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DETAILED MODELLING OF STRONG GROUND MOTION IN TRIESTE

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Abstract

Trieste has been included in category IV by the new Italian seismic code. This corresponds to a horizontal acceleration of 0.05g for the anchoring of the elastic response spectrum.

A detailed modelling of the ground motion in Trieste has been done for some scenario earthquakes, compatible with the seismotectonic regime of the region. Three-component synthetic seismograms (displacements, velocities and accelerations) have been analyzed to obtain significant parameters of engineering interest. The definition of the seismic input, derived from a comprehensive set of seismograms analyzed in the time and frequency domains, represents a powerful and convenient tool for seismic microzoning.

In the specific case of Palazzo Carciotti, depending on the azimuth of the incoming wavefield, an increase of one degree in intensity may be expected due to different amplification patterns, while a nice stability can be seen in the periods corresponding to the peak values, with amplifications around 1 and 2 Hz.

For Palazzo Carciotti, the most dangerous scenario considered, for an event of M=6.5 at an epicentral distance of 21 km, modelled taking into account source finiteness and directivity, leads to a peak ground acceleration value of 0.2 g.

The seismic code, being based on a probabilistic approach, can be considered representative of the average seismic shaking for the province of Trieste, and can slightly underestimate the seismic input due the seismogenic potential (obtained from the historical seismicity and seismotectonics). Furthermore, relevant local site effects are mostly neglected.

Both modelling and observations show that site conditions in the centre of Trieste can amplify the ground motion at the bedrock by a factor of five, in the frequency range of engineering interest. We may therefore expect macroseismic intensities as high as IX (MCS) corresponding to VIII (MSK). Spectral amplifications obtained for the considered scenario earthquakes are strongly event-dependent. Therefore the amplification estimate obtained at a site analyzing the recording of a single earthquake cannot be generalized. The importance of modelling is evident, as it allows to consider amplification scenarios for historical and future events for which there are no recordings available.
Introduction

According to the new seismic code, Trieste has been included in category IV, that corresponds to a horizontal acceleration of 0.05g for the anchoring of the elastic response spectrum. To verify that the value can be used also in the ancient part of the city, where soft surficial sediments of poor geotechnical characteristics are present, a detailed ground motion modelling in Trieste has been done for some scenario earthquakes, chosen according to the seismotectonic regime of the area. Broadband synthetic seismograms have been computed in a laterally heterogeneous anelastic medium with the hybrid approach (Fäh et al., 1993), schematized in Figure 1.

The modal part (Panza, 1985; Florsch et al., 1991) is used to model wave propagation from the source to the beginning of the local profile of interest. It is based on the computation of eigenvalues (phase velocity) and eigenfunctions associated with Rayleigh (P-SV motion) and Love (SH motion) waves for a laterally homogeneous medium (layered anelastic halfspace).

The phase velocity-frequency space is efficiently explored (Panza et al., 2001) also at high frequencies, where nearby modes get extremely close to one another. Anelasticity is taken into account considering, for each layer, a frequency-independent Q value, expressed in terms of attenuation in space and time. Synthetic seismograms can be computed with three significant digits if the condition kr>10 is satisfied, where k is the wavenumber and r is the epicentral distance in km (Panza et al., 1973). A simplified source model can be defined using the spectral scaling laws of Gusev (1983), as reported in Aki (1987), which are appropriate for parametric tests aimed at the definition of the ground motion at the bedrock. In this way, using equations like (2), it is possible to quickly test the influence on ground motion of the parameters that define the focal mechanism of the source.

In the hybrid approach, the seismograms obtained at the bedrock with the modal summation are the input for propagating the wavefield along the selected local profiles, where the finite difference technique allows to deal with complicated lateral heterogeneities, and therefore to adequately estimate site effects.

Here, using the specific knowledge about geology and geotechnical properties described in the cartographic material available for the Trieste area, three profiles (local 2D sections) and several ground shaking scenarios have been considered, varying the source position and magnitude. Three variations of bedrock model have been taken into account for propagating the wavefield from the source to the beginning of the 2D sections. Those models have also been used for the computation of the reference signals (seismograms at the bedrock), to compare with the results of the detailed modeling for the definition of the site effects, described by the ratios of the response spectra (2D/bedrock).

