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Seismic ground motion variations resulting from site conditions

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Abstract: Amplification of seismic ground motions in the territory of Almaty city is evaluated by using different methods. The pattern and probable causes of ground motion variations in different engineering-geological conditions are characterized. An expeditious application of these techniques within a complex methodical approach for Almaty city microzonation is considered.

Key words: ground motion variations; spectral ratio; methodical approach

1 Introduction

Evaluation of seismic ground motion amplification and deamplification caused by the effect of subsurface geology is a critical part of seismic microzonation studies. In Almaty city, as in some other world megalopolises, the amplification of strong motions resulting from a layered medium is complicated by the irregular geological structure of a deep sedimentary basin with alluvium-proluvium filling. We studied the soil response within the city territory from accumulated instrumental data recorded by the Almaty strong-motion network. Previous studies[1] were carried out in cooperation with experts from the German Research Center for Geosciences (GFZ).

At present, with renovation of seismic microzonation of the city territory being initiated, upgrading the methodical basis is required. In this connection we analyzed the possibility of applying some simple and commonly used foreign techniques to the conditions of the Almaty sedimentary basin and the advisability of their introduction into a complex methodical approach for city microzonation.

2 Ground motion variations over the basin territory

Experimental data obtained by the local Almaty strong-motion network during more than a 12-year period[2] and results of engineering-geological studies in Almaty indicate the dependence of ground motion variations on station location over the basin territory. Even if the effects from looser near-surface layers are impossible to separate from those of the dipper basin structure, S waves are considered to be especially affected by loose sedimentary layers up to 100 m thick. This effect can be observed at periods < 1 secondy. By estimating ground motions from 1 to 10 secondy, we can consider the influence of a source and thick sedimentary layers (of up to several kilometers). In Almaty basin, the shaking intensity varies considerably with the increase of sedimentary cover thickness and the steepness of the basement slope. As an example, the accelerograms and Fourier spectra of the February 14, 2005 earthquake ($Ms=5.9$, Rep$=250$ km, $h=5$ km) recorded during the network operation period are shown in figure 1.

We can see amplification of long-period vibrations resulting from the thick sedimentary cover at all stations with the exception of MDO, which is located on rock. In the higher frequency range, the spectral level is increased at stations located on resonating layered soils

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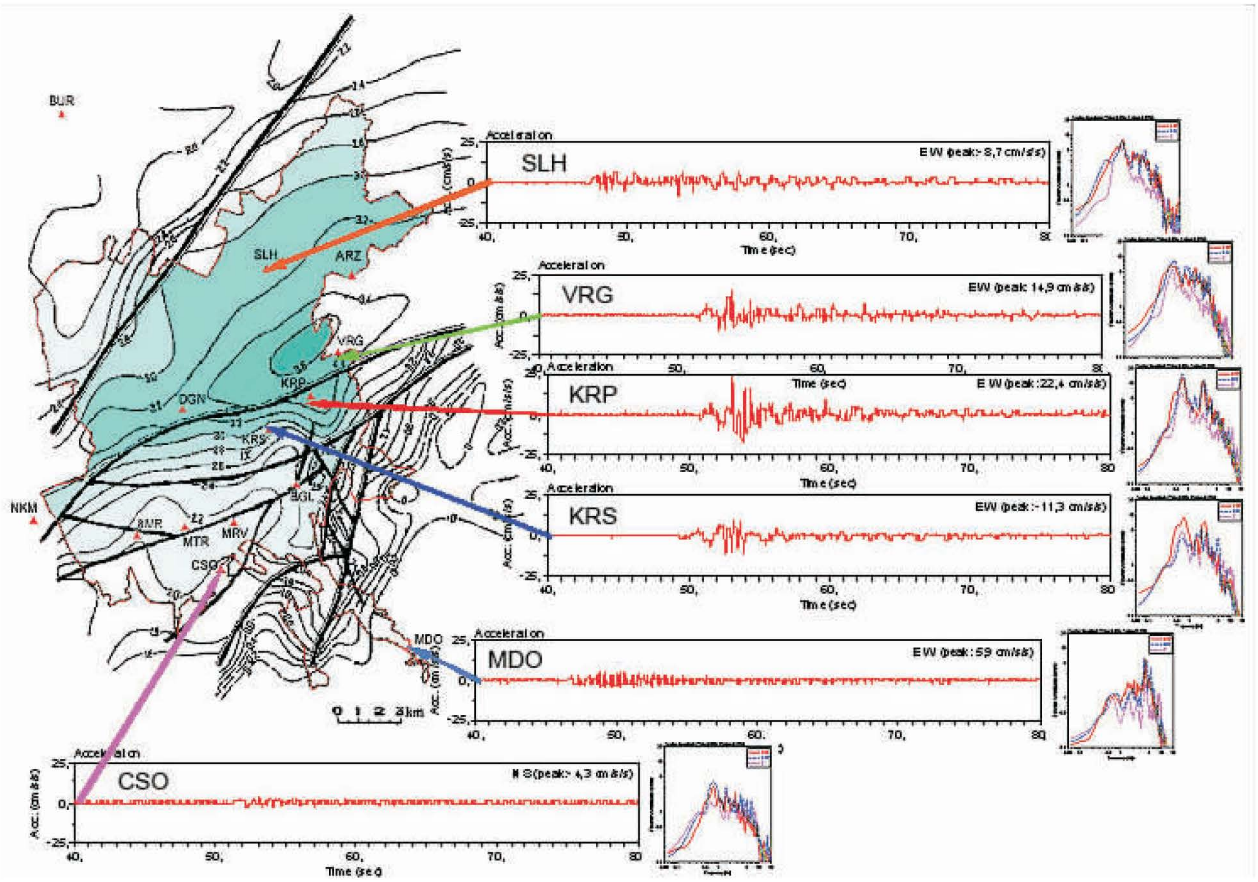

