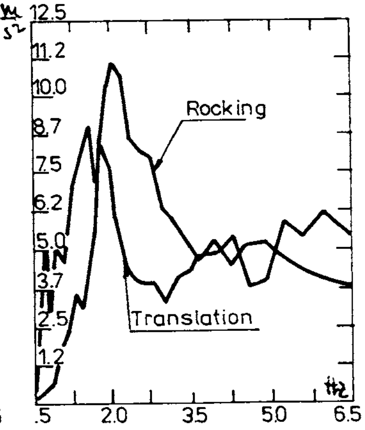


Fig.4 FRS at 2/3 of the SMB height

The rocking motion of the structure expressed by the vertical motion at the lateral edge of the foundation has significant amplitude. Maximum vertical acceleration is 0.09 g, which represents 45 % from horizontal amplitude. Figure 4 shows the FRS computed at 2/3 of the building height generated by the translation and rocking motions at the foundation taking the structure as rigid body. The shapes of spectral curves indicate a high amplitude and narrow band frequency content for the rocking motion versus the wide band frequency content for the horizontal motion. The accelerations obtained by time superposition of the two excitation components are smaller than those resulted for the translation component only. This situation is due to the negative correlation of amplitudes between the two components and praises the trend of SSI effects to reduce the seismic accelerations in the structure. The SRSS (square root of the sum of squares of maximum values) superposition rule often used in seismic analyses is clearly overconservative.
The Figures 5 and 6 contain the acceleration time histories computed at the top of the structure by the complex frequency approach. The graphs praise the radical changes in the structural seismic response as the result of the SSI effects. The FRS computed by the models SSI 2 and FB 2 are drawn in Figures 7 and 8. The structure supported by the deformable soil behaves as a system having dynamic properties completely different than the structure with fixed rigid base.
The maximum amplitudes of response have nearly