The three-component synthetic seismograms, computed in the domains of displacement, velocity and accelerations, have been processed to extract some parameters significant from the engineering point of view. Seismic input definition is obtained from a comprehensive set of time series and frequency-domain information, corresponding to several ground shaking scenarios, and represent a powerful yet economic tool for seismic microzoning.

Choice of the reference bedrock model and of the seismic sources

The first seismic input estimates have been obtained considering three different
bedrock models (Figure 2): dinarb, obtained starting from the work by Mao et al. (1994); dinarb, defined after Chimera (2001); dinarts, obtained modifying the velocities of the seismic waves (P and S) of the uppermost layers of dinarb model, using the values representative of the limestones around Trieste.

The three structural models have been used in a preliminary parametric test, aimed at the analysis of the radiation pattern from the source. The Bovec 1998 event has been selected, whose focal mechanism parameters, according to Bajc et al. (2001) are: strike=315°, dip=82°, rake=189°, h=7.6 km. The angle between the fault strike and the direction to Trieste is 143°. As it can be seen from Figure 3, such an azimuth implies for Trieste an equivalent amount of radiation for the horizontal components of motion. Nevertheless, for the transverse component of motion one can expect much higher values, up to a factor of 5.5, for a strike receiver angle of 90°.

Given the Dinaric trend of the faults system in the source area, it is not logical to consider a rotation of the fault plane: the angle of 90° can be obtained assuming a different location of the source along the active faults recognized in the region. This assumption has been taken into account in the modelling of the most dangerous scenario. From Figure 3 it can be seen that the highest ground shaking is associated with model dinarb. Therefore, to be conservative, the detailed modelling of the seismic input in Trieste has been done with dinarb. Nevertheless, we wanted to check first that the choice of the bedrock model does not influence the distribution of site effects along the considered profiles.

Choice of the profiles for the detailed modelling of ground shaking in Trieste

Analyzing the available cartography, and identifying in Trieste a site of specific interest, representative of the site conditions in the ancient part of the city (Palazzo Carciotti, along the Rive), two representative profiles have been chosen for the engineering applications. Along the two profiles, ground shaking has been modelled with synthetic seismograms computed by the hybrid technique in laterally heterogeneous media.

The highest frequency considered in the computations is 5Hz. In Figure 4 the two profiles considered are shown. The relative cross-sections are given in Figure 5.

Ground shaking scenarios for profile A

The first scenario corresponds to source S1 of Figure 6, localized near Bovec (Slovenia). This modelling is aimed at figuring out the influence of the choice of the reference bedrock model on the pattern of local amplifications obtained along the profile. Therefore, computations have been repeated considering dinarb, dinarb, and dinarts as bedrock models.

As shown in Figure 7, a change in the bedrock model does not perturb the spatial distribution of amplifications, that remain basically confined in the areas characterized by the presence of thin alluvial sediments and fill deposits (marked by the darker tints in the model). What do change are the absolute values of the amplifications, but this is of course expected, and is related to the different amplitude of the reference response spectra computed in the laterally homogeneous medium. The synthetic accelerograms have been computed along profile A using models dinarb, dinarb, and dinarts, and have been scaled for a magnitude 6.0. The example relative to model dinarb is shown in Figure 8. The high amplitudes and the longer durations of the signals in correspondence of the alluvial and fill sediments, of course

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well correlated with the amplification patterns of Figure 7, are observed also with *dinarbf* and *dinarts*.

For the same profile, a more dangerous scenario has been computed, assuming a source located in S2. The only parameter modified with respect to the previous scenario is the epicentral distance, reduced from 65 km to 30 km. Since the parametric tests have shown that the results are not strongly dependent on the choice of the reference model, the computations have been performed only once, adopting the bedrock *dinarb*. The amplifications obtained are shown in Figure 9, and the synthetic seismograms in Figure 10.

