0385

SOIL-STRUCTURE INTERACTION IN MEXICO CITY. WAVE FIELD RADIATED AWAY FROM JALAPA BUILDING: DATA AND MODELLING

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SUMMARY

The wavefield radiated away from a structure located in Mexico City lake-bed area was identified in order to show the importance of taking into account the soil-structure interaction (SSI) effects in the so called "free field motion". We analysed the strong ground motion of seven subduction earthquakes ($5.5 < Mw < 7.5$) recorded in an instrumented structure. The building dynamic behaviour was characterised by parametric and non-parametric methods. We found that the inertial effects are more pronounced in stiffer direction, and due to great similarity between the ground motion recorded at basement and free-field stations, the kinematic interaction effects are not observed. A study of structural distortion in relation to rocking motion, suggests that the soil-foundation system may contribute to the no-linearity. Subsequently, the ground motion recorded in the basement, depth and free-field stations was explored with a time-frequency scheme. Spite the seismic ground motion is governed by incident wavefield, the analysis of records around SSI frequency indicates that there are important differences above and below the site frequency. We attribute such differences to a strong coupling between the relative horizontal and the rocking motion, which is observed in the depth and free-field stations. Finally, we estimated the wavefield radiated when the associated base forces and the moments developed were calculated in the soil foundation interface by using impedance functions. The computation of the motion radiated back into half-space was performed considering these base forces as surface point seismic. The results of this study suggest that the ground motion recorded in the proximity of the foundations structures should be treated with caution and should not be considered as representative of the free-field conditions.

INTRODUCTION

In the last few years the interest in the study of soil-structure interaction (SSI) on the response of structures subjected to strong ground motion has been increasing. In Mexico City case, the interest of structural engineers is due to the peculiar ground motion observed during events occurring over and above 300 km of distance: a) high amplification, b) long duration, and c) monochromatic wave propagation in fundamental period of the site. As for seismology, several hypothesis have been proposed in order to explain such spectacular seismic site effects, many of them discussed, *e.g.*, in Chávez-García *et al.* (1994). However, in all the studies analysed by these authors, an additional effect, which has not been explored yet, is the possible high densely urbanised environment, *i.e.*, the buildings dynamic response has been ignored. Effectively, recent studies have showed that SSI effects can modify the ground seismic motion in distances at least an order of magnitude major that foundations dimensions [e.g., Bard *et al*., 1996; Wirgin and Bard, 1996; Chiaruttini *et al*., 1996; Guéguen and Bard, 1998]. The results suggest that the presence of such effects requires of two conditions: soft soils and coincidence between SSI and surficial layers frequencies. These two conditions are present in Mexico City lake zone, and recent studies have been pointed that such effects should be taken into account to evaluate the free-field motion [*e.g.*, Avilés and Pérez-Rocha, 1998; Bard *et al*.,1996; Guéguen and Bard, 1998].

It is interesting to remark that Mexico City soft soil conditions have been employed to model the wavefield diffracted by structures simulating the physical characteristics of real buildings [Wirgin and Bard, 1996;

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Cárdenas *et al.*, 1998]. A more formal study has been carried out by Bard *et al.* (1996), who include the structural parameters of Jalapa building, which is an instrumented structure with well documented SSI studies [Paolucci, 1993; Meli *et al.*, 1998]. The results of Bard *et al.* (1996) show that such structure diffracts energy back to the soil mainly by rocking moment and it can be recorded at least in 1000 m from base distance. At the present, such effects are not evident at free-field motion due to the lack of field observations and mainly because all energy of ground motion is concentrated around the fundamental soil frequency layers.