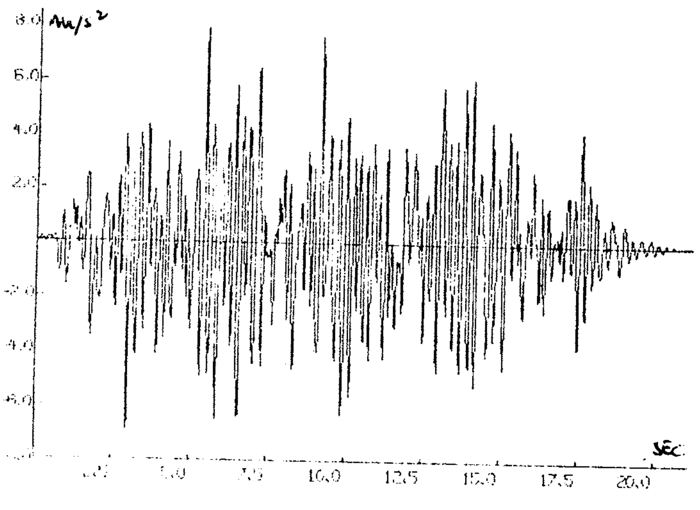


Fig.5 Acceleration at top of SMB.
FB analysis

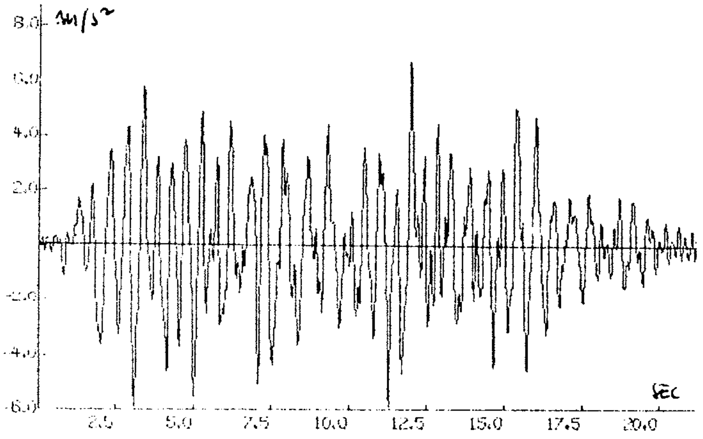


Fig.6 Acceleration at top of SMB.
SSI analysis

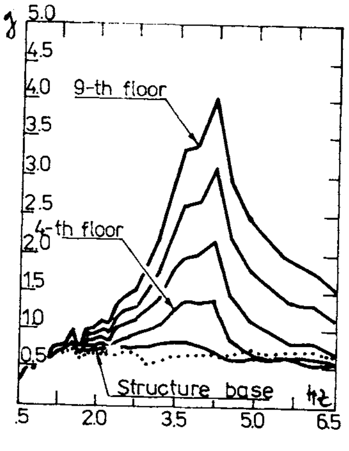


Fig.7 FRS: FB analysis

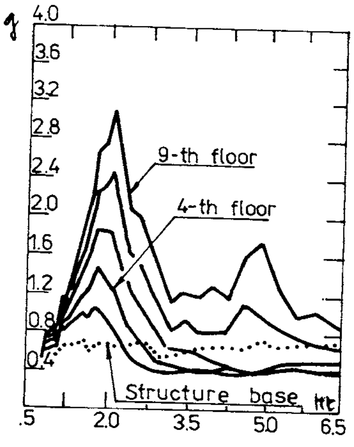


Fig.8 FRS: SSI analysis

values, due to the definition of seismic excitation by a smoothed design spectrum. The SAF for models FB 2 and SSI 2 are plotted in Figure 9.

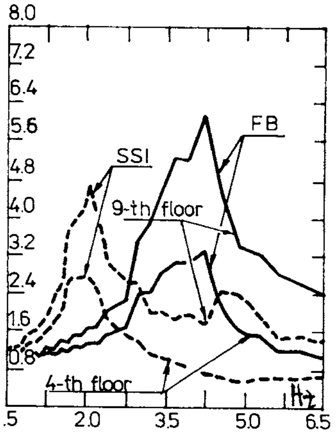


Fig.9 SAF. SSI vs.
FB analysis

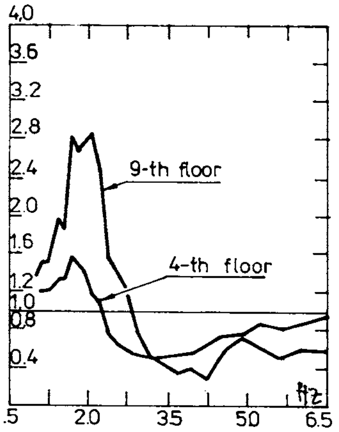


Fig.10 SAF. Ratio
SSI/FB

Figure 10 presents the SAF computed along the structure height, considering as input the seismic response of the fixed rigid base structure (model FB 2) and as output the response of the flexible supported structure (model SSI 2). The spectral curves indicate that for real seismic motions, with possibly maximum spectral peaks in frequency range 1.5 - 2.5 Hz, the SSI effects may produce increases of the acceleration in the structure by more than 100 %.
In Figure 11 are represented the maximum shear forces in the shearwall structure obtained by the two above mentioned approaches. The differences are significantly greater in the lower part of the structure. The SSI effects are favourable or unfavourable depending on the computational model which is considered as reference FB 1 or FB 2, respectively. This situation is generated by the inconsistent modelling of seismic excitation in the modal approach.

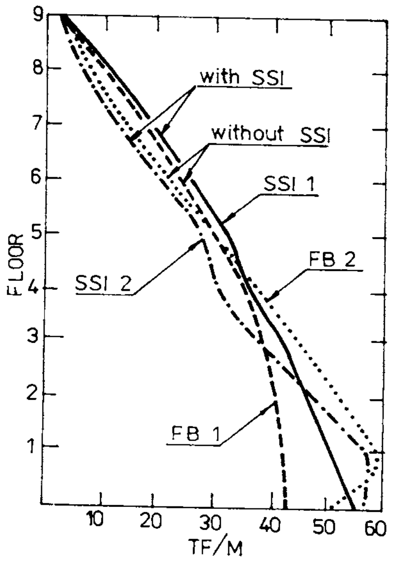


Fig.11 Shear forces in the structure

The mechanic model of the building as inverse pendulum represents a simplified assumption in the modal approach , unadequate for rigid structures, which leads to sensible unconservative estimates of shear forces in the lower part of the structure, up to 30 % for the case study. The maximum shear forces in the structure obtained by complex frequency approach are attained at the level of the first floor and not at the ground floor, as resulting from the modal approach. The use of the triangular distribution (null at the base) or of the distribution after the first few structure mode shapes of the static equivalent seismic forces is structure, which is currently included in the national codes, retains in principle the same inconsistency as the modal approach and may produce sensible underestimates of the shear forces in structural elements.

