0144

STRUCTURAL MODELS FOR TWO INSTRUMENTED BUILDINGS WITH SOIL STRUCTURE INTERACTION

Neftalí RODRÍGUEZ CUEVAS[1]

SUMMARY

In order to understand the dynamic response of two flat slab building under seismic action, structural models were developed to reproduce their motion under earthquake excitation. A methodology was developed in order to take into consideration soil structure interaction, an equivalent tridimensional reticular frame model was programmed. Digital accelerometers were fixed at the basement and at the roof, in order to obtain records of acceleration obtained during seismic motions. Those record were used to define time series at the basement to represent angular and linear displacements generated during the motion. The model developed was fed with that information in order to obtain the time series at two points at the roof, as well as Fourier transforms of the building response. Experimental evidence obtained sustains the idea of a better reproduction of the dynamic response, when five soil motion components are simultaneously fed into the model, to achieve a better reproduction of the measured response of the buildings under study.

INTRODUCTION

Two reinforced concrete buildings built during 1957 at Mexico City, on top of eleven sedimentary strata 20 meters deep (fig 1), were directly based on direct contact with the soil; they have sustained without damage all seismic events during the last 42 years. Both buildings have a flat system, with top panel and conical capitols bellow the slab, supported by continuous circular or square columns at different levels. For a better understanding of their earthquake response, two digital accelerometers were attached at the centre of the roof, and at a corner of their rectangular plan view. Two other accelerometers were attached at two point at the basement, at the same position of those at the roof. Another accelerometer was positioned on the free field, in order to get information on the motion on top of the soil. On the second building, two sites at the roof and two other sites at the basement were selected to record the motion of the building.

The accelerometers have three orthogonal sensors, to record the motion of each site and produce information on the horizontal translation and on the rotational motion generated at the base, during earthquakes generated at distant epicentres. Information on the material properties of the structure and on the topology of the buildings were available; its properties were verified by measurements and laboratory testing, in order to develop a model by digital programming, by which it may be possible to consider the influence of the base motion, on the roof motion and to define mechanical components at each member, and get information on the capacity they have to sustain the motion. The model should be able to consider soil structure interaction, with due possibility of handling the dynamic properties of the subsoil and the excitation produced at its base by earthquake components.

SUBSOIL PROFILE AND FOUNDATION TYPES

An upper crust of artificial top soil (0.6m deep) is supported by a clay (CH) stratum (4.10m); underneath, it was found a deep silt sand stratum (16 m in depth). A five meter stratum of sandy clay (CL), rather compact was detected, on top of sandy silt (ML), 4m deep, very compact. Under these strata, cemented material was found,

[1] *Institute of Engineering, National Autonomous University of Mexico, E-mail: nrc@cem.iingen.unam.mx*

with calcareous deposits that form the sedimentary rock underlying the valley of Mexico. This profile corresponds tot the transition zone between the lake deposits and the hilly part of the city.

To reproduce the above mentioned subsoil profile by analytical methods, three methods were used to define the dynamic shear modulus of an equivalent deposit: a) Mexico City code procedure (ref 1), b) the SHAKE program (ref 2) and c) Romo and Ovando's procedure (ref 3). The first two methods required the determination of dynamic properties of the subsoil, as shear wave velocity and soil period. Ambient vibration measurements and the review of Fourier transforms of seismic records at the neighbourhood were used to define the soil period, which value was 0.4 s; 21.8 m of the upper subsoil strata were used to define the equivalent spring stiffness of five springs at the base of the model.