Figure 1 Accelerograms and Fourier spectra obtained in Almaty territory during the February 14, 2005 earthquake

with lower stiffness (KRP, VRG, and SLH) in comparison with stations located on boulder gravel (CSO). On thick boulder gravels amplification is observed in the zone of steep dipping of the basin boundary and lithological substitution of boulder gravel into loam and loamy sand (KRS). This also produces additional amplification at the KRP station. Amplification in a narrow frequency range at the MDO station may be caused by topography, as the station is located on the mounting slope. The other recorded earthquakes display a similar pattern. Figure 2 clearly displays the difference in the response spectra obtained in three types of soil conditions (rock outcrop, debris cone, and piedmont plain) during the May 22, 2003 Lugovskoe earthquake ($Ms = 5.6$, $h = 10$ km, Rep≈330 km).

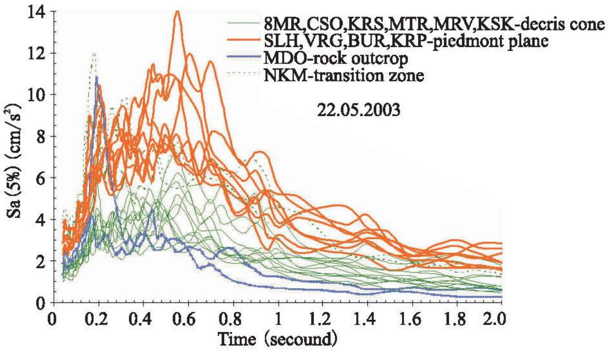

Figure 2 Response spectra of the Lugovskoe May 22, 2003 earthquake at stations located in different soil conditions in Almaty

3 Methodical approach

The microzonation methodical approach commonly used in Kazakhstan and most post-Soviet countries is based on assessment of the macroseismic intensity increment obtained by using different methods (engineering-geological, impedance contrast, seismological, and modeling) with respect to the specified average soils, usually the second category according to Kazakhstan's Building Code. The most usual practice throughout the world is to determine amplification in spectral accelerations (acceleration spectral densities) at high and low frequencies and with respect to soils with good seismic properties (such as class B rocks according to the National Earthquake Hazards Reduction Program classification). Estimations are also made by using empirical methods (reference-site technique, non-reference-site technique, or seismic noise analysis), as well as numerical simulation and modeling, which have become increasingly popular. Estimation reliability depends on both the available data and the proper choice of methodical approach in the specified engineering-geological setting.

