Analysis of the local seismic response designing a viaduct: a study made in Teramo (Italy)

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ABSTRACT: here are introduced the results of a series of numerical analyses relevant to the local seismic response carried out for the design of a viaduct. On account of the complexity of the stratigraphy, viscoelastic models 1D and 2D have been used. They have required the solution of complex equations implemented in the source code DISCRETE-SOIL. The result, compared with the dynamic analysis of the viaduct, have induced the designers to make structural changes with the intention of avoiding the onset of the resonance phenomena. In the end the analysis have pointed out, once again, the influence of the stratigraphic irregularities and also the acceleration spectrum pertinent to the earthquake of project on the local seismic response.

1 Introduction

The damages observed in the seismic sequence Umbria-Marche (Italy) in 1997, have further pointed out the function the principles and methods of Geotechnics Engineering, in particular of the Dynamics of soils, have in the interpretation of the effects caused by the earthquake and in the in the subsequent transfer of the acquired knowledge in the planning and prescriptive choises of post-earthquake.

The knowledge of the features of the soil vibratory movement on the surface after a seismic event is of fundamental importance in order to design framework able to be resistant to seismic events. As we know, such features, in absence of handworks (conditions of free-field) are the result of a group of very complex phenomena which can be grouped in three fundamental categories: source mechanism; propagation of seismic waves from the source of the site; local seismic response. The study of the generation and propagation processes brings to the definition of an entry seismic movement to the site, also defined as “entry signal”. The set of the changes produced in the entry seismic movement by the particular features of the site is the problem of the “local seismic response”. With such definition we mean the set of changes, as regards wideness, duration and content in frequency, that a seismic movement $u_B(t)$, relevant to a basic rocky formation (B) placed at a certain depth underground, undergoes crossing the overlooking terrane strata up to the surface (S), where it assumes the value $u_S(t)$. Since such changes are the result of the interaction between the seismic movement and the dynamic properties of the crossed soils, they can be gathered in a “transfer function” so that the vibratory movement on the surface can be represented in a schematic way by the following linear function (Lanzo & Silvestri, 1999, modified):

$$F_S(f) = H(f) \cdot F_B(t) \quad (1)$$

where $F_B(t)$ and $F_S(t)$ respectively represent the entry signal to the bedrock and the exit signal to the soil, while H(f) indicates the transfer function. In other words, working in the domain of frequencies, the local seismic response can be defined in a simplistic way as the following product: entry signal x transfer function = exit signal.

The existence of numerous measures of vibratory movement both on the surface and in depth, taken in different earthquakes all over the world, have allowed to consider in which way the factor of Dynamic Amplification Factor (expression of the "transfer function") can reach very elevated values such ad to recommend, in case of a design of a viaduct founded on recent warps (figure 1 and 2), the study of the dynamic properties of the site and the analysis of the local seismic response.

Figure 1. Territorial scheme

After considering the stratigraphic complexity, with the interdigitation of compressible silts and gravels in sandy matrix, as well as the strategic importance of the work in project, the dynamic analysis of the site has been carried out using linear viscoelastic models like monodimensional and bidimensional mass+spring+damper, on that occasion deliberately implemented in the source code DISCRETE-SOIL developed by GEO&GEO® Instruments per test in the field of Geotechnics. The mathematic formulation of the problem has been completed using, as entry signal (earthquake of project), the North component of the seism dated 26^{th} September 1997, h. 11.40,, with epicentre Colfiorito (Italy) and applying the spectral analysis both to it and to the exit signal, working therefore in the dominion of frequencies.

The results have pointed out that:

1) The fundamental frequency of the viaduct calculated through modal analysis, is close to the frequency of the first way of vibration of the foundation soils;
2) The earthquake of project strongly binds the result, since they depend on the spectral content multiplied by the transfer function;
3) The spectral content of the Dynamic Amplification Factor remarkably shows traces of the adopted numerical model as well as the investigation level of the geometry and stratigraphy of the subsurface and of the relative dynamic parameters.

In order to get round the first problem some structural changes have been made, such as to increase the mass and to move the period of resonance of the viaduct.

2 Geotechnical model of the subsurface

The viaduct in question, 9 m in width and 50 m in lenght, indispensable for the crossing of the river Salinello, has been planned as a load-bearing structure with prestressed reinforced concrete beams and a collaborating slab-laid in work, which is based on the piers founded in bed (figure 2). The geological surveys have shown the presence of recent soft alluvional soils (Olocene), of about 12 m almost constant thick, which are sandy gravels and compressible silts. People think their genesis has been caused by widespread anthropic protohistoric intervantations and modification of the territory (Gentili & Pambianchi, 1987). The bedrock is made of Pleistocene silt and clays, overconsolidated and fissured (structurally complex clays) whose mechanical features are known in literature (Sciarra, 1988).