The foundation of both buildings are different; the highest building has a compensated foundation, formed by a cellular basement, laying directly on top of the soil; lateral retaining walls 6m in depth form the perimeter walls of the foundation. The second building, with lower height, has a stiff concrete slab, 0.6 m in depth, bearing on the top soil, and supporting the building columns. Several parameters were involved to define the response of the buildings, and are listed below:

A dimensionless wave parameter, *VsTe/H*, being *Te* the first mode period, assuming that the base was built up to a rigid foundation; *Vs* is the shear wave velocity of the soil, and *H* is the height of the building

The slenderness ratio of the building, *H/R*, being *R*, the equivalent radius of the foundation

The ratio *fe/f* of frequencies, being *fe* the dominant frequency of excitation

The ratio between the foundation depth *D*, and the equivalent radius *R* of the foundation

The ratio between the depth of the of the subsoil stratum, *Hs*, and the equivalent radius *R*

The relative mass density of the building respect to the mass of the bearing soil; this ratio ranges between 0.1 and 0.2

The ratio between the foundation mass, *Mo*, to the building mass; its value ranges between 0.1 to 0.3

The percentage of critical damping of the superstructure, and that of the subsoil.

MATHEMATICAL MODEL USED TO REPRESENT SOIL.STRUCTURE INTERACTION.

Equivalent springs and dampers were used at the base of the model, to reproduce soil structure interaction (ref4). A tridimensional TESCOSE model of the superstructure (ref 5) was programmed and it is shown at figure 2; it takes into consideration five of the six springs at the base, and it was fed by time series obtained from seismic records, to generate two orthogonal horizontal displacements, and three orthogonal rotational motions at the base of the model. Computations were carried out, to evaluate the equivalent stiffness and damping at the springs; their values were found from static stiffness of rectangular foundation, by means of the expressions given by Dobry and Gazetas (ref 6) and Kaussel and Pais (ref 7); this approximation takes into consideration the depth of embedment of the higher building into the subsoil; both methods assume semi-infinite homogenous elastic spaces under the foundations. The dynamic stiffnesses were computed from graphs given at reference 6.

The critical percentage of damping was computed from the information contained on reference 8, which uses equivalent circular foundations and gives a procedure to generate dynamic properties. For the estimation of static stiffnesses of the springs, a dynamic shear modulus *G* was chosen equal to 6430 t/m2, based on experimental evidence and on the confining pressure effect, mentioned by Zeevaert, (ref 9); its rather high value indicates that the subsoil behaves as an over consolidated stiff deposit.

PARAMETERS CONSIDERED FOR THE DEVELOPMENT OF THE STRUCTURAL MODEL

The building superstructure, formed by reinforced concrete flat slabs, was analysed by the finite element method (fig 3), in search of a reticular framed equivalent structure, with beams and columns. The beams depth was taken equal to the distance between the top of the column and the centre line of the slab, and this criterion was kept throughout all the building. The equivalent horizontal width of the beams, was defined from the finite element analysis of the model, under lateral force action, with due consideration of membrane action developed at the middle surface of the slab.

Several studies (ref 10) had shown that the equivalent width is a function of the boundary conditions of the flat slab; the type of load; the columns stiffness, the aspect ration *l1/l2*, being *l1* and *l2* the orthogonal spans at the flat slab; the size of the columns relative to the spans *l1* and *l2* are also an important parameter. For the highest buildings under investigation, two equivalent widths of the beams were considered; in the long direction (X direction) an equivalent beam 0.65 m in depth and 0.88 m in width was selected, whereas in the short dimension (Y dimension) 0.65 m x 0.40 m beams were selected at the top stories, to reproduce the dynamic properties of the structure.

Young's modulus for the concrete was obtained from dynamic test carried out at cylindrical samples taken from the buildings, when tested under sinusoidal load, with a period equal to two seconds. Its average value, obtained from 43 tests, was equal to E_c = 190,000 kg/cm2. After a careful visual inspection, all the columns did not show visible structural damage, neither cracks on them, and because their high percentage of longitudinal reinforcement, and helicoidal lateral reinforcement, it was decided to take into considerations the steel bars area in the columns, for the computations carried out to define areas and moments of inertia of the columns. This consideration modified in four percent the vibration periods of the superstructure.