Calculation of spectral ratios using a reference station and the H/V technique, evaluation of soil response by the Haskel-Tompson method, and analysis of spectral amplification by means of the EERA and NERA computer programs enabled us to determine resonance periods, analyze spectral ratio functions, characterize the pattern and probable causes of ground motion variations in different engineering-geological conditions, and estimate an expeditious use of these techniques within a complex methodical approach for microzonation in the city of Almaty. In the following, the results for one of the stations (SLH) is shown as an example.

4 Analysis and interpretation

The SLH station is located in an area with a thick sedimentary cover (3110 m) and a Quaternary layer (250 m) in conditions of a gently sloping basement (Fig. 1). The upper part of the soil profile is formed by loess-like loams with layers of sand and boulder gravel. The shear-wave velocity varies from 250 to 450 m/s and up to 530 m/s in gravel inclusions. The depth of the water level is >5 m. As a reference station we used MDO-the only station located on a rock outcrop within the Almaty territory. The fitness of one of the stations on debris cones (CSO) for this purpose was also checked. The CSO station is located on thick boulder gravels covered by 2−3 m of loams. Sedimentary cover under CSO reaches 1960 m, with a Quaternary layer of 220 m. The shear wave velocity is about 600 m/s, and the depth of the water level is >10 m. Sensors were located on separated concrete pedestals in the building basements in SLH and CSO and on the first floor in MDO.

In the non-reference-site analysis (H/V technique), we considered the Fourier amplitude spectra smoothed by a Parzen window with a width of 0.4 Hz and horizontal-to-vertical spectral ratios averaged over all available records. The results for MDO (33 earthquakes), CSO (34 earthquakes), and SLH (33 earthquakes) are shown in figures 3, 4 and 5, respectively.

Ratios for the MDO station exhibit amplification at frequencies between nearly 2 and 6 Hz perhaps owing to topographic conditions or weathering of the near-surface rock layers. At frequencies < 0.1−0.2 Hz, internal sensor noise dominates. Thus the results for the MDO station may be interpreted at frequencies from 0.2 to 2 Hz. At the CSO station amplification is low. The bump at 1.5−2 Hz is not higher than that at MDO. In the low-frequency range internal sensor noise also dominates, especially for the weaker earthquakes.

For the SLH station the H/V method reveals amplification over a broad range of frequencies. This result corresponds to soil conditions at SLH, giving amplification over the high-frequency range as a result of layering in the upper part of the profile and in the low-frequency range as a result of the very thick sedimentary cover.

The same data were used to obtain spectral ratios by using the reference-site technique (standard spectral ratio, SSR). The spectral amplification at SLH was first calculated with respect to the MDO reference station (23 records) and then to CSO (21 records). The obtained transfer functions, together with the corresponding H/V spectral ratios for SLH, are shown in figure 6.

As was shown before when using the MDO reference station we may interpret data in the frequency range of about 0.2−2 Hz. In this range SLH/MDO spectral ratios display considerable amplification, with not only the horizontal but also the vertical component being amplified. As a consequence, H/V curves provide lower amplification than with the SSR technique. When using CSO as a reference station (SLH/CSO) we also observe vertical component amplification in the same frequency band. In the range where the vertical component is not amplified (2−10 Hz) the spectral ratios obtained by the two methods (H/V and SSR) display good agreement.

The considerably higher amplification of SLH/MDO with respect to SLH/CSO at 0.3−1.3 Hz that was not