HEAVY NUCLEAR BUILDINGS

The computational models of RB used in seismic analyses are presented in figura 12.

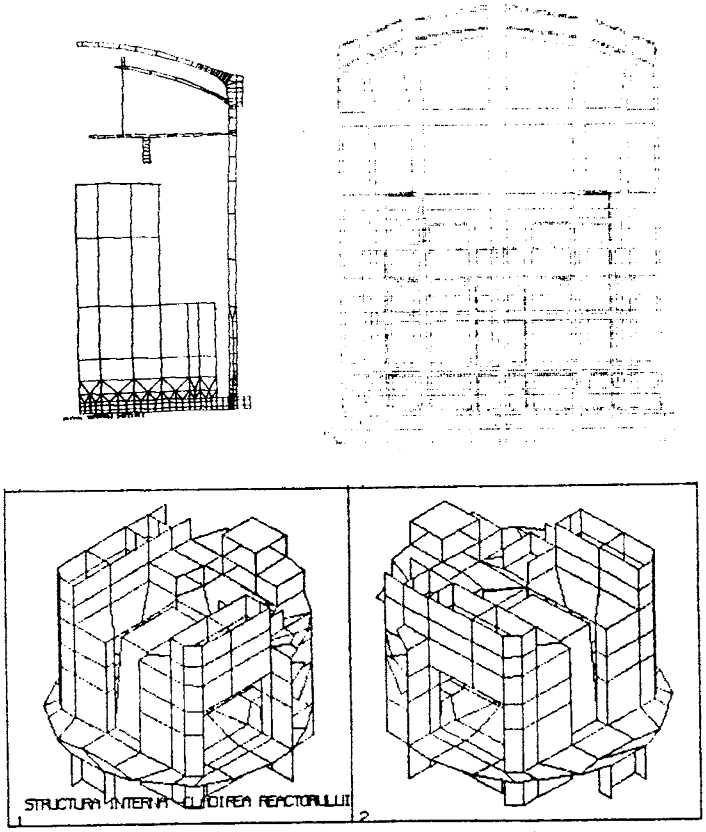


Fig.12 Computational models for RB

For the massive RB it is known that the SSI effects are sensible favourable. For embedded RB founded on medium rigidity soil, $V_s$ = 300 - 500 m/s, the stresses in structure are reduced by 40-60 %, if a proper modelling of SSI effects is made. The shape of FRS used in aseismic design of nuclear equipments and piping systems is severely modified as result of SSI effects, i.e. the spectral peaks are translated towards low frequencies, while the maximum amplitudes are drastically reduced. The SSI effects on equipments and piping systems, are favourable or unfavourable depending of the dynamic characteristics of these systems. The SSSI may significantly influences the structural response of AB and TB, especially for relative soft soil conditions and if an extended subbasemat of RB is considered as design solution.

The seismic response of RB obtained by the modal approach is sensibley conservative. The neglection of the soil mass exagerates the rocking motion of the RB. The underevaluation of soil damping, especially radiation damping and of nonlinear soil behaviour leads to overconservative estimate of structural response.

The natural modes with dominant contribution in total seismic response are plotted in Figure 13. The FRS computed in the internal structure of RB by modal time history approach are illustrated in the Figure 14.

