Proceedings Third UJNR Workshop on Soil-Structure Interaction, March 29-30, 2004, Menlo Park, California, USA.

Evidence of Soil-Structure Interaction from Ambient Vibrations - Consequences on Design Spectra

François Dunand,[a,b] Pierre-Yves Bard,[a,c] Jean-Luc Chatelain,[a,d] and Philippe Guéguen [a,c]

INTRODUCTION

The dynamic response of a structural system to dynamic loading is strongly controlled by the amount of damping involved in each mode of vibration. At design stage, damping characteristics of building structures are usually assumed to some "standard", predetermined values, mainly because it is basically poorly known and very difficult to assess prior to construction. In most cases, damping is thus assumed to have the same value for each mode, and to be independent of the amplitude and frequency of the vibrations (Li 2002). But, as observed by (Jeary 1986) and (Lagomarsino 1993), among others, actual damping values are frequency and amplitude dependent.

In a first part, the Randomdec method is applied on a set of ambient vibration recordings performed in 26 different reinforced concrete buildings, all founded on thick alluvium, to derive their modal characteristics, including frequency and damping values for each identified mode. Damping values do exhibit a clear correlation with frequency and aspect ratio (i.e., ratio between the width of the building parallel to the excitation direction, and its height, which is the inverse of the slenderness ratio). Then, in a second part, this correlation is interpreted as due to soil-structure interaction (SSI) and the associated radiation damping, through a simple SSI model using impedance functions derived from cone models (Wolf 1994).

---

a) Laboratoire de Géophysique Interne et de Tectonophysique, France
b) Bureau Veritas, France
c) Laboratoire Central des Ponts et Chaussées, France
d) Institut de recherche pour le développement, France

EXPERIMENTAL ANALYSIS

In the framework of a preliminary seismic vulnerability analysis within the city of Grenoble (France), (Farsi 1996) performed an ambient vibration survey with broad band velocimeters in a set of 26 buildings ranging from 3 to 28 story, and having a structural system consisting in RC shear walls. As the Grenoble city is settled in a thick post-glacial deposit valley, the soil geology under all these buildings is about the same, with a S-wave velocity around 270 m/s at the surface, a Poisson's ratio larger than 0.35, and a mass density around 1.9 g/cm3, and a thickness exceeding 400 m everywhere (Cornou 2002).

The randomdec method (Caughey and Stumpf 1993, Ibrahim et al. 1998, Vandiver 1982) has been applied on the ambient vibration records obtained at the roof or upper story, and allowed to derive the frequency and damping for the fundamental modes in both transverse and longitudinal directions. The frequency values (f_0) range between 0.6 and 8 Hz, while the damping values (ξ_0) range from 0.7 % to 12 %. As displayed in Figures 1a and 1c, damping values exhibit some correlation with the frequency and, though to a lesser extent, with the aspect ratio *L*/*H* (inverse of the slenderness ratio *H/L*, *L* being the horizontal dimension of the building in the mode direction and *H* the height of the building). A log-linear least-square fit allows to derive the regression equation (1):

$$\ln(\xi_0) = -0.24 + 0.39 f_0 + 0.11 \frac{L}{H} \quad \text{with a standard error } \sigma \text{ of } 1.69 \tag{1}$$

A log-linear equation has been chosen because it better fits to the data than a linear regression. The error σ is defined as the *exp* of the standard deviation of $ln(\xi_{0i})$ to the *ln* of the regression, as follows:

$$\ln(\sigma) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln(\xi_{0i}) - \left(-0.24 + 0.39 f_{0i} + 0.11\frac{L_i}{H_i}\right)\right)^2} \tag{2}$$

A similar result was obtained from same kind of survey in the city of Nice, where sediments are thinner (maximum thickness is about 100 m), and slightly less stiff (*Vs* between 200 and 250 m/s at the surface).

The damping ratio (ξ_0) is indeed reflecting the energy loss of the structure over one vibration cycle. This loss of energy is generally assumed in dynamic analysis to be mainly due to the structural damping, which is generally not considered, at least in every day's practice and in the vast majority of construction codes, as frequency dependent. However, another origin for the energy loss during the vibration of the structure comes from the back-radiation of waves into the soil, associated to soil-structure interaction (Guéguen 2000). This phenomenon is frequency dependent and at least partly explain our observations: we thus checked this hypothesis with a simple numerical model.