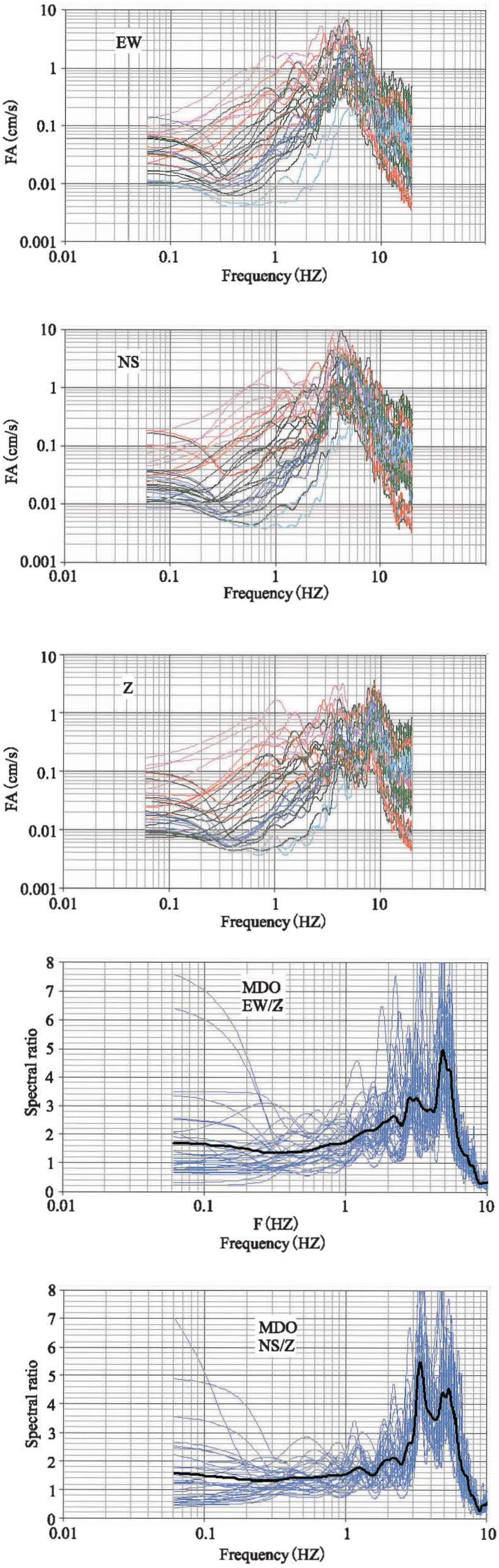

Figure 3 Smoothed FA (Fourier amplitude) and averaged H/V spectral ratios for MDO