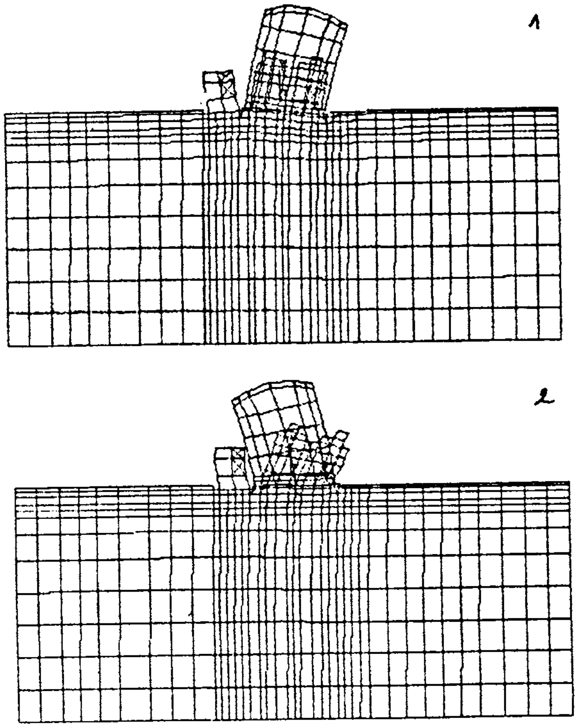


Fig.13 SSI mode shapes

It is to be noted the translation of spectral peaks to low frequency range simultaneously with the significant reduction of their amplitudes as result of SSI effects. The spectral peak computed at 3.5 Hz, which is the fundamental frequency of RB on flexible soil deposit, has no correspondent in the curve for FB. For the internal structure the maximum spectral amplitude in FRS is obtained at frequency 5.4 Hz which represents the fundamental frequency in fixed base analysis. If SSI effects are included this spectral peak is reduced by more than 50 %.

The FRS computed at the top of the containment and internal structure of RB by complex frequency response method are represented in Figure 15. The favourable effects generated by the reduction of seismic soil motion with depth as result of seismic waves propagation are evidenced by comparing the graphs of Figures 15 and 16.

The comparative results obtained by modal ver-

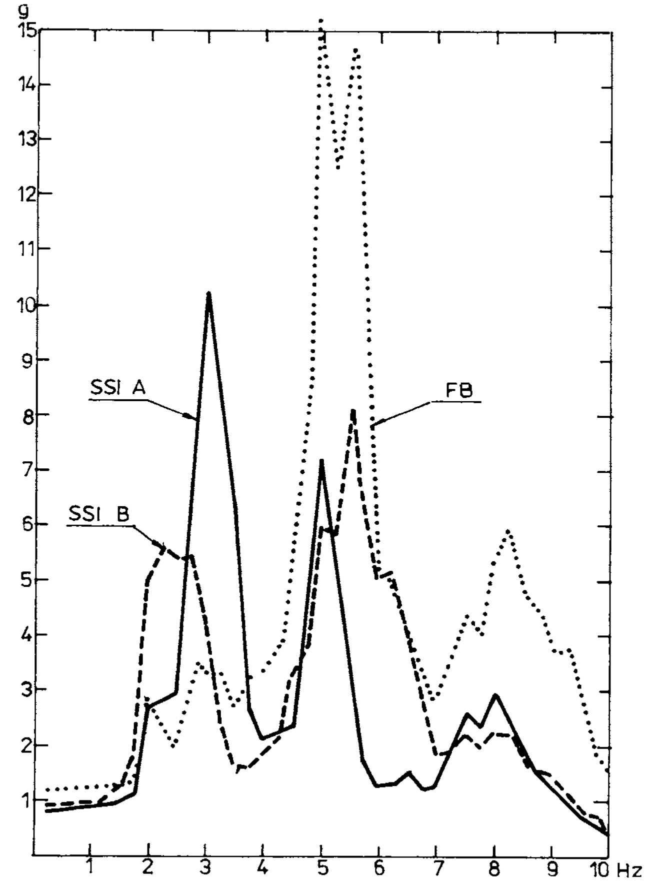


Fig.14 FRS in internal structure of RB

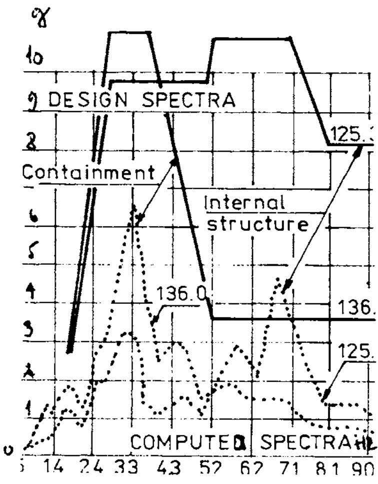


Fig.15 FRS in RB, including deconvolution analysis (site A)