The scope of present work is to show the SSI effects importance in the characteristics of the earthquake ground motion recorded in Jalapa building proximity. The waveform analysis recorded in the structure was carried out in two steps. In the first one, we carried out a SSI study applying a conventional parametric and non-parametric methods. In the second step, we applied a time-frequency [Dziewonsky, 1969] and polarization particle motion [Vidale, 1986] analysis to basement, depth and free-field records in order to identify the seismic wave radiated away from the structure. Finally, we present preliminary results of wavefield radiated by the structure the base shear force and the rocking moment are considered as seismic point sources [Bard *et al.*, 1996; Guéguen and Bard, 1998]

DATA

Data consist on strong motion of seven subduction earthquakes (Table 1) recorded in Jalapa building, a 14-story RC structure instrumented by the Institute of Engineering UNAM and Politécnico of Milan, with three-components digital accelerographs triggered with a common time reference (Fig. 1a). For a brevity sake, we will not dwell on structural characteristics of the building. Information about this structure and its instrumentation can be found in, *e.g.*, Meli *et al.* (1998). It worst to say that the interest in studying this building is due to the fact it is located in the area where the major levels of amplification occur and for the type of its foundation construction (concrete slab on friction pile), this structure is representative of many structures located in the Valley of Mexico soft soils.

Table 1. Events characteristics

Event	Date d/m/y	Long. W	Lat. N	Depth (Km)	Mag. Mw	Epicentral Dist. (Km) & Amax (gal) at EJSC station. [T , L]		
1	15.05.93	98.74	16.43	15	5.8	334.26	3.35	3.83
2	15.05.93	98.72	16.47	15	5.9	330.16	7.90	8.38
3	24.10.93	98.98	16.54	19	6.6	319.66	13.17	9.82
4	23.05.94	100.56	17.97	20	5.6	226.19	6.95	6.47
5	10.12.94	101.56	18.02	20	6.3	296.77	11.98	17.48
6	14.09.95	99.88	16.31	22	7.2	345.83	29.22	27.06
7	09.10.95	104.67	18.74	05	7.3	584.55	11.02	7.90

STUDY OF SOIL-STRUCTURE INTERACTION

The structural dynamic behaviour of Jalapa building has been well documented in the last 6 years. A recent SSI compressive study in this structure has been carried out by Meli *et al.* (1998), who analysed six of the seven events employed in the present work. Data results of the seventh event are presented by Muria-Avila *et al.* (1997). In the figure 1b, we show the SSI importance in this structure. The traces with the grey background show the coupling between the horizontal relative and the rocking motions, which indicate that the building and the base motion are in phase. This characteristic is clearer observed from the strongest events (3, 6 and 7) in L direction. The main conclusions of precedent studies are: a) The structure flexibility permits moderate inertial effects manifested by relative reductions of the fundamental frequencies of the building, b) The kinematic interaction effects are apparent for frequencies greater that 2 Hz, and c) Due to the strong similarity of the motion recorded at basement and free-field stations for all events, the non-linear behaviour of the structure is not related to soil-foundation system.

In this study we have verified the first two conclusions by quantify the SSI resonance frequencies by mean a non-parametric study. The methodology consisted in calculating spectral transfer functions between the difference of the roof and basement (in time) and free-field horizontal motions, longitudinal (L) and transversal (T) directions of the building. We found that, as Meli's *et al.* (1998) results indicate, the inertial effects are more