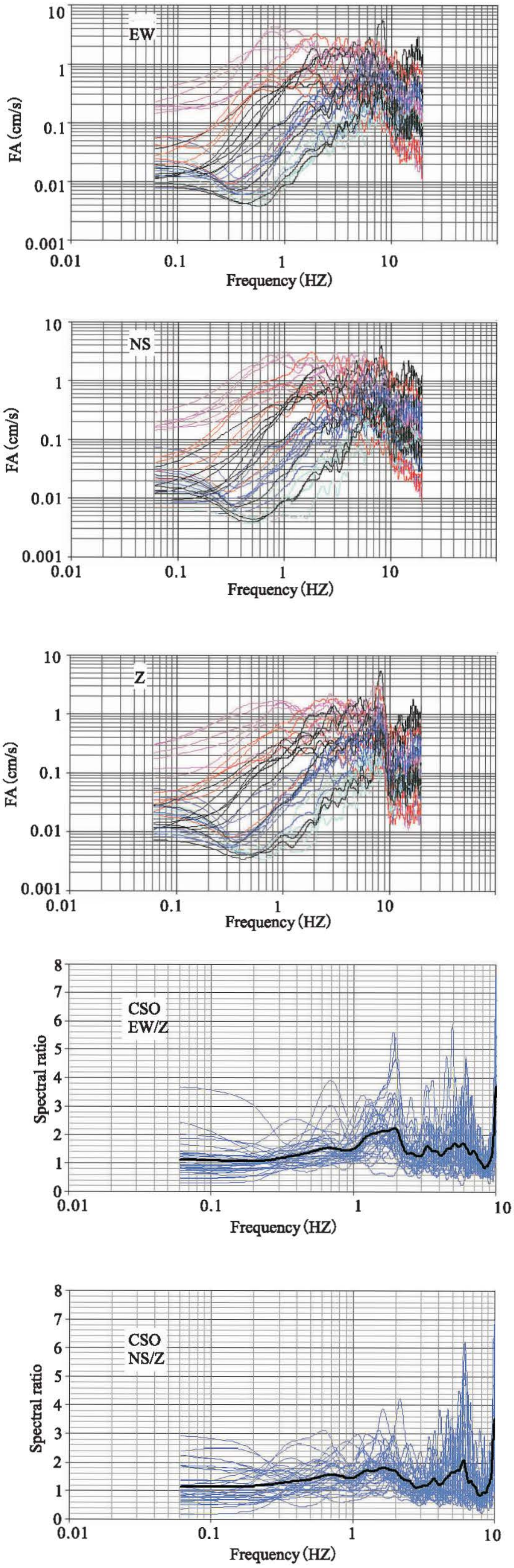

Figure 4 Smoothed FA and averaged H/V spectral ratios for SCO

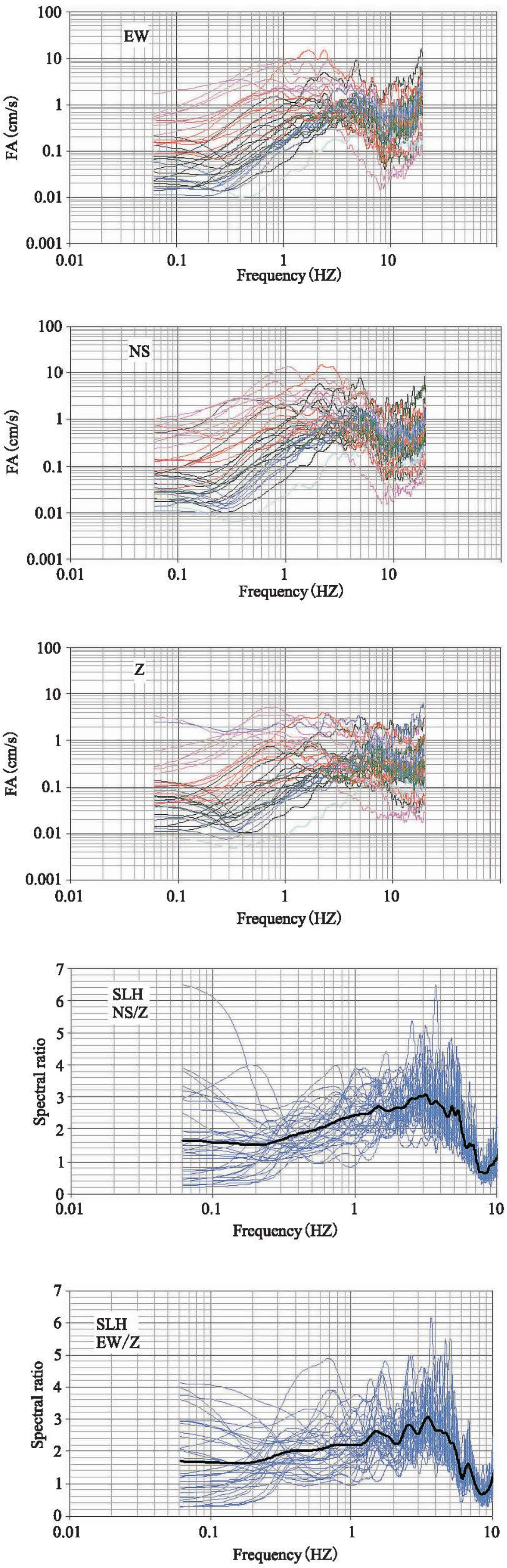

Figure 5 Smoothed FA and averaged H/V spectral ratios for SLH

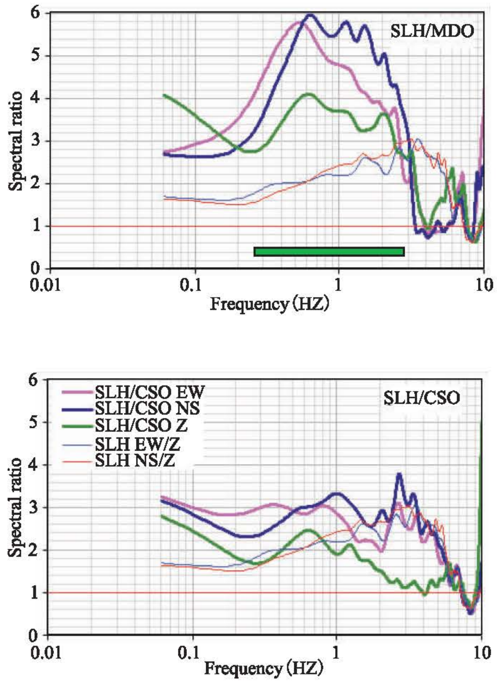

Figure 6 Transfer functions obtained by using the SSR technique for SLH with respect to MDO and CSO; thin lines represent H/V ratios for SLH

apparent on H/V curves for MDO and CSO may indicate probable amplification of the vertical component at CSO as well. This phenomenon was observed not only for CSO but also for other stations of the network within the Almaty sedimentary basin. This prevents us from using any of them as a reference station.

Thus, because of the discovered V-component amplification probably resulting from two- and three-dimensional effects of the deep sedimentary basin, the H/V method can lead to considerable underestimation of amplification under Almaty conditions. However, the method may be useful in the complex analysis when estimating spectral characteristics of a reference station, as in the case of the topography effect at the MDO station.

Simple one-dimensional (1D) models based on the Thomson-Haskell propagator matrix method allow us to estimate the site effect resulting from impedance contrast. Site responses at the SLH station were calculated for characteristic one-, two-, and three-layer models. A one-layer model accounted only for the boundary between the Quaternary sediments (Q) and the upper Neogene (N2), a two-layer model included also the boundary between the upper and the lower Neogene

(N2 and N1), and a three-layer model considered the structure down to the Pz basement. Shear wave velocity for one layer was taken from geophysical studies[3] while for two- and three-layer models weighted averaged values were used. The calculated results from these three transfer functions, together with the empirical SLH/MDO curve, are shown in figure 7.

