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Short Note

Site Effect of the Strong-Motion Site at Tolmezzo-Ambiesta Dam in Northeastern Italy

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Abstract A spectral analysis of strong-motion data and ambient noise at the Tolmezzo-Ambiesta dam accelerograph (TLM1) site is performed to explain the high horizontal peak acceleration of 0.36*g* recorded during the M_w 6.4, 6 May 1976 Friuli (northeastern Italy) earthquake. The spectral response of the accelerographic site is estimated from the mainshocks and aftershocks of the 1976 seismic sequence by different techniques. In addition, new seismic data are used to characterize the near-surface *S*-wave velocity distribution versus depth at TLM1 by means of an analysis of the phase-velocity dispersion of Rayleigh waves. An average, spectral amplification curve is computed for TLM1, whose mean value is at about 1.5. It features two main lobes of amplification with peaks at 2–3.5 Hz and 6–7 Hz that are explained, by the horizontal-to-vertical spectral ratio (HVSR) of noise measurements, as the effects of the vibration of a nearby relief and the dam-reservoir system, respectively. When the site response is evaluated from earthquake recordings, the frequency of resonance due to near-surface *S*-wave velocity profile at about 5 Hz is strongly attenuated in comparison with the 6–7 Hz peak due to the dam-reservoir system. Finally, by filtering the site effects of the 1976 record, the acceleration peak is reduced from the original value of 349.99 cm/sec^2 to 188.76 cm/sec^2.

Introduction

High-peak accelerations at seismic stations located close to dam abutments are not unusual. An acceleration of 1.25*g* was recorded in both horizontal directions at the Pacoima Dam site (California) during the strong San Fernando earthquake of 9 February 1971 (Trifunac and Hudson, 1971). Shakal *et al.* (1984) noted a horizontal peak acceleration of 1.29*g* at Coyote Lake Dam in California during the 1984 Morgan Hill earthquake.

During the 6 May 1976 Friuli earthquake in Italy (M_w 6.4), the Ente per le Nuove tecnologie, l'Energia e l'Ambiente-Ente Nazionale per l'Energia Elettrica (ENEA-ENEL) accelerographic station of Tolmezzo-Ambiesta (TLM1, Fig. 1), equipped with a Kinemetrics SMA-1 accelerograph, recorded acceleration peaks of 349.99 cm/sec^2 and 309.81 cm/sec^2 on the horizontal and vertical components, respectively (Ambraseys *et al.*, 2004). These are among the highest peak accelerations measured in Europe and have been largely used in the past to estimate empirical attenuation relations for Italy (Sabetta and Pugliese, 1987), the eastern Alps (Bragato and Slejko, 2005), and Europe (Ambraseys *et al.*, 1996). As a result, they largely exceed the average values estimated by those attenuation laws (e.g., by about 30% of the value predicted by Ambraseys *et al.* [1996]).

The TLM1 station is located above the abutment of a dam at the top of a calcareous hill, thus we suspect that the high peak values recorded could be strongly influenced by local factors, such as either the site that hosts the accelerograph, or the presence of the concrete arch dam-water reservoir system or the topographic reliefs around it (Fig. 2).

In brief, the goals of this study are: (1) to characterize the V_S profile at the TLM1 site by reviewing the available geophysical data in the light of a new seismic acquisition; (2) to estimate the amplification at TLM1 and interpret the causes of it; and (3) to evaluate the ground motion recorded during the 1976 mainshock by filtering out the local site effects.

Contradictory *S*-wave velocity (V_S) profiles were obtained at TLM1 in the past by using two different geophysical methods (ENEL, 1981). Here, to clarify which of the dated near-surface V_S profiles can be assumed for the TLM1 site, we analyze newly acquired shallow refraction seismic data through a spectral analysis of the Rayleigh wave phase-velocity dispersion.