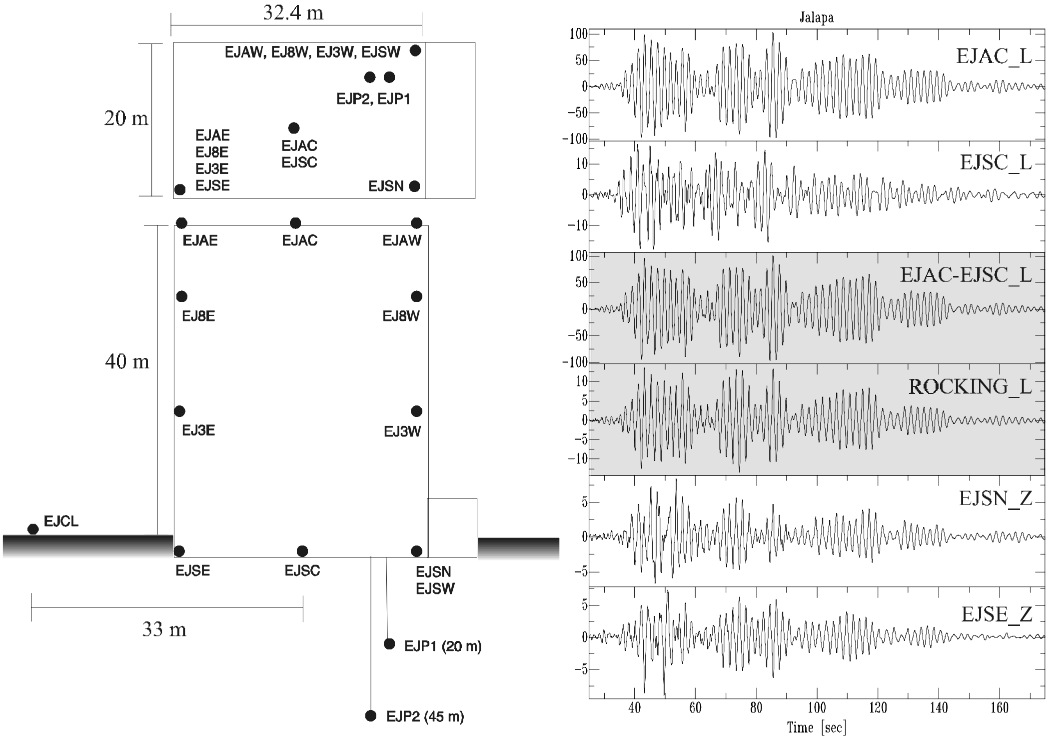

Figure 1. a) Building sketch and their instrumentation. b) Event six records (lowpass filter at 1 Hz) are showed in the right side of each structure. The traces with background grey, relative lateral and rocking motion, are obtained of the difference between total lateral mass and basement motion, and vertical motions at the opposite corners of the basement, respectively.

pronounced in L direction because of relative differences between SSI and fixed-base frequencies, the last ones calculated in similar way following Paolucci (1993). In the same way, we did not find relevant differences in the kinematic interaction study, evaluated by mean spectral ratios between the basement and the free-field motion.

In order to improve SSI frequencies values, we apply a parametric technique developed by Kahan (1996) and used successfully in Farsi (1996) to characterise the vulnerability of many structures. The code computes the response of a dynamic model of *n* degrees of freedom subject to multiple excitations. The identification of the frequency and the damping is in the time domain, minimising the error between observed and computed response. After several tests, we found that the best results are obtained when we employed the horizontal records of all instrumented floors as outputs and horizontal and vertical records of basement stations as inputs. We find that the majors differences between parametric and non-parametric methods occur for that events where the soil and SSI frequencies are closed, *i.e.*, for strongest events in L direction. Figure 2 shows the frequencies and the dampings for the fundamental frequency, plotted as a function of the base pseudoacceleration spectra around of site period (2 sec). In this figure we can observed the importance of SSI inertial effects on structural response; reduction of the interaction frequency in relation the force applied in the base. The effects are more pronounced in L direction. We do not find important changes in the damping; a value of 5% was taken into account as initial value.

These observations suggest that an aspect concerning with SSI phenomenon exist: the non-linearity. In effect, it is well known that in very soft soils, the interaction effects may be quite important because they depend on the relative stiffness between the structure and the soil. Beforehand, it should consider that the soil proprieties do not change for high shear levels due to the wide elastic behaviour of soft clay layers [Ordaz and Faccioli, 1994]. So, a possible explication to the non-linearity is that it is caused by the building. In order to quantify the importance of the relative stiffness between the structure and the soil, we calculated transfer functions between structural distortion (or flexibility) and rocking motions (Fig. 3). The structural distortion was obtained by subtracting from the roof motion the sum of the base and the rocking motion. We can observed the great flexibility in T direction in comparison to L direction where the rocking motion take approximately the 8% of the structural response. This result suggests that in the frequency vibration, there are important interaction effects at soil-foundation level that contribute to non-linear behaviour.