Large impedance contrasts at the deep boundaries give amplification peaks, especially at the lower frequencies. The obtained peaks at the fundamental and higher modes correspond to peaks in the empirical curves for SLH/MDO in the frequency range of interest. The empirical site response displays more peaks and additional amplified areas than the theoretical response. The empirical peaks at about 1 – 1.2 Hz and 1.9–2 Hz are not supported by the models. The discrepancy might be caused by oversimplification of our models. Besides the lateral heterogeneities in the structure, the geometry of the basin and the presence of faults might cause diffraction and scattering effects, complicating the wave field with locally generated surface waves. This might also determine the amplification of the vertical component of the ground motion[1].

In microzonation practice of the layered medium response on the basis of the Tompson-Haskell matrix method, computer programs such as SHAKE, SIREN, KOEF-10, EERA, NERA, and others are used for analysis. We used EERA[4] for an equivalent-linear analysis and NERA[5] for a nonlinear analysis at the SLH station. The influence of the upper 50 m-thick layered sediments over boulder gravels was considered. The shear wave velocity and unit weight profiles of the model are shown in figure 8. The accelerogram recorded by the MDO station during the December 1, 2003 Narynkol earthquake (PGA = 0.013 g, Ms = 5.7, Rep = 286 km) was taken as an input signal. The obtained transfer functions, together with the empirical ratio SLH/MDO and the transfer function obtained for the simplified model for the whole sedimentary cover, are shown in figure 9.

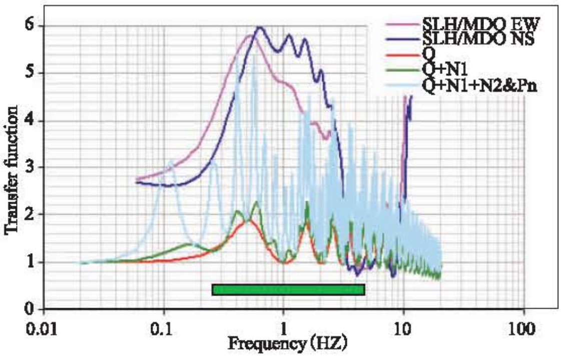

Figure 7 Transfer functions for SLH obtained by using the Thomson-Haskell method for three revealed interfaces