The spectral response of the site to earthquakes is estimated by different techniques, such as the "receiver function technique" (Lermo *et al.*, 1993), the classical spectral-ratio-

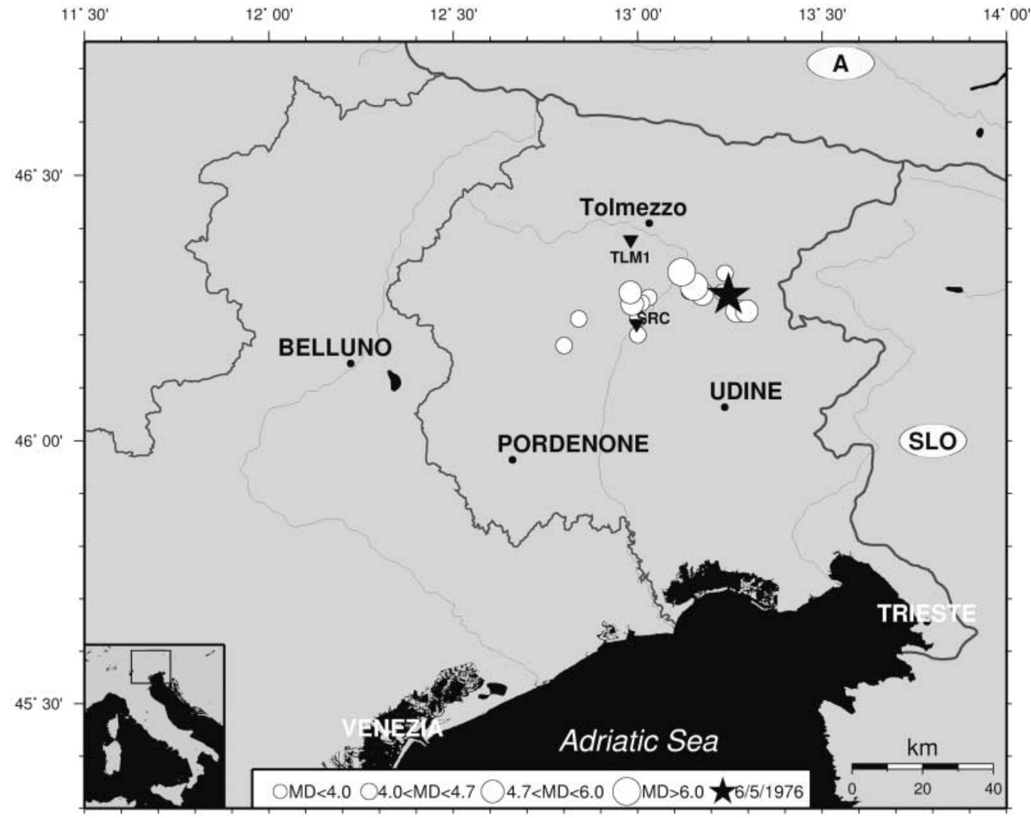

Figure 1. Map of the epicenters of the mainshock (star) and representative aftershocks of the Friuli earthquake used in this study. TLM1, Tolmezzo-Ambiesta Dam station and SRC, San Rocco station, are shown.

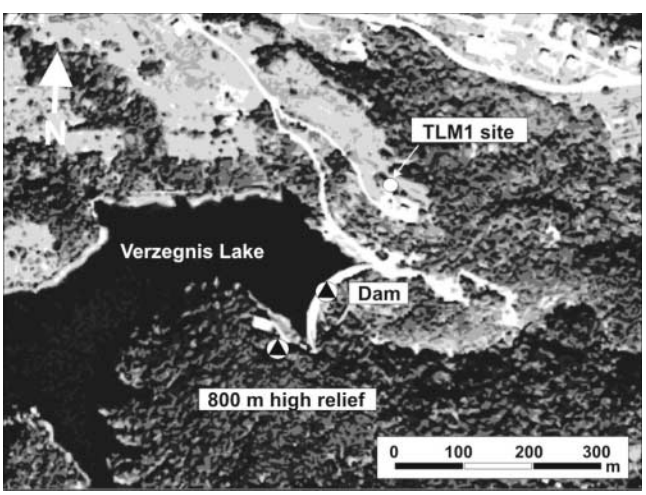

Figure 2. Grayscale sketch of the aerial view over the Ambiesta Dam site. The locations of TLM1 accelerographic station, the dam, and the 800-m-high relief in the southwest are shown. Noise measurements on the southwestern relief and at the middle-top point of the dam are marked by black triangles.

to-reference-site method, and the "generalized inversion technique" (Andrews, 1986; Castro *et al.*, 1990; Boatwright *et al.*, 1991). In addition, the ratio between the response spectra of the mainshock and that predicted by using the attenuation relations by Ambraseys *et al.* (1996) for this site are also considered.

Ambient noise has been recorded on the accelerograph hill, close to the TLM1 site, along the top of the dam, at its abutments and basement, as well as on the flank of the southwestern relief (Fig. 2). These signals are analyzed by using the noise horizontal-to-vertical spectral ratio (HVSR) technique and allow us to interpret the causes of the site amplification.