This new scenario allows us to estimate the amplitude increase in the seismograms, due to the shorter epicentral distance. The peak value, about 46 cm/s², is now obtained for the radial component of motion, roughly in the middle of the profile (Figure 10), while for the source in S1 the peak (about 8 cm/s²) was observed in the transverse component of motion at the end of the profile (Figure 8).

**Ground shaking scenarios for profile B**

Profile B has been traced for the modelling of the most dangerous scenario in Trieste, due to an earthquake located in S3, that is the active fault closest to the city (see Figure 6).

Before going on with the specific modelling of the worst scenario, a preliminary parametric test has been done to estimate the influence of the local stratigraphy on the amplifications obtained along the profile. Again, model *dinarb* has been adopted as reference bedrock.

Since profile B intersects with profile A near Palazzo Carciotti, attention has been focussed on the results obtained there. To recapitulate, in the first scenario modelling for profile B, the only modification with respect to what has been already shown in Figures 7 and 8 is the local stratigraphy. Any other parameter, most notably the strike-receiver angle and the epicentral distance from the beginning of the profile remained unchanged.

The obtained amplifications are given in Figure 11, and the accelerograms are shown in Figure 12. The comparison between the amplifications modelled at Palazzo Carciotti, (the circle in Figure 7a for profile A and Figure 11 for profile B), shows that the highest amplification obtained is about 6 for the radial component of motion, for frequencies around 2 Hz. In the comparison between Figure 7a and Figure 11, as with any other comparison of amplification maps, to evaluate the significant differences one has to remember that doubling a value roughly corresponds to a jump of one grade in the macroseismic intensity scale, and therefore minor variations should be neglected (e.g. Dolce et al., 2004). In the specific case of Palazzo Carciotti, the difference in amplification (6 and 2 respectively in Figures 7a and 11) implies a difference in macroseismic intensity of 1 or 2 grades, as a function of the direction of arrival of the seismic excitation. What can be noticed instead, is the good stability of the periods at which the amplification can be expected, that is about 1 Hz and 2 Hz.

In Figure 13 the accelerograms obtained at palazzo Carciotti with the modelling for profiles A and B (extracted from Figures 8 and 12) are shown together with their response spectra (5% damping, acceleration). Looking at the peak values in the time series, it can be seen that the component most sensible to the change in the profile’s geometry is the radial one. The peak values are bigger by a factor of about two for profile A. It can be seen from Figure 5 that in profile B the length of the segment characterized by the presence of the surficial fill deposits is much shorter than in profile A, and possibly this can explain the difference in amplitude obtained with the modelling.
The outcome of this test is that at a specific site, for the same epicentral distance and for the same mechanism at the source, we can expect a change of one grade of macroseismic intensity, as the seismic waves travel across a different stratigraphy along the path from source to site.

A second test has been made for profile B, properly orienting the focal mechanism so as to obtain a maximum of radiation towards Trieste for the transverse component of motion. A strike-receiver angle has been considered, keeping any other parameter unchanged. The amplification patterns obtained along the profile for the transverse component are very similar to those obtained in the earlier tests, where the angle was 143°. It has to be remarked that in this test the amplifications obtained for the radial and vertical components are not significant, as the energy carried by those components is minimal (see Figure 3a). The synthetic seismograms computed along the profile are shown in Figure 14. The signals obtained in the area of Palazzo Carciotti are given in Figure 15, together with the acceleration response spectra (5% damping).

The next step has been the modelling of the most dangerous scenario, corresponding to a source placed in S3, at an epicentral distance of about 17 km from the beginning of profile B. The fault strike and the location of the epicentre lead to an angle close to 90° between the fault strike and the direction of the profile. This angle corresponds to a maximum of radiation for the transverse component of motion (Figure 3). According to the seismogenic potential determined by the morphostructural zonation (Gorshkov et al., 2004) and with the historical seismicity of the region, a magnitude of 6.5 has been chosen for this worst-case scenario. The amplifications and the synthetic seismograms for this scenario are shown in Figures 16 and 17 respectively.

