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Site effect studies in Khorog (Tajikistan)

Marco Pilz[1], Dino Bindi[1], Bolot Moldobekov[2], Sagynbek Orunbaev[2], Shahid Ullah[1], Stefano Parolai[1]

1 GFZ German Research Centre for Geosciences, Centre for Early Warning Systems EWS, Telegrafenberg, 14473 Potsdam, Germany

2 Central Asian Institute for Applied Geosciences, Timur Frunze Street 73/2, 720027 Bishkek, Kyrgyzstan

During the past centuries, many cities in Central Asia have suffered significant damage as a result of earthquakes. Two crucial steps towards the mitigation of earthquake risk due to future events involves the definition of the optimal engineering designs for civil structures and the accomplishment of site response studies. Therefore, to accurately identify variations in site response at different locations within urban area, earthquakes recorded by seismic networks as well as measurements of seismic noise can be used for estimating the resonance frequencies and for evaluating the expected variability of ground motion at different sites. Additionally, the measurements can help to identify site specific features such as multi-dimensional resonances and directional effects. This information can be complemented with array measurements of ambient seismic noise that are carried out in order to estimate local shear-wave velocity profiles, an essential parameter for evaluating the dynamic properties of soil, and to characterize the corresponding sites.

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In the process of updating probabilistic seismic hazard assessment (PSHA) maps in Central Asia, a first step is the evaluation of the seismic hazard in terms of macroseismic intensity. Figure 1 (top) shows the seismic hazard for the whole country of Tajikistan derived from the smoothed seismicity model, using the Frankel (1995) approach, based on a shallow (up to 50 km deep) seismic catalog. Therein, the evaluation of the probability of exceedance of any given intensity over a fixed exposure time is mainly based on the seismic histories available at different locations without requiring any *a-priori* assumption about seismic zonation. The effects of earthquakes, which are not included in the seismic history, can be accounted for by propagating the epicentral information through an Intensity Prediction Equation.