Near-Surface *S*-Wave Velocity Profile at TLM1

A shallow seismic refraction survey (SR77) carried out at TLM1 in 1977 (ENEL, 1981) defined a V_S vertical profile with a strong contrast at 20 m of depth, where the V_S velocity goes from 450 m/sec to 1300 m/sec. In 1981, a cross-hole (CH81) and sonic log test (ENEL, 1981) identified a V_S profile, very different from SR77 in the shallowest 20 m, and consisting in a gradually increasing velocity from 600 m/sec at the surface to 1300 m/sec at the depth of 14 m; in the deeper part, down to 60 m, the estimated velocity was constant with V_S = 1300–1400 m/sec. The two profiles are shown in Figure 3. Up to now CH81 profile is considered more reliable than SR77 profile and is generally used for TLM1 site classification (e.g., Ambraseys *et al.*, 1996), without any convincing explanation of the V_S differences in the shallow part. Note that the two profiles define quite different $V_{S,30}$ values, that is, 700 m/sec and 1000 m/sec for SR77 and CH81, respectively, and correspond to different soil classes (C for SR77 and B for CH81) according to the National Earthquake Hazards Reduction Program (NEHRP) classification.

To clarify this issue, we carried out a specific study based on a new seismic survey and a modern spectral analysis of high-frequency Rayleigh waves (Fig. 4). The layout of the seismic acquisition follows that recently used for multichannel analysis of surface waves (MASW method; e.g., Xia *et al.*, 2005): a simple weight drop source of 120 kg, 12 vertical-component geophones with 1-Hz natural frequency and 2 m spacing, to avoid spatial aliasing. Eighty-four seismograms are recorded by moving the source at a different distance from 20 m to 120 m from the geophone array. The recorded section (Fig. 4, inset) evidences a clear refractor at about 20 m of depth with a *P*-wave velocity of about 2.6 to 2.7 km/sec. At shallow depth *P*-wave velocity is about 0.75–0.85 km/sec.

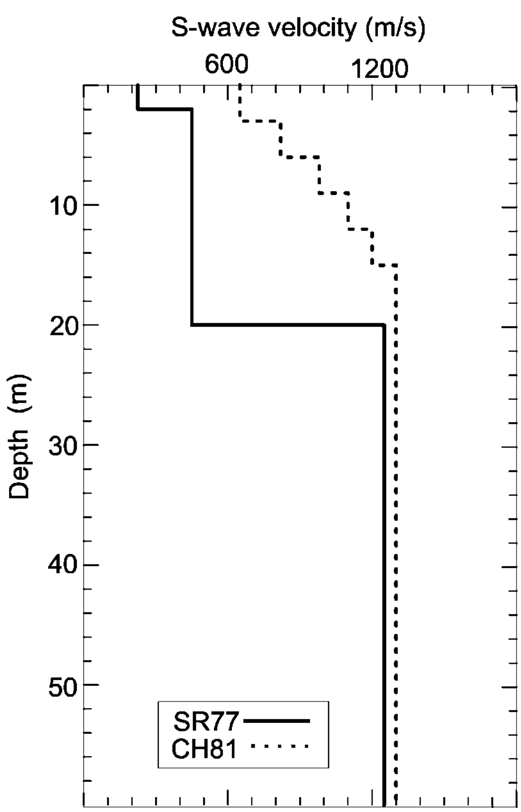

Figure 3. V_S seismic profiles obtained by seismic refraction data in 1977 (SR77) and cross-hole seismic measurements in 1981 (CH81) at the TLM1 site. The V_S profile for SR77 is defined from the *P*-wave velocity profile by using a constant V_P/V_S ratio of 2.

A 2D transform has been applied to the recorded wave field to enhance the detection and separation of the Rayleigh wave-phase velocities. The algorithm was developed by Herrman (2005) and follows the formalism described by McMechan and Yedlin (1981): the phase-velocity dispersion curves are obtained from an array of seismic traces by using a $p - \tau$ stack followed by a transformation into the $p - \omega$ domain. The results obtained with our data (Fig. 4, background panel) show the minimum velocities of about 0.6 km/sec in the high-frequency band.