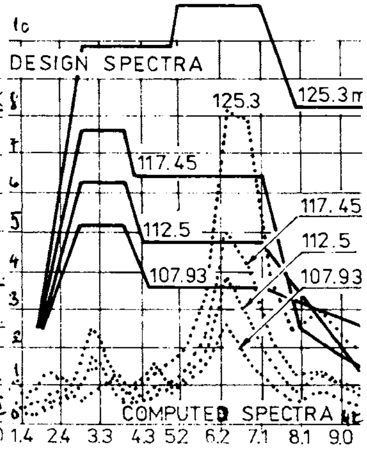


Fig.16 FRS in internal structure (site A)

sus complex frequency approach show significant differences of response estimates. It is remarked that the maximum accelerations at the top of the RB obtained by SSI analyses are 0.82 g in the modal approach and only 0.48 g, in the complex frequency response method by comparison with 1.10 g obtained for nondeformable soil foundation. The spectral peak corresponding to the fundamental mode of RB soil deposit system decreases by approximately 50 % in the complex frequency approach.

An aspect largely investigated consists in SSSI between RB and neghbouring buildings, i.e. AB and TB (Figure 17). The SSSI effects are more pronounced for TB and AB in the case of soft soil conditions.

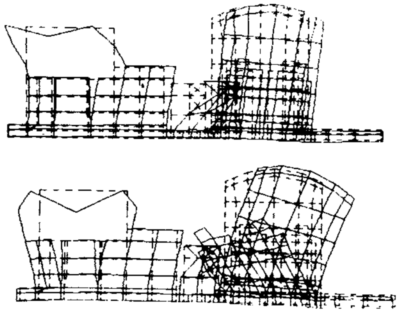


Fig.17 SSSI mode shapes

There are significant changes in the shape and amplitude of FRS. It is noted that in the case of extended subbasemat foundation solution for RB and soft soil conditions the SSSI effects are amplified(Figures 18 and 19).

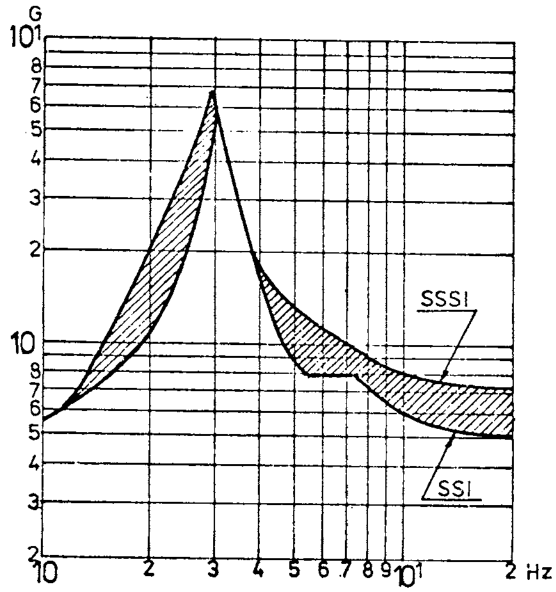


Fig.18 FRS in TB structure

The results obtained by the two computational procedures have divergent trends for TB. The SSSI effects for TB are severely greater if the complex frequency response method is applied (Figure 20). The dissipative coupling due to radiation of seismic waves away from extended subbasemat of RB are neglected in the modal method. Unfavourable effects are generated by the out-of-phase motions of the TB foundation and the subbasemat of RB (there is a short distance of approximately 3 m between them). The presence of surface waves at the base of TB is illustrated by the existence of a vertical translation motion at soil-structure interface and by the increase of rocking