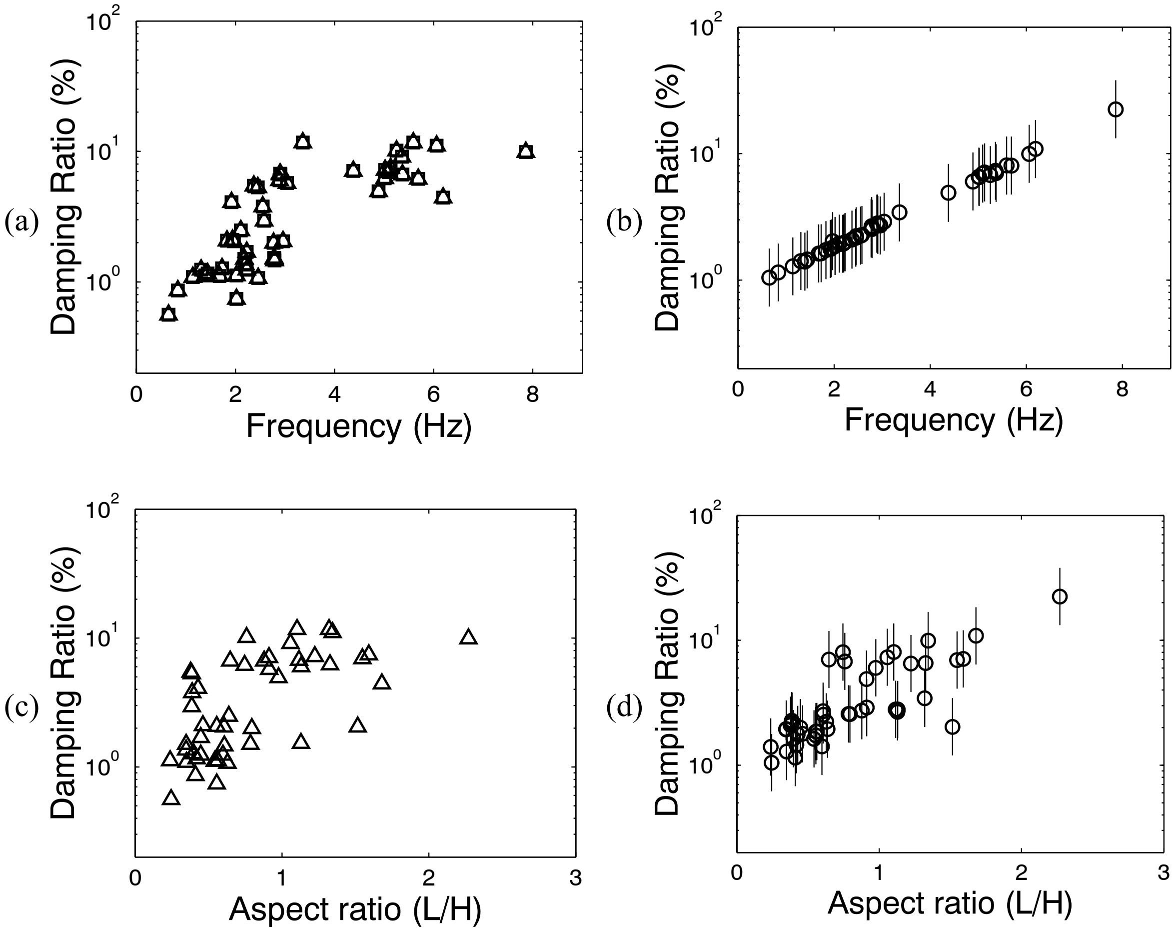

Figure 1. Observations from Ambient vibrations data (Grenoble data set). Damping (ξ_0) versus frequency (f_0) (a) for the Grenoble data set, (b) following the regression of equation (1), which depend on frequency (f_0) and aspect ratio (L/H) of buildings. The vertical lines are the standard error (σ). Damping (ξ_0) versus aspect ratio (L/H) (c) for the Grenoble data set, (d) following the regression of equation (1), which depend on frequency (f_0) and aspect ratio (L/H) of buildings. The vertical lines are the standard error (σ).