The stratigraphic features and the geotechnical properties of the soils have sprung from the execution of continous core soundings, supplemented with static penetrometric test (CPT), dynamic penetrometric tests (DPSH), geophysical prospecting such as that of the refractional seismic type and Down-Hole (DH) and through laboratory tests.

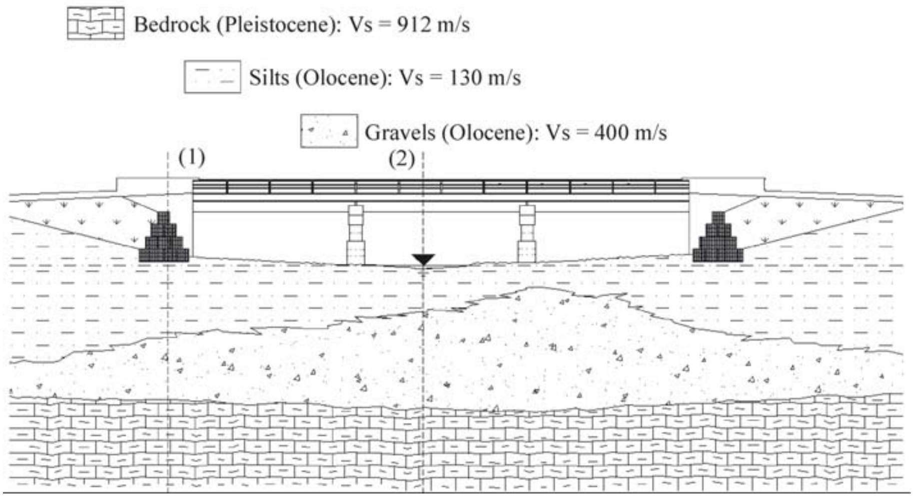

Figura 2. Stratigraphic section

Particular attention has been given in executing some seismic prospecting, since they themselves have been used for the reconstruction of the velocity profile of the subsurface as regard the propagation of cutoff waves, polarized on the horizontal plain (V_{SH}) and for the determination of the damping report (D). To calculate this last parameter has been used a geometry with double triaxle geophone of high sensitivity (natural frequency of 4 Hz), in order to register a couple of values for every energization. Manipulating statistically all the registered couples and applying a law of the signal decay, it has been possible to calculate an attenuation coefficient of the signal (α):

$$\alpha = \frac{\ln\left(A_1 \cdot R_1 / A_2 \cdot R_2\right)}{\left(R_2 - R_1\right)} \qquad (2)$$

where A_1 and A_2 represent the widness signal and R_1 ed R_2 the distance of the geophones from the source of impulses. Since α represents both the “geometrical camping” of a seismic wave and the “material camping” for the proper method of seismology, it has been subsequently used as representative of the camping report. All the geotechnical parameters, both dynamic and mechanical, are ultimately summarized in tables 1 and 2.

Table 1. Principal dynamic parameters

Soils	V_P [m/s]	V_{SH} [m/s]	E_D [MPa]	G_D [MPa]	D [%]
Silts	225	130	550	250	2.16
Gravels	750	400	6800	3100	1.12
Bedrock	1489	912	24000	18000	-

Table 2. Principal mechanical parameters

Soils	γ [kN/m^3]	c' [MPa]	ϕ' [°]	E' [kPa]	s_u [kPa]
Silts	19.4	3	24.5	1020	25÷43
Gravels	18.2	0	34	12000	-
Bedrock	21.6	20÷200	27	64000	> 250

The values of the dynamic modules (E_D e G_D), which represent the slope of the initial part of the stress-deformations curve (in the field of very small deformation) have been calculated through the following expressions, starting from the propagation velocity of the compressional (P) and cutoff (S_H) waves:

$$E_D = \left(V_{SH}^2 \cdot \gamma\right) \cdot \left[\left(3V_P^2 - 4V_{SH}^2\right) / \left(V_P^2 - V_{SH}^2\right)\right] \quad (3)$$

$$G_D = V_{SH}^2 \cdot \gamma \quad (4)$$

3 Numerical analyses

The analyses of the local seismic response have been carried out through two different types of formulation of the problem (1-D e 2-D) according to the articulation of the contact between the silts and gravels of the subsurface. As a matter of fact, as for a homogeneous stratum of H thickness the period relative to the first way of vibration is given by the following expression (Okamoto, 1973):

$$T \cong \frac{4 \cdot T}{V_{SH}} \quad (5)$$

The application of the (5) to two different sections (figure 2) requires that the resonance of the system varies from 4,58 Hz (section 1) to 6,52 Hz (section 2) according to the mean velocity which varies from 220 m/s in the first case to 315 m/s in the second case.
Therefore it is necessary to get more detailed information since the results greatly affect the aseismic design of the viaduct in question.