An infinite moment of inertia was assumed at portions of the beams near the column axis and the capitol edge; also at the top of the columns up to the slab centre line and their bottom, from the slab centre line to the top of the panel, infinite moment of inertia was assumed. An important parameter that controls the earthquake response of the model is the critical damping percentage; initially it was taken equal to five percent, but latter on, its value was modified to reproduce the dynamic response, taking into consideration the maximum amplitude of the roof displacement, the energy content in the Fourier spectra and the transfer functions.

STRUCTURAL MODELS DEVELOPED

Several analytical models were developed to understand the structural response of the buildings, as well as its capacity to stand strong seismic motions:

1. A finite element model to define the equivalent width of the beams used for an equivalent reticular model of the flat slab

2. SAP90 reticular model, with built in conditions at the base

3. TESCOSE tri dimensional reticular model, to consider five degrees of freedom at the base, and to excite the model with five time series at its base, to reproduce the motions generated by earthquakes

4. Pushover model, to estimate non linear behaviour of the model, and the ultimate capacity of the structure frames.

The first two models did follow the SAP90 method (ref 11) as a comparison basis, to define the dynamic characteristics of the third model. A TESCOSE tridimensional model, is based on a Hamiltonian approach (ref 5), and by means of a matrix scheme, a reticular model is generated, assuming that the superstructure is fixed to a rigid slab at its bottom, supported by equivalent springs and dampers. The model accepts five time series at its base, which represent the translation and rotational components of motion generated by earthquakes. It also considers damping between the building and the soil; it can use several values for damping reproduction, for the different vibration modes. The dynamic solution of the system is carried out by Jacobi´s method and uses Rayleigh's criteria for damping estimation.

The pushover model was based on DRAIND 2D program; by a simplified technique for non-linear analysis, based on incremental lateral forces, computed from load patterns that represent the inertia force distribution on the height of the building, when structural members undergo inelastic behaviour. The method gives an evaluation of the deformation demands at critical elements, and gives an estimate of the superstructure capacity, without soil structure interaction.

EARTHQUAKE RECORDS RETRIEVED FROM THE INSTRUMENTATION

Information on acceleration measurements at the higher building is available from the seismic events mentioned on Table I.

TABLE I

Event	Date	Time (GMT)	Epicentre Position Latitude	Epicentre Position Longitude	Depth (km)	Magnitude	Records Obtained
1	16/12/97	11:49	15.85 N	99.16 W	10	5.9	2 at the roof 2 at the basement
2	22/12/97	05:22	17.25 N	100.90 W	10	5.6	2 at the roof
3	03/02/98	03:02	15.74 N	96.44 W	23	6.3	2 at the roof 2 at the basement
4	20/04/98	22:59	18.54 N	101.20 W	--	5.4	2 at the roof 2 at the basement 1 at free field
5	15/06/99	20:42	18.20 N	97.47 W	92	6.7	2 at the roof 2 at the basement 1 at free field
6	21/06/99	17:43	18.08 N	101.74 W	43	5.8	2 at the roof 2 at the basement 1 at free field

All records have been fed at the base of the TESCOSE model and its response at the roof level have been computed. Fourier transforms at the base and the roof have been computed and used to compare measured and computed values. An statistical analysis of variance at each channel of the digital accelerometers is under development, to define the constants of a model that defines the maximum acceleration at each measuring point, as a function of epicentre position, distance to the epicentre, azimuth angle of the vector connecting the epicentre and the accelerometer, as well as the magnitude of the earthquake.

RESULTS FOUND FROM ANALYTICAL MODELS

On table II are shown dominant vibration periods, computed from the TESCOSE and SAP90 models, compared with those obtained from seismic records. First three modes are quite similar in shape and period, as those obtained from measurements; differences were observer for the second modes.