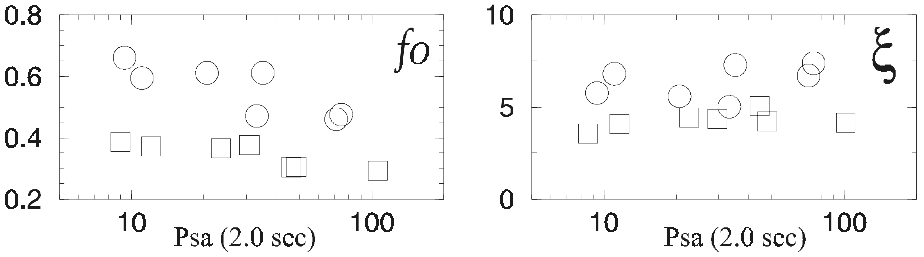

Figure 2. The frequencies (frame left) and the dampings (frame right) of the building fundamental vibration mode obtained by the parametric study. The circles represent values in longitudinal direction and the squares in transversal direction.

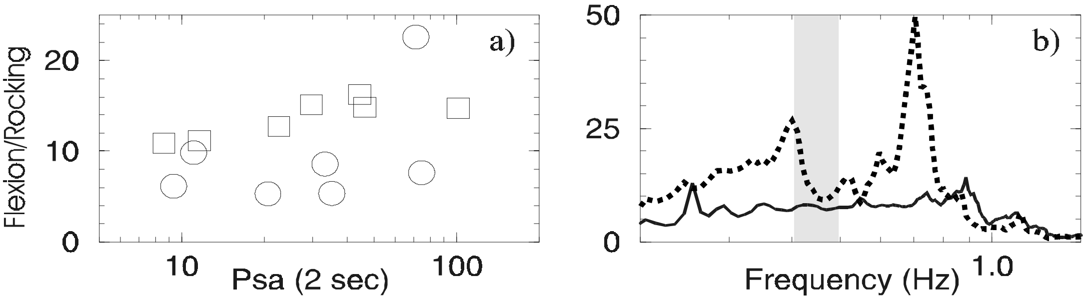

Figure 3. Structural distortion between rocking motion ratios. a) Spectral values obtained by the average around of frequency building vibration (dashed band of figure b). The circles and the squares correspond to longitudinal and transversal directions, respectively. b) Example of the event 6 spectral functions used for calculate the figure a). Continue and dotted lines represent the spectral ratio in longitudinal and transversal direction, respectively.

FTAN AND POLARIZATION PARTICLE MOTION ANALYSIS

Before applying this identification scheme, it was applied to experimental data recorded in the Eurosite-Test of Volvi (Greece), where a 6-story RC structure (1:3 scale) was forced into vibration and the surface motion was recorded close to the structure [Guéguen and Bard, 1998]. The results of this experiment show clearly the surface waves radiated away of the structure at SSI frequency. The FTAN and polarization analysis confirm that the major amount of energy is propagated around the coupled system frequency and the associated motion correspond to surface waves. Figure 4 shows the polarization analysis applied to a station located in the perpendicular direction to applied force. We observed that all of the motion is registered in the component coinciding with the force direction, and the polarization filter predict correctly the particle ground motion; 0° of strike and dip. For a station located in the force direction, the dip is in average 45° due to the P-SV wave polarization. For a station located in the diagonal, the recognition is more unstable due to inhomogenity of the soil, however, the directional parameters are well identified too.

FTAN scheme applied to ground motion recorded in three observations points at Jalapa building (basement centre, depth and free-field stations) shows that it is difficult to identify SSI effects on surrounding soil. This is due to the possible energy diffracted by the structure during SSI are immersed in the incident wavefield propagating around of the soil fundamental frequency (0.5 Hz). This result suggests that in order to apply the polarization identification scheme, it is convenient to take apart the waves propagating in the SSI frequency. So, the ground motion records have been filtered around of the coupled system frequency computed in parametric study. The filter used correspond to one of the gaussian filters employed in FTAN technique. The first characteristic observed in filtered records is the difference in shape wave form. Above the frequency site, we appreciate similitude in the wavetrain form only in the L components for records of events 1, 2, 3 and 4. Around, or below this frequency (events 5, 6 and 7), the ground motion in basement, depth and free-field records in horizontal directions is similar. However, in the vertical filtered records, the waveform is different in the three observations points. The figure 5 shows the ground motion filtered at SSI frequency in L direction for events 3 and 6. In this figure we observe that the transversal motion above of the site frequency (event 3) present significance differences.