The V_S profiles SR77 and CH81 shown in Figure 3 are then used to compute the theoretical phase-velocity dispersion curves by using a normal mode code (Herrmann, 2005). We compare in Figure 4 the theoretical dispersion curves obtained using the V_S profiles SR77 and CH81 (see Fig. 3) with those calculated with our data set. There is no doubt that only the V_S profile SR77 is consistent with the low-phase velocities observed using our seismic data, and that TLM1 can be classified as *C* according to the $V_{S,30}$ value.

Site-Response Estimation

To investigate and quantify the spectral site response of the TLM1 station, a spectral analysis on the 1976 Friuli seismic-sequence earthquakes is carried out, considering the data taken from European Strong Motion Database (Ambraseys *et al.*, 2004). A temporary array of 11 accelerographic stations was installed in the epicentral area after the main event (Basili *et al.*, 1976). Among these stations, San Rocco (SRC) was the nearest to the permanent accelerographic site TLM1 (Fig. 1), being located at distance of about 23 km, and we use it as a reference site to study the site response of the Tolmezzo-Ambiesta dam. According to Muzzi and Vallini (1977), station SRC is on calcareous stiff soil.

Table 1 lists the events used in this study. Azimuth and hypocentral distances are calculated from Ambiesta station (TLM1). M_L values are from Ambraseys *et al.* (2004). The last two columns indicate the stations that recorded the events.

Several methods have been proposed to estimate the site response from instrument recordings, removing the source and path effects. The most widespread empirical technique is the "spectral-ratio-to-reference-site." This approach was introduced by Borcherdt (1970) and can be considered as the classic technique for estimating the seismic response of a site. In this study, we use SRC San Rocco station as a reference site for TLM1.

Another reference-site method applied is the generalized inversion scheme, as proposed by Andrews (1986) and modified by Boatwright *et al.* (1991). Here, the source parameters for each event, the path-effect parameters, and the response for each site are solved simultaneously. However, because this method assumes that an isotropic source spectrum is observed at all sites, it may fail for large sources, where some features of the rupture process, as for instance