To model such a large event at relatively small epicentral distances, the simplified scaling by Gusev (1983), as reported by Aki (1987), is far from being optimal, being based on the perturbation of just the amplitude spectrum. Considering the fault length, of the same order of the epicentral distance, one cannot neglect the influence of the rupturing process. Therefore, a more sophisticated approach than the one described by equation (2) had to be used. An algorithm for the simulation of the source radiation from a fault of finite dimensions, named PULSYN (PULse-based wide band SYNthesis) has been developed. The representation of a source of finite dimensions is made using a “constellation” of point sub-sources, distributed along linear segments, each characterized by its own time function. To compute the synthetic seismogram at a specific site, the time function of each sub-source is multiplied by the proper Green function, and the seismic moment tensor of the corresponding point source. With this technique, it is possible to quickly obtain broadband signals that reproduce the directivity effects and the rupturing process of the source. This approach requires CPU times and computing resources much reduced compared to the methods based on the sum of the single emissions from the rupturing plane, generally limited to frequencies around 1 Hz.

The application of this sophisticated approach, appropriate for profile B when the source is placed in S3, is shown in Figure 18 for the signals modelled at Palazzo Carciotti. The three columns of seismograms represent, from left to right, the transverse, radial and vertical components of motion. The first row of seismograms has been computed with the classic approach of Gusev (1983) as reported by Aki (1987), and correspond to the signals shown in Figure 17. The next three rows are obtained with the PULSYN approach, considering three different azimuth (0°, 90° and 180°) with respect to the direction of rupture propagation. Focussing on the transverse component, dominating over the radial and vertical
ones, it can be noticed that with respect to the simplified approach (shown in the first row), the peak value diminishes and the signal duration increases. The amplitude spectrum of the synthetic seismograms obtained with the PULSYN approach is equal to the one obtained with the simplified approach, but the phase spectrum is modified, leading to more complicated waveforms that better account for source complexity. For source S3 and profile B, the most realistic angle is 90°.

\[ O_{ij}(\omega) = E_i(\omega)P_{ij}(\omega)S_j(\omega) \quad (1) \]

where \( E \) is the source term, \( P \) is the path term, and \( S \) is the site-effect term. In the time domain (1) becomes

\[ O_{ij}(t) = E_i(t)P_{ij}(t)S_j(t) \quad (1b) \]

where * indicates the convolution operator.

The most traditional techniques, for the estimation of the S term, are based on the computation of the ratio between the spectrum of the signal (or a portion of it) at the sedimentary site and the spectrum of a reference signal, preferably recorded at a nearby bedrock site. Similarly, Nakamura’s (1989) method is based on the computation of the spectral ratio between horizontal (usually the square root of the product between the spectra of the NS and EW components is used) and vertical components (H/V) obtained from seismic noise (microtremors). Theoretical investigations (e.g., Lachet and Bard, 1994; Dravinski et al., 1996) and experimental studies (e.g., Field and Jacob, 1995; Field, 1996) have shown that Nakamura’s method can reveal the fundamental resonant frequency of a site but usually it is not able to give the correct amplification level. Furthermore, Nakamura’s (1989) assumptions seem questionable since several studies (e.g., Lachet and Bard, 1994; Konno and Ohmachi, 1998) have demonstrated that the horizontal to vertical ratio is strictly correlated with the polarization of Rayleigh waves. For a more comprehensive comparison of the various empirical techniques the reader is referred to Bard (1997).