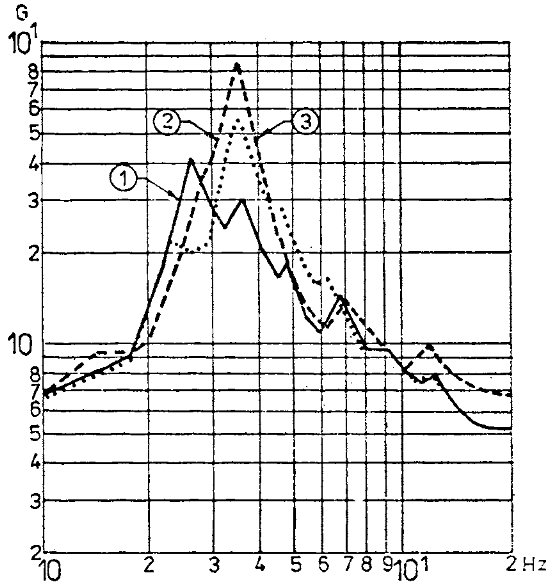


Fig.19 FRS in AB structure. Modal approach
1 - SSSI, extended basemat ;
2 - SSSI ;
3 - SSI

motion of TB structure.

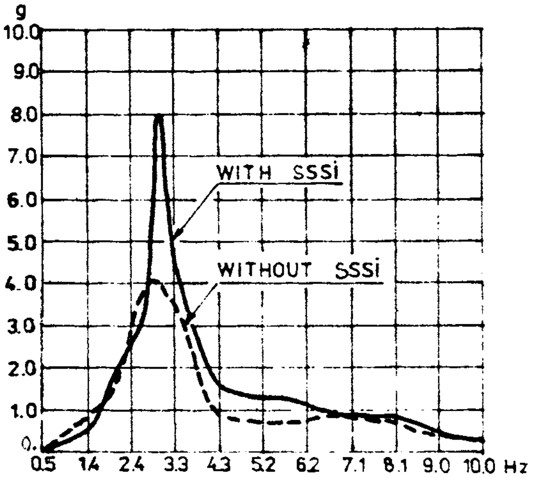


Fig.20 FRS in TB structure
Complex frequency approach

The results obtained for RB via modal time history approach illustrate that the global structural response is weakly influenced by SSI and SSSI if soil damping ratio is considered with same value 10 % (for smoothed design spectrum). Two sites having different soil conditions are investigated ; site A, $V_s$ = 750 m/s and site B, $V_s$ = 400 m/s. Sensible differencies are remarked between FRS at the basemat of RB, especially in the domain of higher frequencies 5 - 10 Hz , for both translation and rocking motions.
For site B characterized by a more deformable soil, spectral ordinates are amplified in range 5 - 10 Hz due to initial SSI while for site A the spectral amplifications are at frequencies over 10 Hz (Figure 21).