TABLE II

Vibration Mode		Period, in seconds	
	Experimental	TESCOSE	SAP90
First mode, Y direction	1.43	1.42	1.41
First mode, torsion	1.24	1.23	1.22
First mode, X direction	1.13	1.15	1.13
Second mode, Y direction	0.45	0.61	0.53
Second mode, torsion	0.58	0.48	0.46
Second mode, X direction	0.35	0.52	0.46

At figure 4 are shown the changes in absolute acceleration and relative displacement of the roof with respect to the basement, when event 4 was used as excitation, when damping is changed from three percent to seven percent, and compared to the results obtained from the model at five percent damping; the response changed between 20 to 70 percent. Negligible differences were found when rotational excitation at the base is added; differences were found in the Y direction. Computed acceleration found from the TESCOSE model at the central roof station, showed small initial acceleration, when only the translation motion was fed to the model. When rotational excitation was added at the base, computed record were quite similar to those obtained from measurements.

Due to the rectangular shape of the buildings, the influence of the rotational action in the longitudinal direction was minimal; in the orthogonal direction, rotational action was significant. Computed Fourier spectra were quite similar in both directions to those measured, as shown in figure 5. Damping percentage is highly significant in order to get a closer comparison. Transfer functions computed from measured time series recorded at free field and the central station at the basement, always showed a 20 percent decrease of acceleration at free field. The pushover model indicated that inelastic behaviour may appear when a 62 gals acceleration is generated at the bottom station, on either direction.

FINAL COMMENTS AND CONCLUSION

The investigation made it clear that it is possible to reproduce the building response, as far as time series, Fourier spectra and transfer function is concerned, when translation and rotational excitation were fed at the base of the model; analytical time series at top of the building were quite similar to those measured by the accelerometers. Acceleration measured at roof level are highly dependant on the building geometry. Information obtained from measurements indicated that the response due to translation excitation amounts 90 percent of the total response along the longitudinal X direction . The rotational excitation at the base contributed 35 percent on the response along the transverse Y direction. Rotational stiffness at the base in the X direction is four times bigger than that about the Y direction; this fact explains the above mentioned differences.

Results at one of the buildings made it clear that when the rotational effects at the base are considered in the excitation, it was possible to reproduce initial accelerations found in the time series. It was also clear that the over consolidation of the subsoil underneath the buildings, generated by the sustained load at top of the soil during 40 years, increased the dynamic shear modules, and increase the spring stiffness' at the base of the model, changing the dynamic response of the buildings. Age effects were also observed in an increase of Young's modulus of the concrete samples tested, increasing the dynamic properties of the buildings under investigation. Computations of a safety factor against overturning of the buildings, gave a very high value, close to 800, due to the great stiffness of the base against rotation.

A general conclusion can be drawn: The methodology presented in this paper, that combines experimental evidence and the development of tridimensional models able to include rotational component at their base, are useful for a better understanding of the seismic response of buildings with soil-structure interaction.

ACNOWLEDGMENT

The assistance of Rolando Reyes Greco, Luis Ibarra Olivas and Raul Maldonado Alaniz on the experimental measurements at the buildings is acknowledged.

REFERENCES

5. Arnal, L., Betancourt, M., "Nuevo Reglamento de Construcciones Para el Distrito Federal", Editorial Trillas, México D.F., (1996).

6. Shnabel, P., Lysman, J., Seed, H., "SHAKE A Computer Program for Earthquake Response of Horizontally Layered Sites", EERC, University of California at Berkeley, California, (1972).

7. Romo, M., "Clay Behaviour, Ground Response and Soil-Structure Interaction Studies in Mexico City", Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, pp 1-29, St Louis Missouri, (1995).

8. Hadjian, A., "Seismic Soil-Structure interaction; A Full Circle"., X Congreso Nacional de Ingeniería Sísmica, pp 1-16, Puerto Vallarta, México, (1993).

9. Rodríguez Cuevas, N., Sarcos Portillo, A., "Acción Sísmica Tridimensional de Estructuras con Interacción Suelo-Estructura", IX Congreso Nacional de Ingeniería Estructural, SMIE y UAZ. Zacatecas, Zacatecas, Vol. 1, pp 397-404, (1994).