3.1 Model 1-D

For the monodimensional analysis the method of response of a simple harmonic oscillator (Muzzi F., 1990; Lanzo & Silvestri, 1999) has been adopted, arriving at the following set of equation:

$$FAD = \left[\cos^2\theta_1 \sin^2\theta_2 + 2\left(\frac{\gamma_2 V_{21}}{\gamma_3 V_3}\frac{\gamma_1 V_1}{\gamma_3 V_3} - \frac{\gamma_1 V_1}{\gamma_2 V_2}\right)\sin\theta_1 \cos\theta_2 \sin\theta_1 \cos\theta_2 + \frac{\gamma_1^2 V_1^2}{\gamma_2^2 V_2^2}\sin^2\theta_1 \sin^2\theta_2 + \right.$$

$$+\frac{\gamma_2^2 V_2^2}{\gamma_3^2 V_3^2}\cos^2\theta_1 \sin^2\theta_2 + \frac{\gamma_1^2 V_1^2}{\gamma_3^2 V_3^2}\sin^2\theta_1 \cos^2\theta_2 \Bigg]^{-\frac{1}{2}} \tag{6}$$

$$Y = -0.3568 \cdot \ln(X) + 1.2986 \tag{7}$$

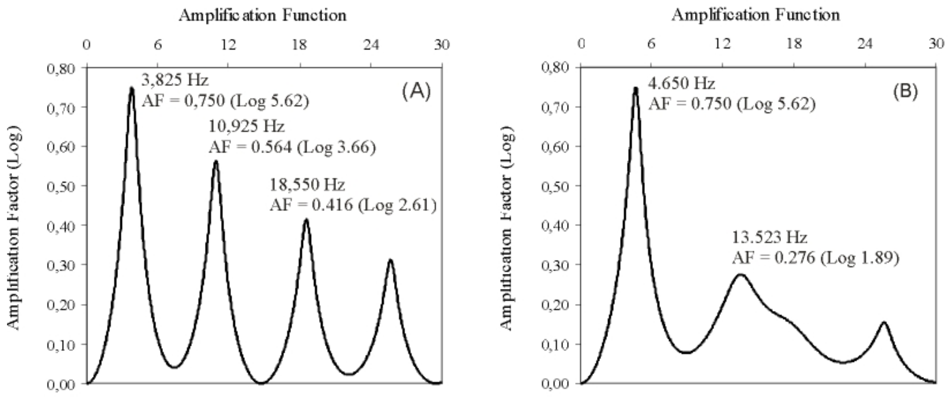

Figure 3. Spectral content of the DAF: A) model 1-D; B) model 2-D.

The equation (6) represent the solution of a system characterized by two viscoelastic strata on a bedrock capable of being deformed (Carrara et al. 1999), while the Eq. (7) a law of relaxation (or decay) derived from experimental data, where X and Y respectively reveal the frequency and the report of damping. Therefore the adopted camping is function of the content in frequency. The fundamental advantage in operating in the domain of frequency consists of being able to express the amplification phenomena through the operation of "convolution", or of a product frequency by frequency (Lanzo & Silvestri, 1999) between the Fourier spectrum of the movement to the soil.

3.2 Model 2-D

The adoption of more complex models has required some changes essential to the source code DISCRETE-SOIL, in order to adapt the numerical solutions developed with the method with the finite elements. In the specific case it has been used a model of concentrated masses linked among each other through springs and viscous dampings, able to simulate a system of "n" degrees of freedom. The parameters which characterize such model are the shims (h_i), the masses (m_i), the rigidities of the spring (k_i) and the viscous damping coefficients (c_i), where m_i, k_i and c_i depend on the density (ρ_i), cutoff modules (G_o) and on the viscous coefficients (η_i). Combining among them such parameters we get a system of linear differential equations, such as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = F(t) \tag{8}$$