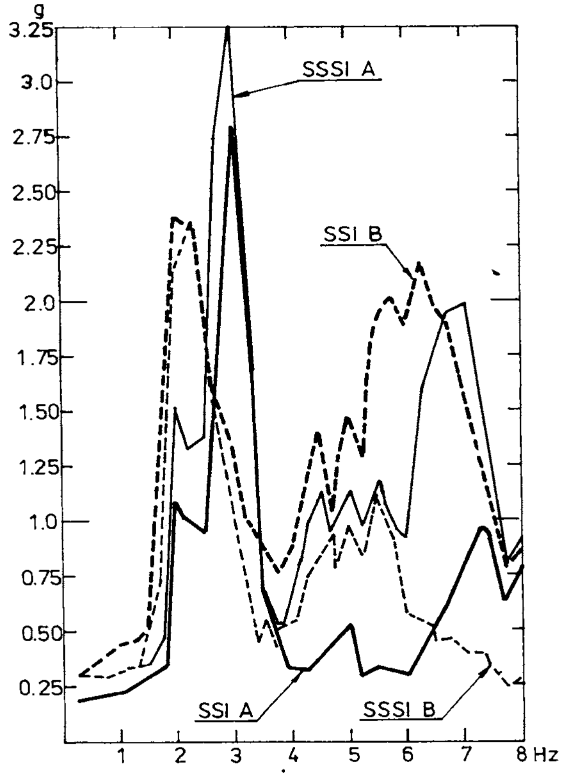


Fig.21 FRS at the basemat of RB

It is interesting to note that the amplitude crosscorrelation between the translation and rocking motions of the basemat is weakly positive for site A, but strongly negative for site B in the range 5 - 10 Hz (this pointed out the presence of SSI natural modes in the mentioned range of frequencies). For internal structure which has a complex spatial configurations, the natural frequencies of local - coupled - global modes of vibration are in the same range 5 - 10 Hz (Figure 22).
The consequences are significant, The local amplification of the accelerations along the generator box (top of structure) is from 0.53g to 0.83 g for site A and from 0.59 g to 1.08 g from site B.
The SSSI effects are unfavourable for site A and favourable for site B. This qualitative result is due to the modification of the natural frequencies of vibration for the RB - soil system. This modification leads for site B to other coupled modes of vibration of the whole structure - soil - structure system obtained for site A. The SAF for site B/ site A computed at the top of RB are drawn in Figure 23.
The SSSI effects on local amplifications within internal structure are pronounced as shown Figure 24. This is in fact the consequence of the elastic coupling of the dynamic subsystems (RB, TB and AB) having nearly tunned frequencies. Vibration energy is transfered from the

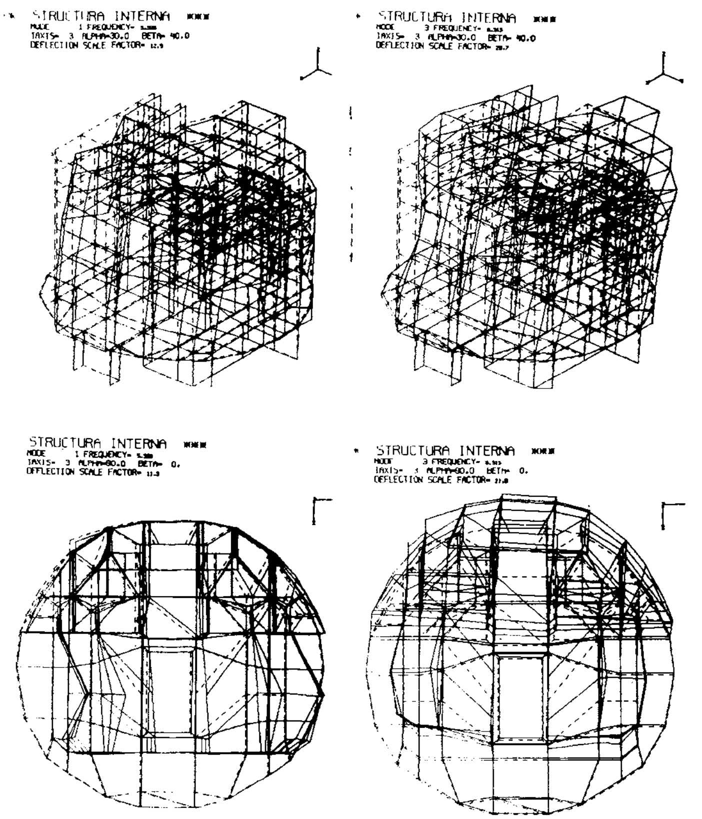


Fig.22 Spatial mode shape of internal structure

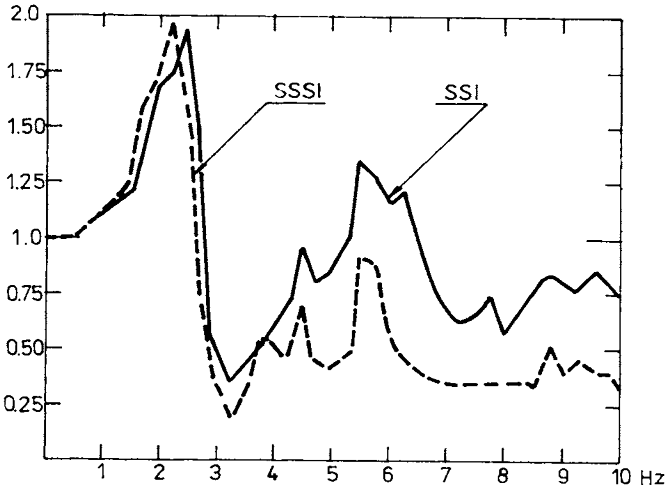
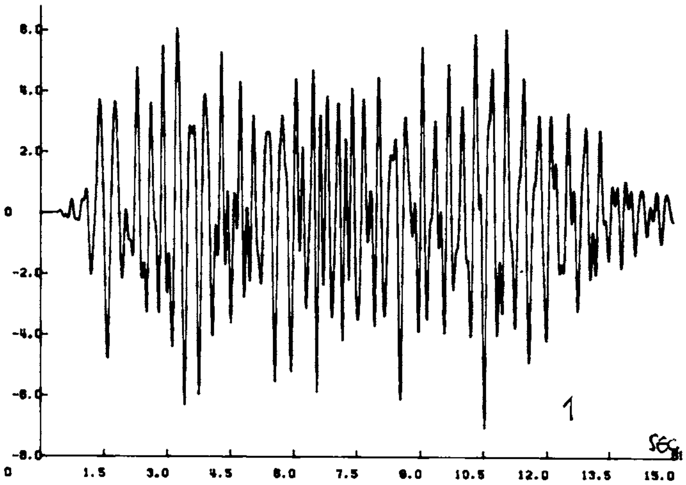