MODELLING

We used a single degree of freedom (SDOF) structural model accounting for soil structure interaction (and radiation damping) through impedance functions estimated with the cone model proposed by (Wolf 1994). This model, depicted in Figure 2, allows to derive the impulse response of the whole [soil+structure] system, and thus their fundamental frequency and damping values through the logarithmic decrement method (Clough and Penzien 1993). This simple model has been applied to the set of Grenoble buildings taking into account their actual size (height *H*, horizontal dimension *L*), and the soil mechanical properties. Figure 3 shows that a rather satisfactory agreement (standard error (σ) of 1.84) exists between the model results and the observations: in particular, the computed damping exhibits a clear trend to increase with frequency (corresponding to a more efficient soil-structure interaction and therefore higher radiative damping, for stiffer buildings), and also some trend to increase with the aspect ratio (although the scatter is large). We therefore infer that one possible explanation for this frequency dependent damping is the soil-structure interaction.

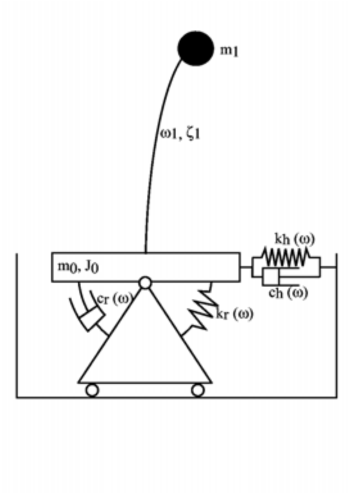

Figure 2. The 1 DOF oscillator with soil-structure interaction.

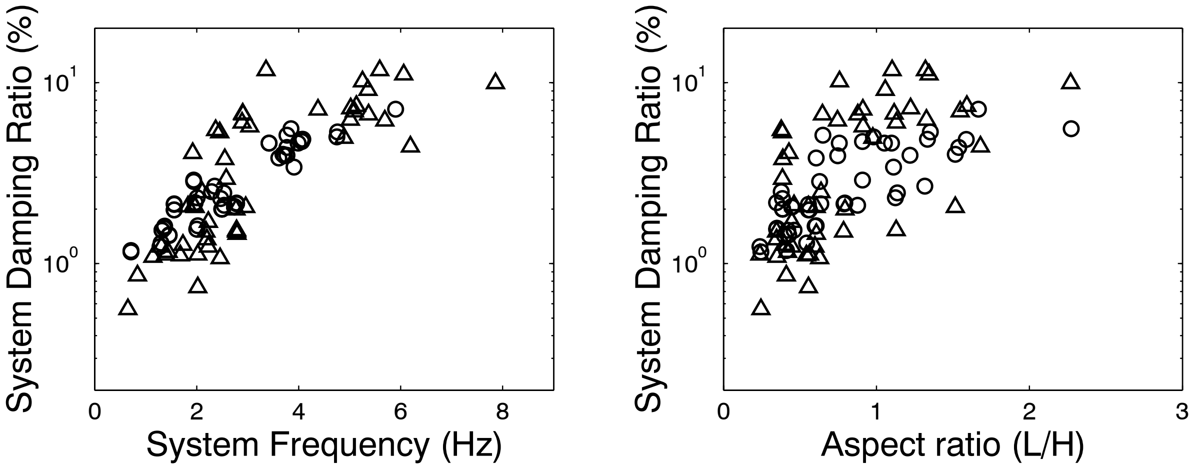

Figure 3. Comparison of observed data and numerical simulation. Triangles: observed data, circles; numerical simulation.

CONSEQUENCES

Obviously, the damping values derived under ambient vibrations cannot be extrapolated directly to the damping values under strong shaking: a lot of non-linear material degradation phenomena occur in both the structure and the soil, which should most generally increase the damping values of the whole [soil+structure] system at large strains. However, one may consider that the frequency values derived from ambient vibration recordings are an upper bound for the actual frequency values under stronger shaking, while, simultaneously, the ambient vibration damping values are a lower bound for the actual damping for strong motion.

Therefore, as the usual design practice is to consider one "standard" damping value, generally associated only with the construction material (RC, steel, masonry, wood, ...) and/or the structural system (frame, shear wall, ...), and never with the building height and frequency, we propose that the damping is most generally underestimated for stiff structures resting on soft or medium-soft soils. Therefore, their design is probably conservative, at least more conservative than the design of taller buildings having lower fundamental frequencies. As an example, Figure 4 is showing the design spectra corrected for the minimum damping value (as measured from ambient vibration recordings), for the Grenoble area and thick soils with medium stiffness (site category S3): the design spectra is modified only beyond 4 Hz, since, according to equation (1), the damping value exceeds 4 % (the standard recommended value for RC structures) for frequencies larger than 4 Hz. One may see that, at 10 Hz, the response spectrum ordinate corresponding to the actual damping value is 56 % less than the design spectrum.