10. Dobry, R., Gazetas, G., "Dynamic Response of Arbitrarily Shaped Foundations", ASCE Journal of Geotechnical Engineering, Vol. 112, pp 109-135, (1986).

11. Kaussel, E., Whitman, R., ERsabee, F., “The Spring method for Embedded Foundations”, Nuclear Engineering and Design, Vol. 48, pp 377-392, (1978).

12. Comisión Federal de Electricidad, “Manual de Diseño de Obras Civiles, Diseño por Sismo”, Instituto de Investigaciones Eléctricas, (1993).

13. Zeevaert, L., “Equipos para la Investigación de Parámetros Dinámicos del Suelo”, San Diego, California, (1990).

14. Hwang, S., Moehle, J., “An Experimental Study of Flat Plate Structures under Vertical and Lateral Loads”, UBC/EERS 93-03, University of California at Berkeley, (1993).

15. Wilson, E., Habibullah, A., “SAP90 Structural Analysis Program”, Computers and Structures Inc., (1992).

Figure 1 General view of the buildings

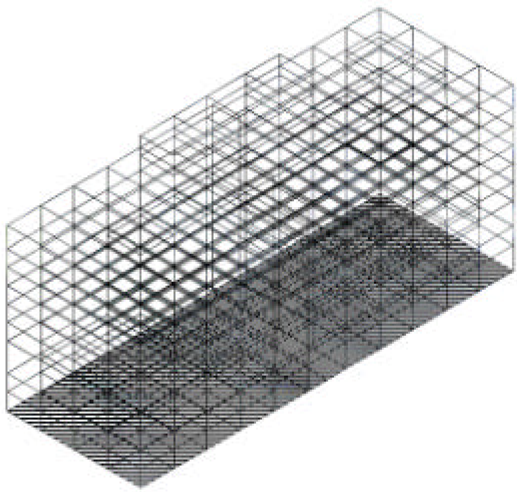


Figure 2 TESCOSE model for one building

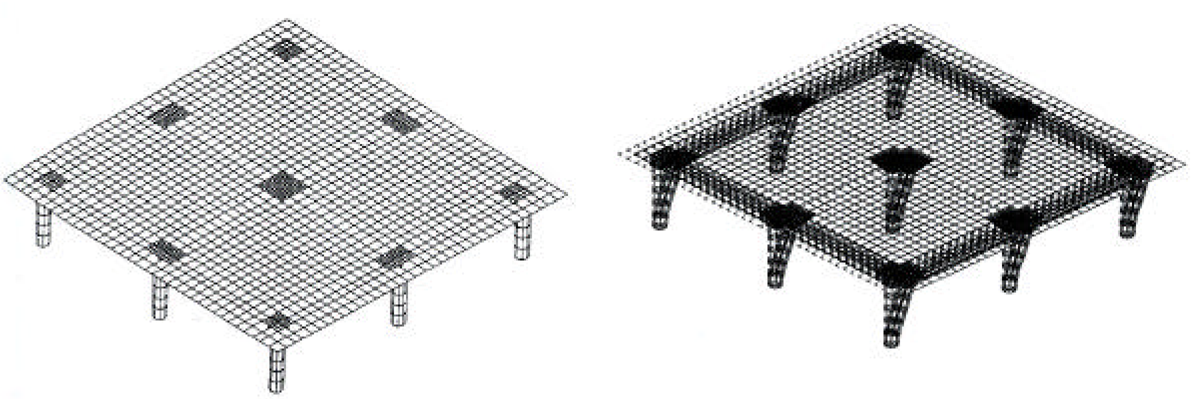


Figure 3 Finite element model of the flat slab system