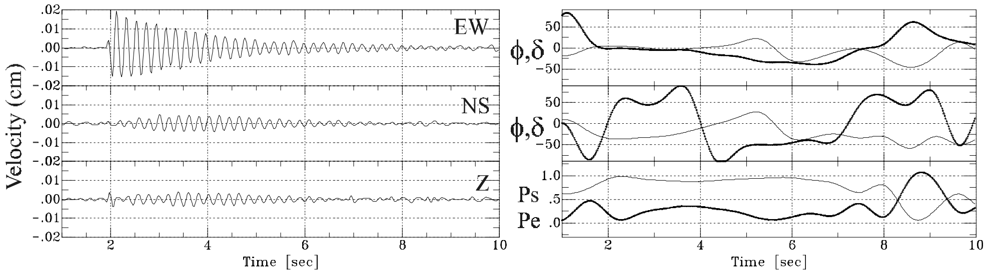

Figure 4. a) Orthogonal velocity records obtained during a SSI experimental test. b) Polarization particle motion analysis of velocity records. In the firth two frames, the thick and thin lines represent the strike (ϕ) and the dip (δ), respectively. The directional parameters of the first frame are obtained when we considered the EW record as radial component. In the second frame, the analysis is carried out considering the NS record as radial component. The third frame show the elliptical component (Pe) and strength (Ps) of polarization in thick and thin line, respectively.

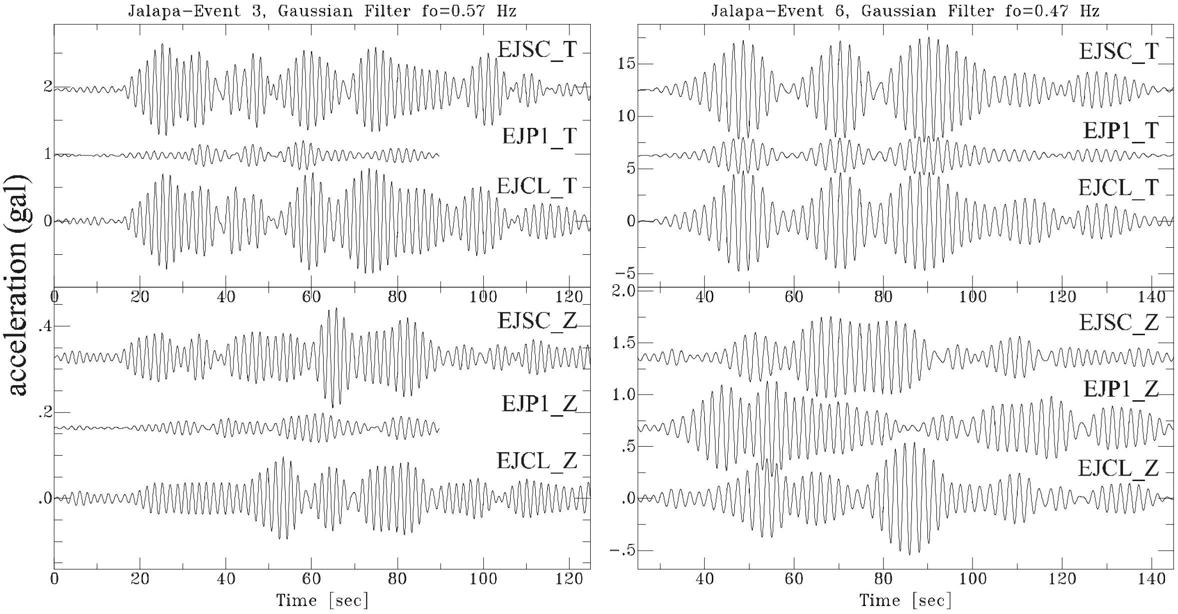

Figure 5. Ground motions records (basement, depth and free-field) filtered in longitudinal SSI frequency vibration for events 3 and 6. Note the prevalent differences in the vertical waveform at frequencies above and below of the site frequency (0.5 Hz).