where U represents the displacement of the masses and F(t) the "forcing" in the time domain. The local seismic response is given by solving the equation (8) of the movement, as we know the seismic excitation in correspondence with the bedrock. The matrix of masses [M] is diagonal:

$$[M]=\begin{bmatrix} m_1 & & & \\ & m_2 & & \\ & & ... & \\ & & & m_{n+1} \end{bmatrix} \quad (9)$$

while the matrixes of the dampings [C] and the rigidities [K] are banded:

$$[C]=\begin{bmatrix} c_1 & -c_1 & & \\ -c_1 & c_1+c_2 & -c_2 & \\ & & ... & \\ & & -c_n & c_n+c_{n+1} \end{bmatrix} \quad (10)$$

$$[K]=\begin{bmatrix} k_1 & -k_1 & & \\ -k_1 & k_1+k_2 & -k_2 & \\ & & ... & \\ & & -k_n & k_n \end{bmatrix} \quad (11)$$

the resolution of the system has been reached applying the method of the finite difference to the equation (8), when we consider that the state of the system is known at time t and when we calculate the displacements at the time t+Δt (Hutton D.V., 2004). In other words we have to solve the equation:

$$[M]\left\{\ddot{u}(t+\Delta t)\right\}+[C]\left\{\dot{u}(t+\Delta t)\right\}+[K]\{u\}(t+\Delta t)=F(t+\Delta t) \quad (12)$$

for every $\{u(t+\Delta t)\}$. Among the various techniques to the existent finite differences for this specific case the method of Newmark has been used, also defined as the method of constant acceleration. In it the acceleration must remain constant and equal to a mean value during the integration pass Δt. Referring to specialistic texts for a complete treatment of the Newmark method, from the equation (12) we have:

$$\frac{4}{\Delta t^2}[M]\{u(t+\Delta t)\}+\frac{2}{\Delta t}[C]\{u(t+\Delta t)\}+[K]\{u(t+\Delta t)\}=\{F(t+\Delta t)\}+[M]\cdot\left(\left\{\ddot{u}(t)\right\}+\frac{4}{\Delta t^2}\left\{\dot{u}(t)\right\}+\frac{4}{\Delta t^2}\{u(t)\}\right)+$$

$$+[C]\cdot\left(\left\{\dot{u}(t)\right\}+\frac{2}{\Delta t}\{u(t)\}\right) \quad (13)$$

The Eq. (13), even if at first appears complex, it actually correspond to an algebraic system, where the matrixes of masses, rigidities and camping are well know, which is unknown in the camping u at the time t+Δt. All that, as for paces Δt of constant integration, the matrixes have to be calculated once. The DAF is at last defined as report among the entry spectra to the bedrock and the spectra to the soil.

3.3 Seismic input

As an entry datum to the bedrock (earthquake project – Figure 4) it has been used the North component of the seism occurred on 26th September 1997, h.11.40, with epicentre Colfiorito (Italy) of 5,8 magnitudo.

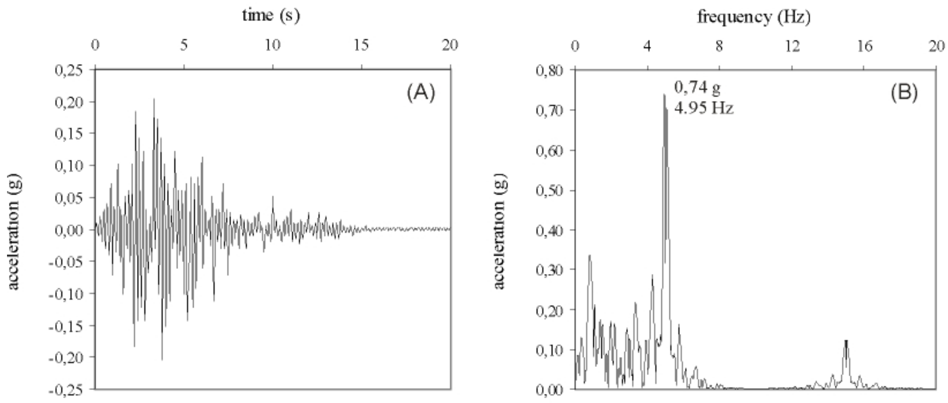

Figure 4. Earthquake project: A) in the domain of time; B) in the domain of frequency (FFT).

The passage from the time history of the acceleration regist or calculated according to the spectral content and vice versa, which was necessary to operate in the field of the frequencies domain, in the case of monodimensional model, or in order carry out the spectral analysis for the model 2-D, has required the implementation of the DISCRETE-SOIL code of effective algorithms which execute quickly direct Fourier transform (Fast Fourier Trasformation) and inverse (IFFT).