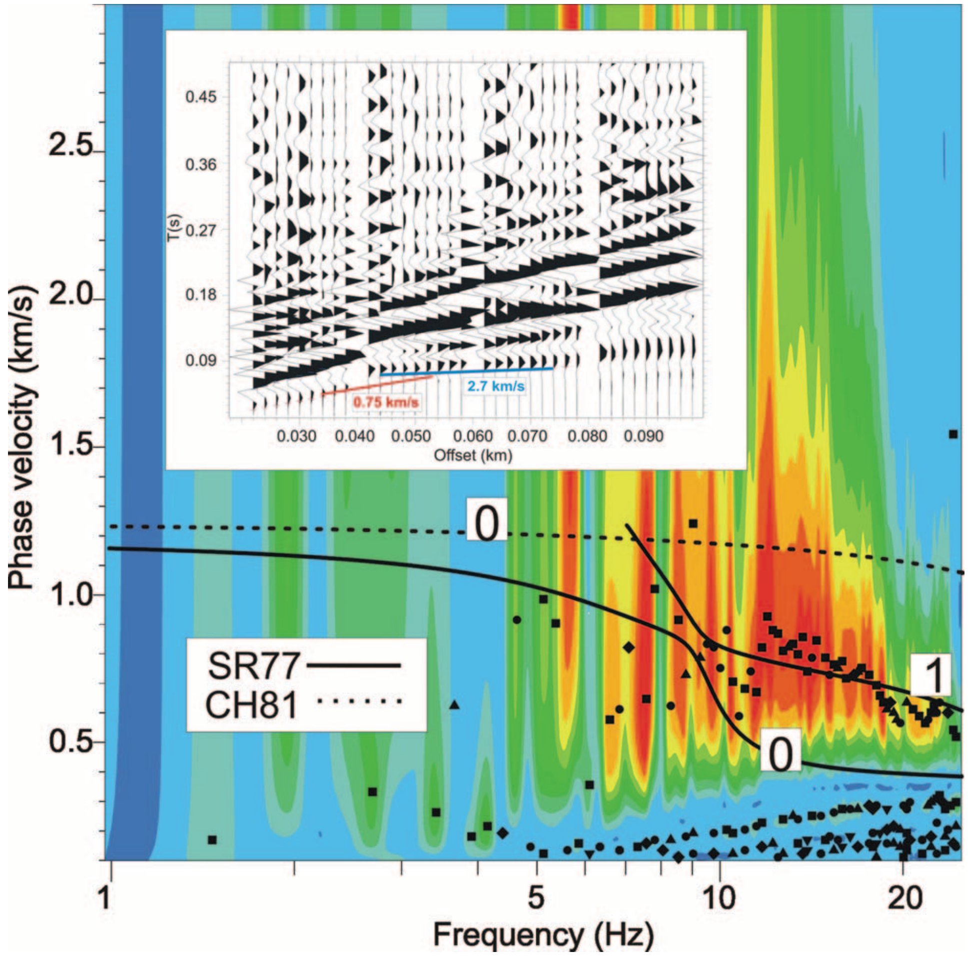

Figure 4. (inset) Seismic section recorded at the TLM1 site (background panel) Phase-velocity stack values of the seismic data shown in the inset. The colors indicate the stack value (the largest values in red). The black symbols represent the peaks chosen from the stack after a 2D search over the phase velocity–frequency grid. The solid and dashed black curves represent the theoretical dispersion values for SR77 model (0 = Rayleigh wave fundamental mode; 1 = first higher mode) and CH81 model (0 = Rayleigh wave fundamental mode), respectively.

source directivity and slip distribution, may strongly violate this assumption.

An alternative reference-site analysis was performed here using as a reference the median response spectra predicted for rock soil by European attenuation relations (Ambraseys *et al.*, 1996). The 5% damping response spectra of the mainshock was compared with the median one predicted for a rock site using the attenuation relations developed by Ambraseys *et al.* (1996) for Europe.

Because of the lack of a very close rock reference site, a non-reference-site-dependent technique was also used to analyze earthquake data. A simple technique consists in taking the spectral ratio between horizontal and vertical components of the shear-wave part (Lermo *et al.*, 1993). This procedure, which is analogous to the so-called receiver-function technique applied to upper mantle and crustal studies from teleseismic records (e.g., Langston, 1979), assumes that the local site conditions do not affect the ground motion on the vertical component. For local sources located relatively close to the site, the spectral ratios may be used to identify the frequency bands of amplification, although the amplification value is considered unstable by many authors and thus not reliable.

Figure 5 illustrates the spectral response estimated for site TLM1 from the Friuli 1976–1977 earthquake sequence by using the four methods described previously. All the curves feature the same frequencies of amplification, although the estimated amplitude differs somewhat among the various methods. Three frequency amplification bands are clearly recognized at about 2 Hz, 3.8 Hz, and 6–8 Hz, respectively. The mean response, estimated by the spectral ratio of TLM1 to SRC reference site by using the events recorded by both stations (Fig. 5a), shows the same frequencies indicated previously. The generalized inversion

Table 1
List of the Recorded Events Used in This Study

Date	Time	Lat	Lon	Depth	M_L	Azimuth	Dist (km)	TLM1	SRC
06.05.1976	19:59:06	46.277	13.239	9.0	4.5	111.09	30.09	X	
06.05.1976	20:00:13	46.292	13.253	7.0	6.4	104.91	26.91	X	
07.05.1976	00:23:49	46.245	13.269	5.0	5.0	118.57	30.56	X	
07.05.1976	13:42:50	46.316	13.236	10.0	4.2	34.63	11.89	X	
08.05.1976	03:10:06	46.280	13.230	10.0	4.2	103.07	15.65	X	
09.05.1976	00:53:44	46.245	13.295	9.0	5.6	123.01	32.94	X	
11.05.1976	22:44:01	46.258	12.985	6.0	5.3	171.62	14.83	X	
13.05.1976	13:04:51	46.200	13.000	10.0	4.2	176.07	20.28	X	
18.05.1976	01:30:09	46.270	13.030	7.0	4.2	251.15	38.67		X
01.06.1976	17:21:09	46.230	12.840	9.0	4.1	212.13	20.13	X	
09.06.1976	18:48:17	46.260	13.010	13.0	4.1	170.95	13.73	X	X
11.06.1976	17:16:36	46.230	13.000	9.0	4.5	184.25	12.48	X	X
17.06.1976	14:28:51	46.180	12.800	15.0	4.5	212.06	26.48	X	
26.06.1976	11:13:49	46.282	13.140	4.0	4.3	121.69	15.21	X	
11.09.1976	16:31:11	46.280	13.286	4.0	5.4	215.89	22.33		X
11.09.1976	16:35:03	46.277	13.175	12.0	5.7	216.20	24.26		X
15.09.1976	03:15:19	46.291	13.153	5.0	6.2	214.99	21.39		X
15.09.1976	09:21:19	46.318	13.119	8.0	6.1	211.36	16.73		X
16.09.1977	23:48:07	46.280	12.280	8.0	5.3	180.65	13.56	X	X