In spite of the excellent results of polarization method applied to experimental Volvi data, the analysis of strong motion at Jalapa building is not successful. This fact is due to the fact many of the motion recorded have the influence of the incident wavefield. The directional parameters of the particle motion seem are affected by vertical differences observed in the frequencies studied. In effect, the FTAN results confirm this observation. The figure 6 shows the spectral amplitude contours for the free-field and base relative horizontal motions. In this figure we can observe that many of seismic energy is propagating around site frequency (0.5 Hz). However, if we observe the relative motion, we found that the energy has a maximum in the SSI frequency (indicated with a horizontal line on FTAN diagram), So, in order to eliminate part of the incident wavefield, we decided to analysed the relative structure motions. For this, we filtered the relative basement motion (temporal difference between basement and free-field or depth records) around SSI frequency. The figure 7a shows this results for seventh event records. We can appreciate a common wavetrain in all traces appearing after 125 sec of record. If the same traces are explored in other frequency band, result difficult to find such wavetrain (Fig. 7b).

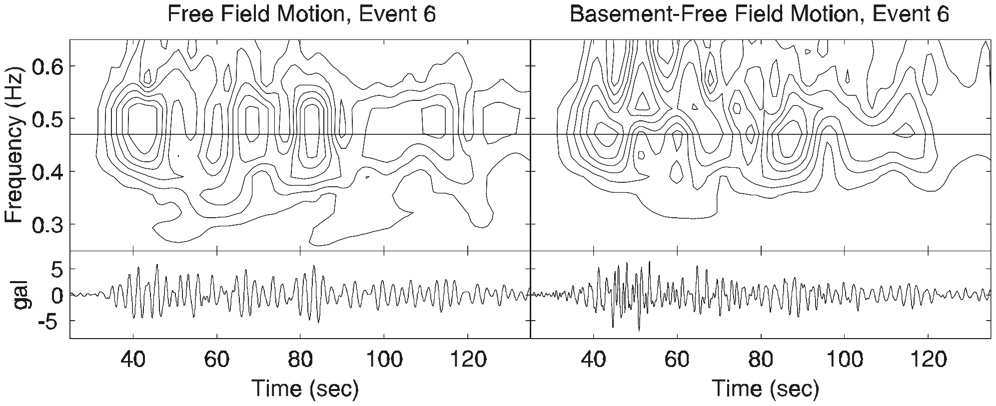

Figure 6. Frequency Time Analyses applied to the horizontal free-field and relative motions for sixth event. The horizontal line along of the spectral contours indicates the Soil-Structure Interaction frequency value.