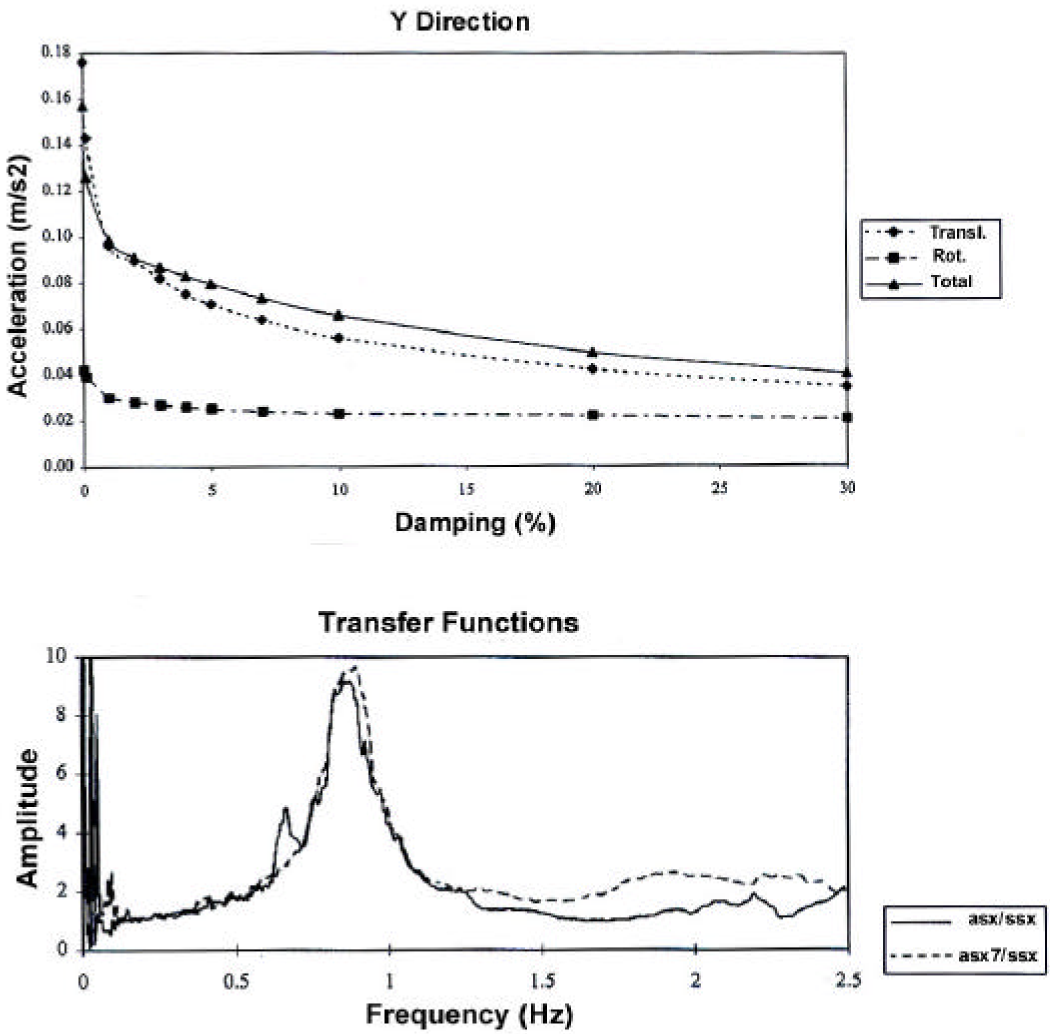
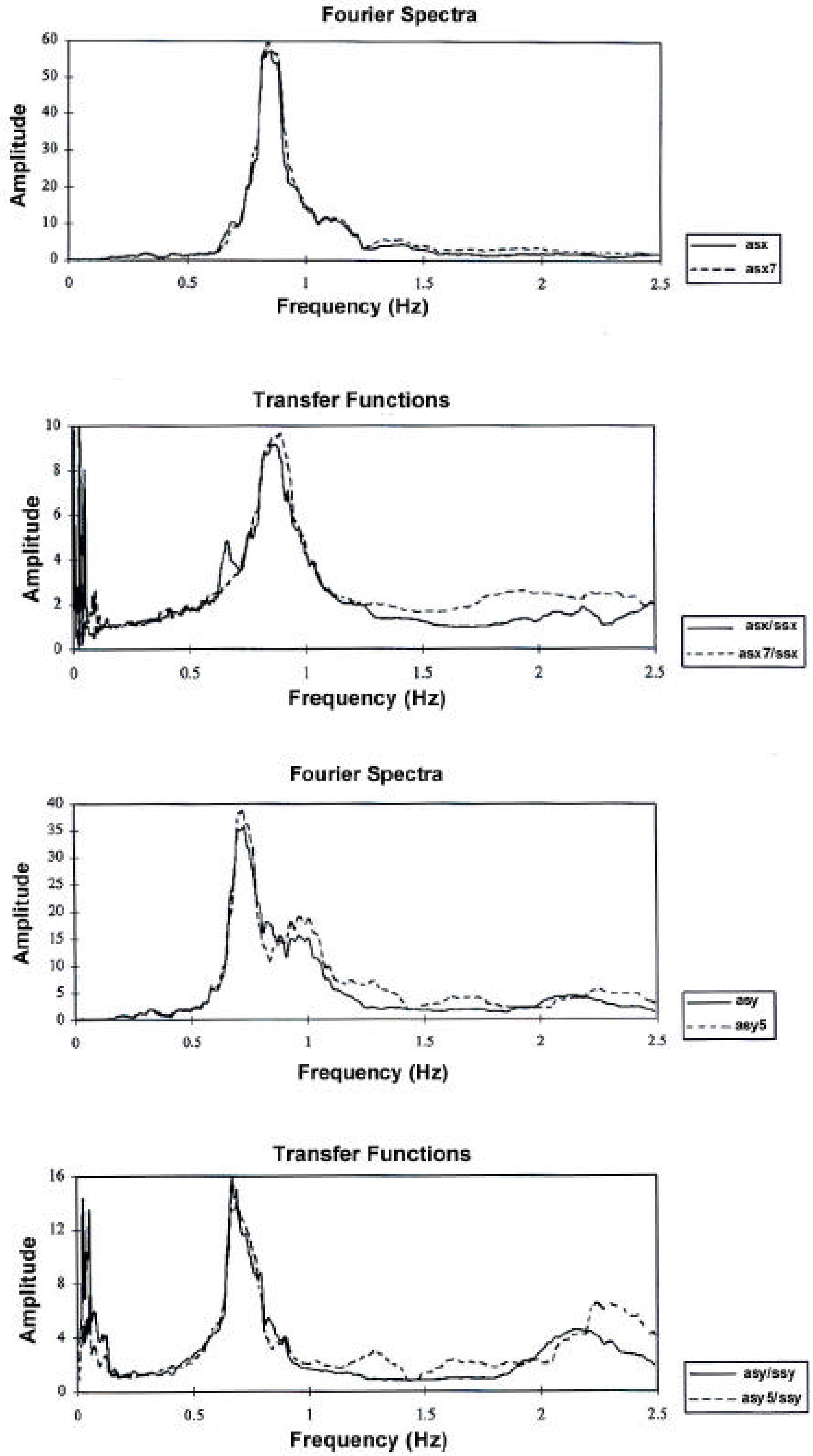


Figure 4 Effect of damping on roof acceleration



asx: Spectrum on roof, X direction, accelerometer	asy: Spectrum on roof, Y direction, accelerometer
asx7: Spectrum on roof, X direction, analytical model	asy5: Spectrum on roof, Y direction, analytical model
asx: Spectrum on basement, X direction, accelerometer	ssy: Spectrum on basement, Y direction, accelerometer

Figure 5 Computed and measured Fourier spectra of accelerations at the central station at roof level