method (Fig. 5b) locates the peaks at 2.5 Hz, 3.8 Hz, and 6 Hz, respectively. The median response spectra predicted for rock soil by the European attenuation relations does not feature such sharp peaks (Fig. 5c), but the amplification bands are again marked at the same frequencies of 2 Hz, 3.8 Hz, and 6–8 Hz, respectively. Finally, the receiver function method (Fig. 5d) slightly underestimates the frequency of the low-frequency peak, locating it at about 1.8 Hz, whereas it confirms the other two peaks at 3.8 Hz and 6–8 Hz, respectively.

To estimate the spectral amplification factor, we have computed the arithmetical average of the spectral ratio to reference site and generalized inversion spectral ratios (see Fig. 5e), because the receiver function method may not represent amplification values correctly. It can be seen that the site amplifies the ground motion in the band 1–7 Hz, with a larger lobe in the band 1–4 Hz (with values up to 3) and a smaller lobe in the band 5–7 Hz. On the other hand, the site deamplifies the ground motion in the low-frequency band ($f < 1$ Hz).

Interpretation of the Response

Many studies carried out in the past have addressed the fact that the dynamic response induced by the presence of a dam-water reservoir system may affect the seismic response of surrounding sites. This effect may be further complicated by the response of the hills the dam leans on and that often surround the reservoir (Clough *et al.*, 1990). Next, we show that the two amplification lobes identified by the spectral analysis at TLM1 can indeed be interpreted as the combined effect of the vibration of the 800-m-high surrounding hill, the Ambiesta dam-reservoir system, and the site response at TLM1.

The first analysis of the resonance frequencies of the Ambiesta dam was performed in 1978 by Castoldi within an integrated research program aimed at improving knowledge of the seismic behavior of large dams (Castoldi, 1978). He pointed out the resonance frequencies and amplification at the Ambiesta dam arch crest using the earthquake records of the 1976 aftershocks and some vibration tests. In his analysis, the author estimated a resonance frequency of 3.8–4.4 Hz for the first mode and 5–10 Hz for the higher modes. These resonance peaks were found when water was already in the reservoir, therefore under conditions similar to those of the 1976 seismic sequence.

To identify the resonance frequencies of the site and understand the possible causes of amplification, we performed some noise measurements. A total of 11 measurements were made on the accelerograph hill to the left of the dam, along the dam, and on the southwestern relief at the right side of the dam. Figure 6 shows the HVSR curves estimated at three locations corresponding to the relief, on the southwestern side of the reservoir, the dam at middle-top point, and the TLM1 site. The site located on the relief flank shows a clear HVSR lobe in the band 1–3 Hz, with the largest peak at about 2 Hz. The HVSR measured on the middle-top point of the dam features a wide lobe in the frequency band 3–8 Hz. This lobe includes the first mode of vibration of the dam at 3.8–4 Hz, whereas the higher modes of resonance correspond to the peaks at about 7 Hz and 10 Hz. Finally, the HVSR recorded at TLM1 displays a main lobe in the band 1.5–3 Hz and a peak at 4–5 Hz. Note that the higher-frequency peak does match exactly the fundamental resonance for the shallowest part of the V_S profile, which can be easily predicted at 4.9 Hz.

From the HVSR described previously it is possible to interpret the overall response at TLM1 site. We believe that