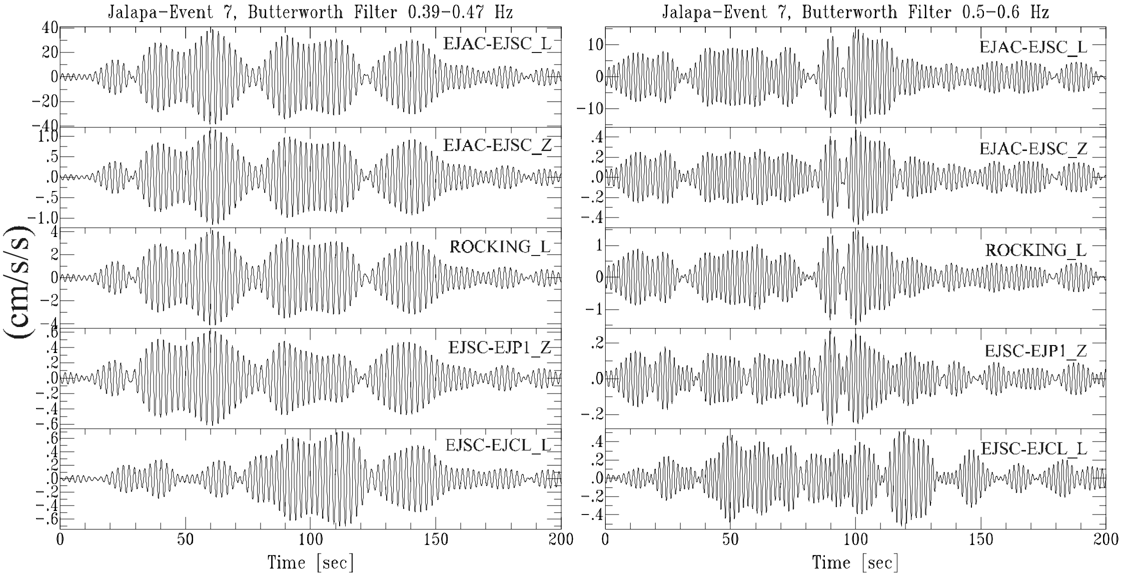

Figure 7. a) Relative motions obtained of the seventh event records. The traces are filtered in the Soil-Structure Interaction band. b) Same traces of the figure a) filtered in other frequency band.

PRELIMINARY WAVE-FIELD DIFFRACTED MODELLING

In order to quantify the ground motion produced by the Jalapa building during SSI, we calculate the building response and the associated radiated wavefield following Guéguen and Bard (1996) method. The numerical simulation is performed by associating the structure to a simple 3 degree of freedom model. As input motion excitation, we took the horizontal record at CU station (hardrock site) for the sixth event. The structure characteristics were taken from Paolucci (1993) and for the soil layer (depth of 40 m) and half-space, 65 and 600 m/s for shear wave velocity, respectively. The relative horizontal and rocking foundation motions were employed to calculate the base shear force and rocking moment, respectively, by using the impedance functions of the soil-foundation system. The wavefield radiated back into the half-space by these forces was computed using the discrete wavenumber method. The Green's functions was computed for a viscoelastic stratified half-space, even when point sources and receivers are in very close depths. Point sources were represented by the base forces, shear and moment, which was uniformly distributed along of soil-foundation interface. The superficial wavefield radiated was computed along L direction in two receivers located from 100 to 1000 m from building base centre. The results for the surface motion radiated by the rocking moment are showed in the figure

8. Some differences with acceptable amplitude in waveform are observed in the lateral structural response (roof motion). We observed a small amplitude and significant waveform differences of computed motions in relation to the observed free-field motion. However, we should consider that the wavefield modelled is only the contribution of a single structure.

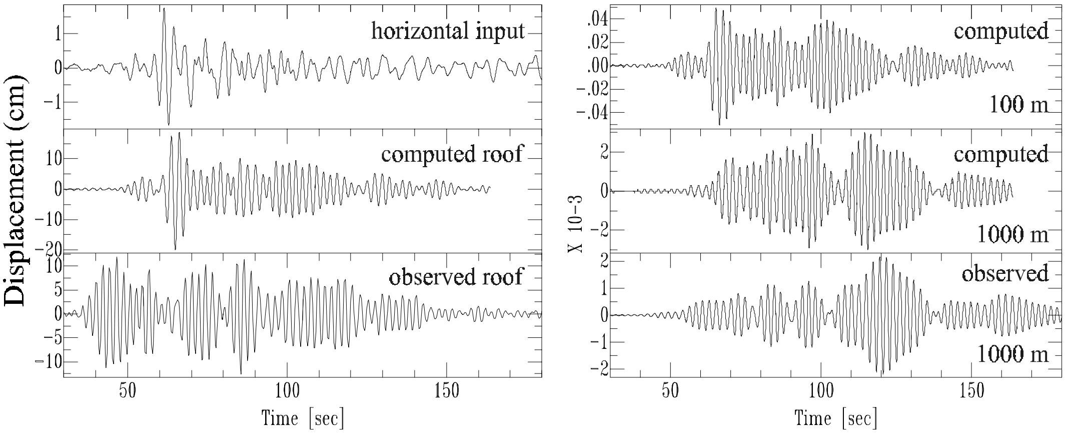

Figure 8. Wavefield diffracted modelling from Jalapa building. The horizontal input trace correspond to motion recorded at CU station for the event six. The traces labelled with computed are the surface motion radiated by the rocking moment. The free-field motion observed record is filtered around building frequency vibration (0.47 Hz).