The most frequently used techniques for the empirical estimation of site effects, based on (1), supply reliable information about the site response to non-interfering seismic phases or to single modes of vibration; they are not adequate in most real cases when the seismic sequel is formed by several interfering waves or equivalently by several modes. In fact, in the far field (and point source) approximation – i.e. in the mathematically simplest possible situation – the l-th component of seismic ground displacement is given by:

\[ u_l(t) = \sum_{ij} M_{ij}(t)G_{il}(t) \quad (2) \]

where \( G \) is the Green's function, that represents the medium response and \( M_{ij} \) are moment tensor rate functions, that represent the source properties (e.g. Sileny and Panza, 1991; Sileny...
et al., 1992). If they are considered to be independent in the description of the source, the above equation is linear (it corresponds to a mechanism generally varying with time). However, if we constrain their independence and ask for a constant mechanism (even unconstrained one, i.e. the full moment tensor), i.e. if we impose the constraint:

\[ M_{ij}(t) = M_{ij}.m(t) \]  

(3)

the problem becomes non-linear because of the product \( M_{ij}.m(t) \) (both \( M_{ij} \) and \( m(t) \) are the model parameters controlling source properties). Thus, the problem in the time domain is non-linear even without the double-couple constraint (an additional non-linearity here), usually assumed for seismic sources. In the frequency domain it may seem simpler because the convolution in (2) is converted to pure multiplication and the equation is solved for each frequency separately. Within linearity we get \( M_{ij}(\omega) \) but to split the source time function and the mechanism again a non-linear constraint is needed, so the advantage of the frequency domain is fictitious only. In general the non-linearity deriving from the double-couple constraint derives from the fact that the double-couple constraint imposes a non-linear combination of the components of the moment tensor, namely zero value of its determinant.

An alternative to the questionable empirical approach to site response estimation is based on computer codes, developed from the detailed knowledge of the seismic source process and the propagation of seismic waves (e.g. Field, 2000 and Panza et al., 2001). This approach can simulate the ground motion associated with a given earthquake scenario. In such a way, using available geological and geotechnical information, a low-cost parametric analysis can be performed without using the convolutive approaches, based on the questionable general validity of (1).

From all the modelling done, one can see how the different source locations allow to estimate the stability of site effects as a function of the epicentral distance. In some synthetic scenarios (e.g. Romanelli and Vaccari, 1999) different amplification patterns have been observed, along a given profile, when the properties of the source are changed. This observation contradicts the generally accepted statement about site effects, that is, their independence on the source characteristics.

Amplification or de-amplification effects can dominate the seismic response at a site whenever local heterogeneities are present, like for instance a complicated topography or soft sedimentary basins. A simple physical explanation for local amplification of seismic ground motion, due to soft surface layering, is the trapping of seismic energy due to the impedance contrast between soft surface soils and the underlying bedrock. Moreover, the relatively simple onset of vertical resonances can evolve into a much more complicated pattern, strongly dependent on the characteristics of the subsurface topography of the sedimentary deposits. In the last decade, a huge amount of literature has been devoted to the estimation of site effects. A practical definition of site effects, that combines the purposes of the engineering and seismological communities, is proposed by Field (1996): "the unique behavior of a site, relative to other sites, that persists given all (or most) of the potential sources of earthquake ground motion in the region". Such a definition implicitly reveals the difficulties connected with the correct site response estimation, i.e., identification of the different ingredients involved in the resulting ground motion signal: source, path (including the presence of lateral heterogeneities) and local soil effect including its possible nonlinear behaviour.
Comparison between observed and theoretical amplifications

The local amplifications estimated with the modelling have been compared with some experimental observations recorded in the city of Trieste (Fitzko et al., 2005). The response spectra ratios (acceleration with 5% damping) computed at Palazzo Carciotti and at three bedrock sites (on limestones, sandstones and flysch) have been compared with the corresponding ratios obtained using the recorded seismograms at the stations CARC, DST and TRI (see Figure 4 for station location).

The acceleration response spectra (5% damping) observed for five regional events recorded by stations CARC and DST, are shown in Figure 19. The theoretical response spectra, computed along profile A for the Bovec event are shown in Figure 20 for a site on limestone (site n.5 along the profile), on sandstone (site n.17), flysch (site n.42) and fill sediments (site n.68). It can be seen that the periods excited, for both observations and synthetics, are those below 2 s. Therefore, when showing the response spectra ratios (Figure 21 for the observations of the five events, Figure 22 for the modelling of the Bovec event), we decided to focus on that range.