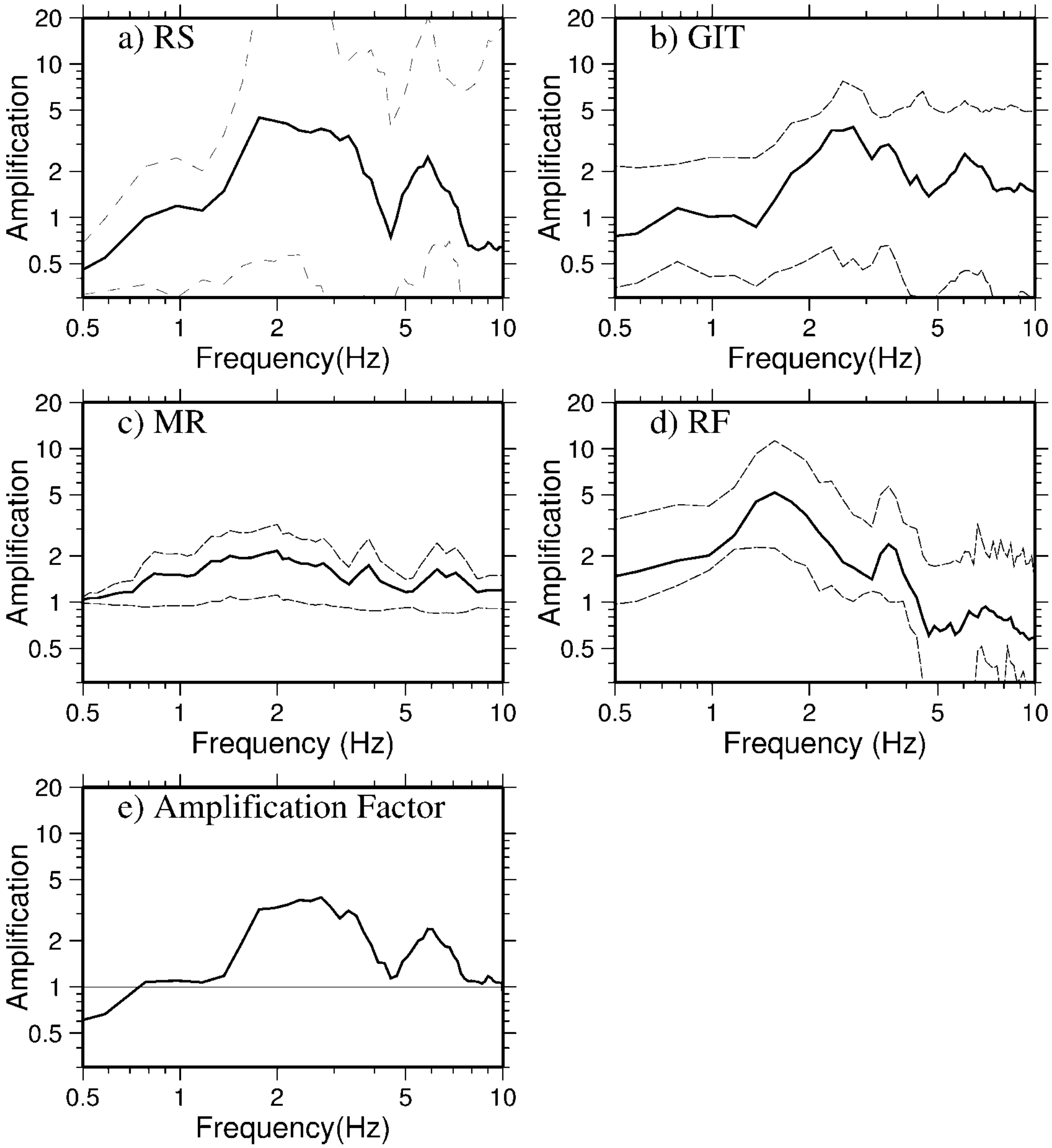

Figure 5. Spectral ratio estimates of site response at the Ambiesta TLM1 site. The dashed lines represent standard deviation. (a) Spectral ratio to San Rocco reference site (RS). (b) Generalized inversion technique (GIT). (c) Median response spectra predicted for a rock soil by European attenuation relations (Ambraseys *et al.*, 1996) (MR). (d) Receiver function (RF). (e) Spectral amplification function estimated as an average from the spectral ratio reference site and generalized inversion scheme.

the low frequency of vibration of the 800-m-high relief can be transmitted to the accelerograph site located on the hill through the dynamic interaction of the dam with the rock foundation. For this reason, the amplification lobe at 1.5–3 Hz is still present, although weaker, in the HVSR recorded at both TLM1 and the dam.

The second peak at the higher frequency of 4–5 Hz corresponds to the near-surface response of TLM1 site, that is, of the uppermost 20 m of soil. In addition, the response of the overall system is further complicated by the interaction of the dam-hill system with the dam-reservoir system, which may also affect the vertical component of the motion (Clough *et al.*, 1990).

As already observed by Boore *et al.* (2004) at the Coyote Lake Dam, California, this study confirms that an abutment station may undergo the effects of a very complex structural situation that can substantially affect the ground motion at the site. This is indeed the case of the Ambiesta station, and for this reason great care must be taken in using the original Ambiesta recordings for routine applications in ground-motion prediction and seismic-source studies of the 1976 Friuli earthquake.