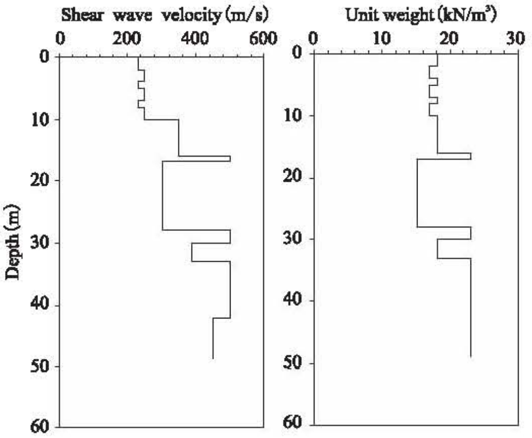

Figure 8 Shear wave velocity and unit weight profiles used in the calculations

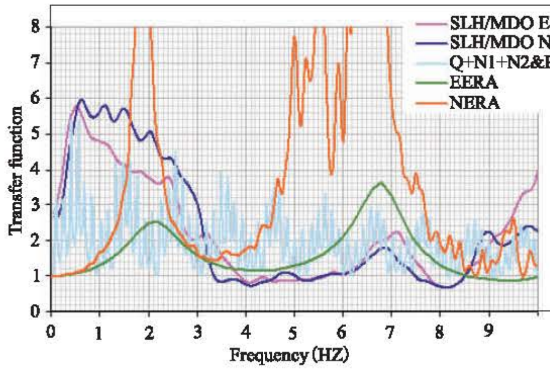

Figure 9 Transfer functions given by the EERA and NERA programs for the input model

By accounting for the 50 m subsurface layered soils in the input model we obtained response characteristics in the high-frequency range (>1 Hz). More detailed modeling of layering gave a peak at about 2 Hz in the empirical SLH/MDO functions that was not seen in the simplified 1D calculation describing only the boundaries between Q, N1, N1+Pg, and Pz. Apart from the peak at 6.7 – 7 Hz observed for all obtained transfer functions, the nonlinear calculation provided amplification within the range of 4.8–5.6 Hz that was not seen in the empirical functions because of topographic amplification in this range at the MDO station and that was undisplayed in the linear-equivalent calculation. The amplification level given by EERA is underestimated and that by NERA is overestimated with respect to the empirical one. NERA was designed for considerably stronger input signals, which might be displayed as overamplification in our case. Underestimation from EERA may be related to unequal modeling and neglect of two-and three-dimensional effects of the deep basin. Thus 1D modeling for low-and high-frequency bands gave peaks at frequencies corresponding to empirical ones (where the reference station allows them to be observed). An amplification area was also obtained in the zone where empirical data interpretation was impossible owing to site characteristics of the reference station. The peak at 1.1 Hz in the SLH/MDO ratio that was not duplicated in the modeling results is an exception to this pattern. It might be caused by some unaccounted for boundary below 50 m or by the influence of surface waves caused by the basin geometry.

5 Conclusions and discussion

Thus on the basis of the presented study on site response analysis under the conditions of Almaty city we may conclude the following:

1) The H/V technique should be used with caution because of the amplification of the vertical component at practically all city stations. Owing to probable two- and three-dimensional effects of the deep sedimentary basin this method can lead to considerable underestimation of amplification over a wide frequency range.

2) When applying the reference station method it should be kept in mind that the MDO station used as a reference has limitations for data interpretation. Its transfer function has a large amplification peak at 2–6 Hz owing to the effect of topography and rock weathering, and internal sensor noise (for ETNA) dominates below 0.1–0.2 Hz.

3) Modeling should be used in conjunction with empirical methods. The assumption of horizontal homogeneity of layers is not fulfilled for a basin and this can cause peak omissions and underestimation of amplification level. The results of NERA calculations with stronger input should be compared with empirical ratios from an area with similar site conditions and available high-energy records.

4) Modeling of two- and three-dimensional effects is important for site response analysis in Almaty.

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