4 Discussion of the results and conlcusions

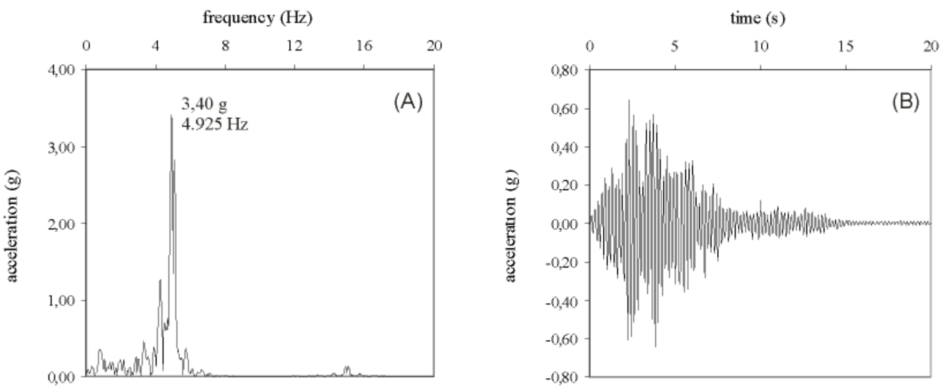

Figure 5. Earthquake to the soil: A) in the frequencies domain; B) in the time domain (IFFT).

This analysis has shown the importance of the in-depth knowledge of the local stratigraphy which, together with the dynamic feature of the soils, greatly influences the calculation of the Dynamic Amplificator Factor (DAF). In the Figure 3, in semilogarithmic scale (with the intention to exalt the minor frequencies) in evident the discrepancy between the result of the monodimensional model and the dibimensional model, in which the only common factor is the first way of vibration (Log 5,62 = 0,75). all this happens since the 3A graphic ie relevant to a single vertical section (section 2 – Figure 2), highlighting how it does not represent the behaviour of the whole section. After detailing the entire structure of the subsurface, as for the case of mode 2-D (Figure 3B), we have very different results both in the form of DAF and in the substance.

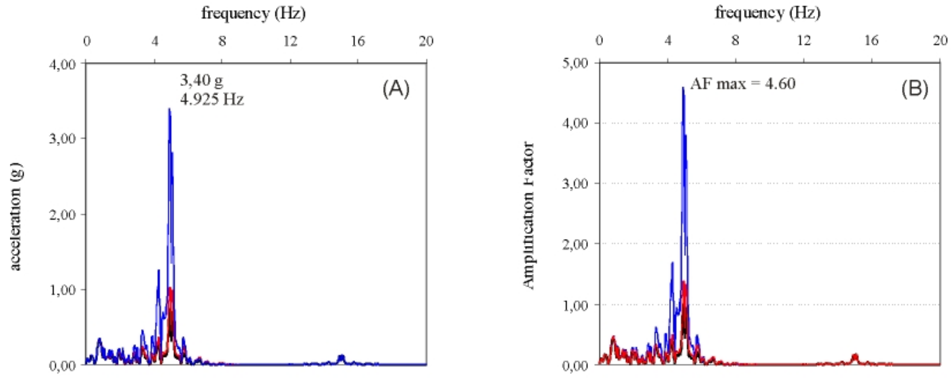

Figure 6: A) Comparison among the acceleration spectra; B) normalized spectra of acceleration.

Another element which characterizes the analysis in the spectral content of the earthquake of project (Figure 4), which, for this specific case, has given a peak frequency of 5,05 Hz, close to that of the analysed section (4,65 Hz – Figure 3B). All that has involved the onset of resonance phenomena (Figure 5) as better highlighted in Figure 6A, while Figure 6B, where the response spectra have been normalized as regards the extreme entry acceleration to the system, further points out such effect. In these figures the response spectra to the bedrock compared (low) to the silts-gravels contact (centre) and to the soil (high). In Figure 6B it is clear that the highest Amplification Factor, calculated for the entire analysed section, compared with the extreme acceleration to the bedrock (defined by the abscissa axis 1,00), is equal to 4,06.
Finally, as the structural calculations of the viaduct, made through modal analysis, have pointed out a resonance frequency of 5,05 Hz and, if we consider the low values of the damping report of the soils, modifications to the masses, such as to move the first way of vibration of the work and to avoid the onset of resonance phenomena, have been carried out.

5 Reference

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