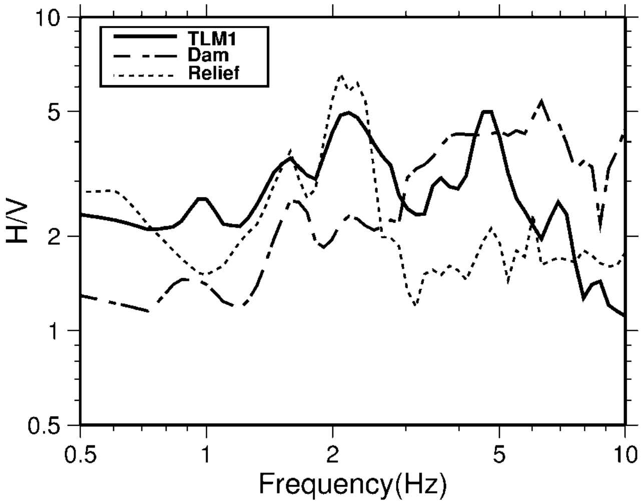

Figure 6. HVSR estimated from noise measurements at Ambiesta TLM1 site (solid line), at the middle-top point of the Ambiesta dam (dash-dot line), and on the relief (dotted line). Refer to Figure 2 for the location of the measurement sites.

Conclusions

The data recorded during the 1976 Friuli earthquake by TLM1 station have been analyzed with the aim of investigating possible site effects as a cause of the high-acceleration peaks featured. Being located at the top of a calcareous hill, above the eastern abutment of the Ambiesta dam, there is a strong suspicion that the seismic response of TLM1 is affected by the presence of the dam-reservoir system and the surrounding hills. Two previous geophysical investigations provided contradictory *S*-wave velocity (V_S) profiles at TLM1 (ENEL, 1981) and left most questions unanswered.

The spectral analysis performed on the 1976–1977 earthquakes using different techniques provides consistent results and confirms the fact that the TLM1 site amplifies the ground motion with a frequency-dependent factor. The analysis emphasizes two amplification lobes, the largest in the band 1–4 Hz and a smaller lobe in the band 5–7 Hz.

To explain the seismic response of TLM1 site, we carried out new geophysical measurements with the aim of (1) resolving our doubts about the local V_S structure and (2) identifying and separating in the TLM1 response the different contribution by the dam-reservoir system and the surrounding hills.

We have found that the V_S profile of the site corresponds with that estimated by the seismic refraction survey (SR77), which defines low V_S values in the shallow part and a strong velocity contrast at about 20 m depth. According to the$V_{S,30}$ value estimated from this profile, TLM1 comes out as a C-class NEHRP site.

Two amplification lobes are evidenced in the spectral response as due to (1) the 800-m-high relief (frequency band from 1.5 Hz to 3 Hz) at the southern abutment of the dam, and (2) the near-surface response of the accelerographic site (5–7 Hz). The dam, through dynamic interaction with the foundation rock and the reservoir system, contributes to transmitting the vibration of the relief to the TLM1 hill and further complicates the response of the overall system.

As a final step of this study, we consider it to be of some importance to estimate the effect of the spectral amplification correction on the peak values. To do that, we have filtered out the TLM1 site response from the original records of the 1976 mainshock. Table 2 summarizes the peak ground acceleration (PGA) and peak ground velocity (PGV) values before and after the correction for the site response. Note that after the correction, the peak values are reduced by a factor of about 1.6–1.8, and the largest PGA value of 349.99 cm/sec^2 becomes 188.76 m/sec^2. Compared with the Ambraseys *et al.* (1996) ground-motion prediction equation, the reduction is lower, being about 1.35. These correction factors represent the site-correction factors for TLM1 with respect to a rock site that should be considered for the peak values within ground-motion prediction studies.

Acknowledgments

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Table 2
Peak Values Recorded during the M_w 6.4 Mainshock of 6 May 1976 and Corrected for the Site Response

	Component	Original	Site-Corrected	Observed to Site-Corrected Ratio	Ambraseys *et al.* (1996) Prediction Law	Ambraseys *et al.* (1996) to Site-Corrected Ratio
PGA (cm/sec^2)	east–west	309.81	196.88	1.5736	262.85	1.3351
	north–south	349.99	188.76	1.8542		1.3925
PGV (cm/sec)	east–west	32.632	19.73	1.6536	—	—
	north–south	20.621	22.87	0.9016		

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