CONCLUSIONS

In this study we identify the wavefield diffracted during the Soil-Structure Interaction (SSI) of Jalapa building, a structure located in Mexico City soft soils. The analysis of ground motion data suggest that inertial effects are the main cause of wave radiation. Such effects are mainly manifested in the free-field motion when SSI and site frequencies are close. The wavetrain observed in the base building vicinity, may be produced by the coupling between relative horizontal and rocking motions. Numerical simulation suggest that the contribution of this structure to the seismic ground motion, is small relatively to 1D resonance of the Valley. However, we should consider that Mexico City is conformed by a highly urbanised environment and the effect of a large number of buildings vibrating at the same time might modified the amplitude and duration of free-field motion. Finally, the results of this study suggest that the ground motion recorded near the foundation structures should be treated with caution and should not be considered as representative of the site conditions.

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REFERENCES

Avilés, J. and L.E. Pérez-Rocha (1998). Site effects and soil-structure interaction in the Valley of Mexico, *Soil Dyn. and Earthq. Engrg*. **17**: 29-39

Bard, P.-Y., P. Guéguen and A. Wirgin (1996). A note on the seismic wavefield radiated from large building structures into soft soil, *Proc. Eleventh World Conf. on Earthq. Engrg.*, June 23-28, Acapulco, Mexico, paper No. 1838, Elsevier Science Ltd.

Cárdenas, M., M. Bermúdez and F.J. Chávez-García (1998). Ground Motion in Mexico City. Contributions of Building Stock, *Proceedings of the Second International Symposium on the Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, 1-3 December, 421-426.

Chávez-García, F.J. and P.-Y. Bard (1994). Site effects in Mexico City eight years after the September 1985. Michoacan earthquakes, *Soil Dyn. Earthquake Eng*., **13**, 229-247.

Dziewonsky, A., S. Bloch and M. Landisman (1969). A technique for the analysis of transient seismic signals, *Bull. Seism. Soc. Am.*, **59**, 427-444.

Farsi, M.N. (1996). *Identification des structures de Génie Civil à partir de leurs réponses vibratoires. Vulnérabilité du bâti existent*, Ph.D. These of Universite Joshep Fourier, Grenoble France, 189 pp

Guéguen, P. and P.-Y Bard (1998). Contamination of ground motion by building vibrations, *Proceedings of the Second International Symposium on the Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, 1-3 December, 407-412.

Kahan, M.M. (1996). *Approches stochastiques pour le calcul des ponts aux séismes*, , Ph.D. Thèse de l'Ecole National des Ponts et Chaussés, France, 172 pp.

Meli, R., E. Faccioli, D. Muria-Vila, R.Quass and R. Paolucci (1998). A study of site effects and seismic response of an instrumented building in Mexico City, *Journal of Eartquake Engrg*., **2**, 89-111.

Muria-Avila, D., L. Alcantara, L.E. Pérez-Rocha, R. Duran, A. Tena, M.A. Macias, R. Vazquez y S. Maldonado (1997). Edificios Instrumentados, *Ingenieria Civil*, **343**, 7-30. (In spanish).

Ordaz, M. and E. Faccioli (1994). Site response analysis in the Valley of Mexico: selection of input motion and extent of non-linear soil behaviour, *Earthquake Eng. Struct. Dynan*., **23**, 895-908.

Paolucci, R. (1993). Soil-structure interaction effects on an instrumented building in Mexico City, *European Earthquake Engineering*, **3**, 33-44.

Vidale, J.E. (1986). Complex Polarization Analysis of Particle Motion, *Bull. Seism. Soc. Am*., **76**, 1393-1405.

Wirgin, A. and P.-Y. Bard (1996). Effects of buildings on the duration and amplitude of ground motion in Mexico City, *Bull. Seism. Soc. Am*., **86**, 914-920.