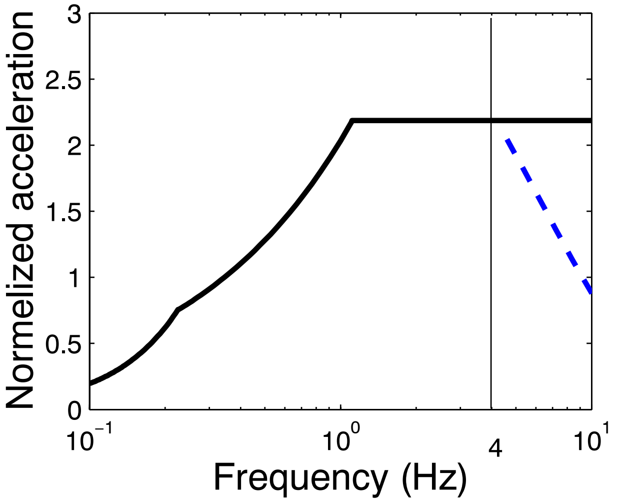

Figure 4. Consequences of the soil structure interaction on the design spectra. The black line represent the French design spectra for a S3 site category (Grenoble) and a damping ratio of 4 % (reinforced concrete structures). The dotted line represent the modification of the French design spectra by using the proposed damping correction of equation (1) if the corrected damping is greater than 4 %.

CONCLUSION

Estimation of 26 RC buildings modal frequencies and damping ratio from ambient vibration recordings shows that their damping ratio is increasing with the structure modal frequency, to the contrary of what is usually used in seismic codes. This dependency can be explained by soil-structure interaction with radiation damping due to the back-radiation of waves in the soil by structures. As our observations comes from ambient vibrations, the damping values are a lower bound for the actual damping for strong motion. By introducing our observed damping dependence to frequency in the French code it is shown that seismic forces are overestimated in the code for high frequency structures (tall structures, $f_0 > 4$ Hz) at least for those that are founded on soft soil.

REFERENCES

T.K. Caughey and H.J. Stumpf, 1993. Transient response of a dynamic system under random excitation. *Journal of Applied Mechanics*, pages 563–566, 1961.

R.W. Clough and J. Penzien, 1993. *Dynamics of structures*. McGraw-Hill,.

C. Cornou, 2002. Traitement d'antenne et imagerie sismique dans l'agglomération grenobloise (Alpes françaises) : implication pour les effets de site. PhD thesis, University of Grenoble, France.

M.N. Farsi, 1996. Identification des structures de génie civil à partir de leurs réponses vibratoires. PhD thesis, University of Grenoble, France.

P. Guéguen, 2000. Interaction sismique entre le sol et le bâti : de l'interaction Sol-Structure à l'Interaction Site-Ville. PhD thesis, University of Grenoble, France.

S.R. Ibrahim, J.C. Asmussen, and R. Brincker, 1998. Vector triggering random decrement for high identification accuracy. *Journal of Vibration and Acoustics*, 120: 970–975.

A.P. Jeary, 1986. Damping in tall buildings - a mechanism and a predictor. *Earthquake Engineering and Structural Dynamics*, 14: 733–750.

S. Lagomarsino, 1993. Forecast models for damping and vibration periods of buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 59: 131–157.

Q.S. Li, K. Yang, N. Zhang, C.K. Wong, and A.P. Jeary, 2003. Field measurments of amplitude-dependant damping in a 79-storey tall building and its effects on the structural dynamic responses. *The Structural Design of Tall Buildings*, 11: 129–153.

J.K. Vandiver, A.B. Dunwoody, R.B. Campbell, and M.F. Cook, 1982. A mathematical basis for the random decrement vibration signature analysis technique. *Journal of Mechanical Design*, 104: 307–313.

J.P. Wolf, 1994. *Foundation vibration analysis using simple physical models*. PTR Prentice Hall, Englewood Cliff, USA.