Fig.23 SAF. Ratio site B/site A



Acceleration at the top of generators box

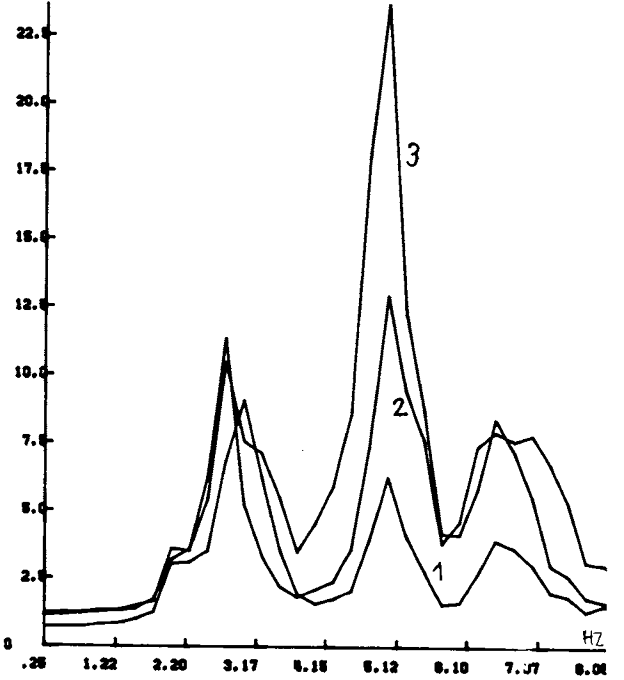


Fig.24 FRS at the top of generators box
1 - SSI, without local amplification;
2 - SSI, local amplification ;
3 - SSSI, local amplification

"heavy parts" toward "light parts" of the system (depending on frequency, from subsystem having greater modal mass to the other sub - systems).

CONCLUDING REMARKS

The SSI and SSSI comparative analyses performed via modal synthesis and complex frequency response approaches lead to some concluding remarks :

- Modal synthesis approach under_evaluates the shear forces in lower part of the rigid structures. Improvement may be obtained by including the effect of residual (higher order, modes.
- Radiation damping effects are considerable only for heavy rigid structures, as nuclear

reactor buildings. For current multistory buildings the energy radiation is sensible weaker.

- For through-the-soil coupled structures, energy radiation may have unfavourable effects due to transfer of vibration energy from one foundation to the other. Inconsistencies of the modal approach in handling energy disipation by radiation in SSI and SSSI analyses are pointed out.
- The SSI may significantly influence the local amplifications of vibration within the complex configuration structures.
- The SSSI influences the structural response of neighbouring heavy buildings. Elastic coupling may be significant when SSI modes of the structures are nearly tunned. In such cases the decomposition of complete SSI problem in cinematic interaction and inertial interaction is not correct.

Energy transfer from one structure to other and viceversa is frequency dependent, being strongly influenced by the ratio of modal masses of the structures for each coupled mode of the whole structure - soil - structure system. As consequence, the SSSI increase the seismic response of the light structures sitted in vicinity of heavy ones. Local amplifications of vibration within complex structures may be sensibley affected by SSSI coupling effects.

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