For the horizontal spectral ratios (SA_{CARC}/SA_{DST}) shown in Figure 21, for all the considered events, a characteristic amplification around T=0.5 s can be recognized. Such a feature is also reproduced in the modelling of Figure 22, where the ratios between the acceleration response spectra obtained at Palazzo Carciotti (n. 68) and those obtained at the three reference sites on limestone, sandstone and flysch are shown.

In the period range considered, the spectral amplification values are strongly dependent on the considered earthquake, as shown in Figure 21. As a consequence, site amplification estimates obtained using the recordings of a single event cannot be generalized. The importance of the modelling is evident, as it allows the preparation of several amplification scenarios for all the events, future and historical, for which recordings are not available.

A confirmation of the variability of amplifications can be found in the analysis of the response spectra ratios for profile B. The synthetic seismograms used for this analysis are those obtained at Palazzo Carciotti (site n. 94 along the profile) and at reference sites on limestone (site n.5), on sandstone (site n.21) and flysch (site n.40). The response spectra ratios (5% damping) obtained using the three reference sites are given in Figure 23. A comparison with the results shown in Figure 22 for profile A can give an estimate of the variation in the amplifications that may be expected due to changes in the geometry of the profiles, since the source and the geotechnical properties of the materials are the same for the two modelling.

The importance of having more than one amplification scenario for a single site is again evident from the response spectra ratios (SA 5%, shown in Figure 24) computed for Palazzo Carciotti (Figure 24) considering profiles A (above) and B (below). For each profile, the response spectra ratios have been computed dividing the response spectrum obtained at Palazzo Carciotti for the laterally heterogeneous profile by the response spectrum obtained at the same site using the bedrock model dinarb. Different results have been obtained at the same site for the two profiles, and both differ from the ratios shown in Figures 22 and 23, confirming the impossibility to generalize what is observed in a single scenario.
Conclusions

To verify the efficiency of the new seismic code, for some scenario earthquakes, chosen according to the seismotectonic regime of the area, a detailed ground motion modelling has also been performed for the ancient part of the city, where soft surficial sediments of poor geotechnical characteristics are present. Using the specific knowledge about geology and geotechnical properties described in the cartographic material available for the Trieste area, three profiles (local 2D sections) and several seismogenic scenarios have been considered, varying the source position and magnitude. Three variations of bedrock model, characterized by values representative of the limestones around Trieste, have been taken into account for propagating the wavefield from the source to the beginning of the 2D sections. The three-component synthetic seismograms, computed, with a broad band content and in laterally anelastic models in the domains of displacement, velocity and accelerations, have been processed to estimate the site effects and to extract some parameters significant from the engineering point of view.

From all the modelling done, one can see how the different source locations allow to estimate the stability of site effects as a function of the epicentral distance. In the case of the Palazzo Carciotti site, the modelling done leads to the conclusion that, for the same epicentral distance and for the same mechanism at the source, we can expect a change of one grade of macroseismic intensity, as the seismic waves travel across a different stratigraphy along the path from source to site. The local amplifications estimated with the modelling have been compared with some experimental observations recorded in the city of Trieste, showing that in the considered period range, the spectral amplification values are strongly dependent on the considered earthquake. As a consequence, site amplification estimates obtained using the recordings of a single event cannot be generalized.

The seismic code, being based on a probabilistic approach, can be considered representative of the average seismic shaking for the province of Trieste, and can slightly underestimate the seismic input due the seismogenic potential (obtained from the historical seismicity and seismotectonics). Furthermore, relevant local site effects are mostly neglected.

Both modelling and observations show that site conditions in the centre of Trieste can amplify the ground motion at the bedrock by a factor of five, in the frequency range of engineering interest. We may therefore expect macroseismic intensities as high as IX (MCS) corresponding to VIII (MSK). Spectral amplifications obtained for the considered scenario earthquakes are strongly event-dependent. Therefore the amplification estimate obtained at a site analyzing the recording of some earthquakes cannot be generalized. The importance of modelling is evident, as it allows us to consider amplification scenarios for historical and future events for which there are no recordings available.

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