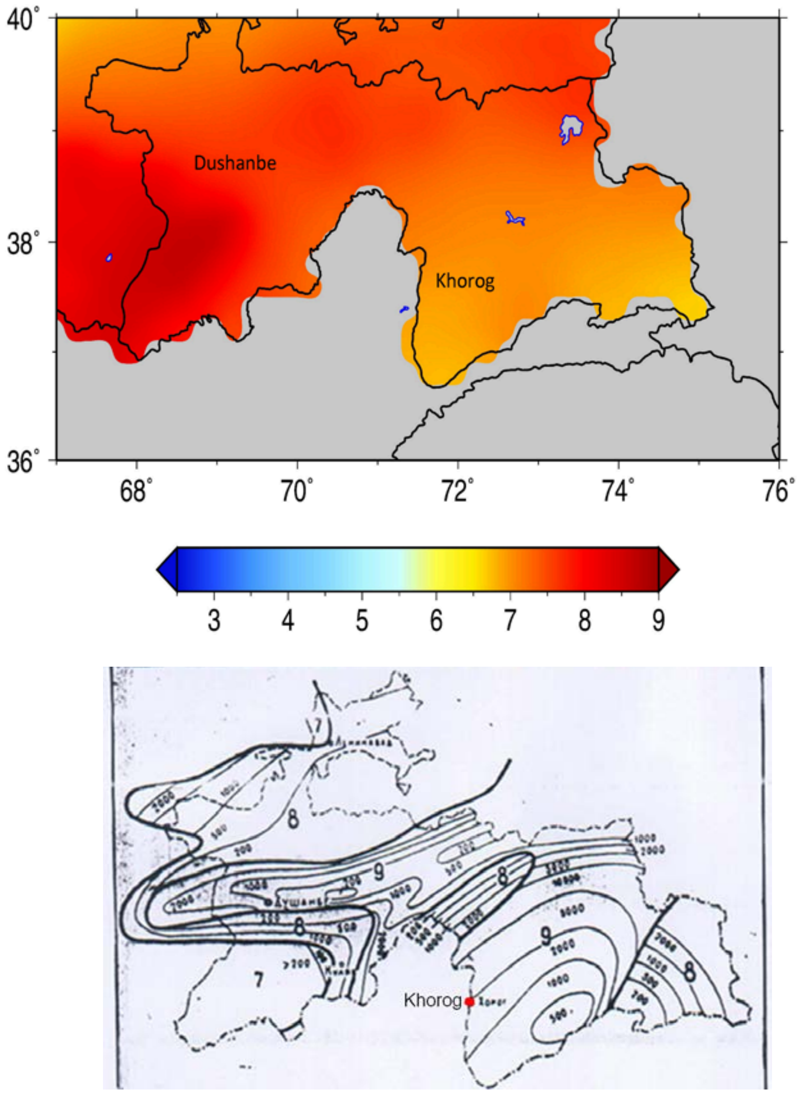

Figure 1: Top: Probabilistic Seismic hazard assessment using the smoothed seismicity approach expressed in terms of MSK-64. The map shows the 10% probability of exceedance in intensity over 50 years. Bottom: Former seismic zonation of Tajikistan with isolines having repetition of maximum intensity in years (Babaev and Mirzoev 1976).

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For comparison, Figure 1 (bottom) shows an earlier attempt at the seismic zonation of Tajikistan (Babaev and Mirzoev, 1976). As can be seen, in the early map the assigned intensity is significantly higher in the Badakhshan region and in the regional capital Khorog, reaching up to intensity 9. The new PSHA map, which is only based on a reviewed seismic catalog and is carried out for the whole region, assigns an intensity of 7 for a 10% probability of exceedance in 50 years for Khorog, i.e. a return period of 475 years. Figure 2 shows the annual probability of exceedance for Khorog city in terms of intensities. The hazard curve is obtained from the smoothed seismicity model. The expected intensities for 10% and 2% probabilities of exceedance in 50 years are also shown by black and red lines, respectively. These values highlight the necessity for a detailed, updated study of site effects in this city.

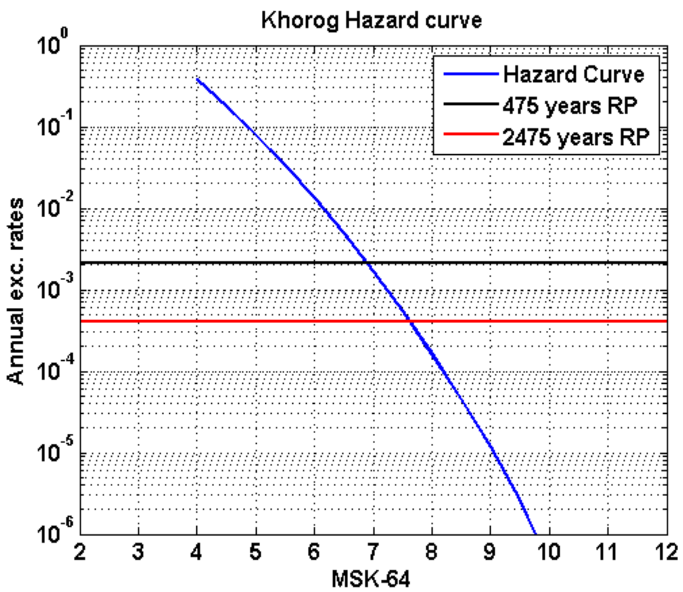

Figure 2: Hazard curve for Khorog City using smoothed seismicity approach.

The city of Khorog (population 30,000), the administrative center of the Gorno-Badakhshan autonomous oblast, is located in the southwestern region of the oblast in a narrow valley some 2000 m above sea level where the Gunt River enters the Panj River. The valley is filled with Holocene and Pleistocene deposits (Figure 3) which are expected to have a large thickness as the slope of sharp-edged canyon suggests.

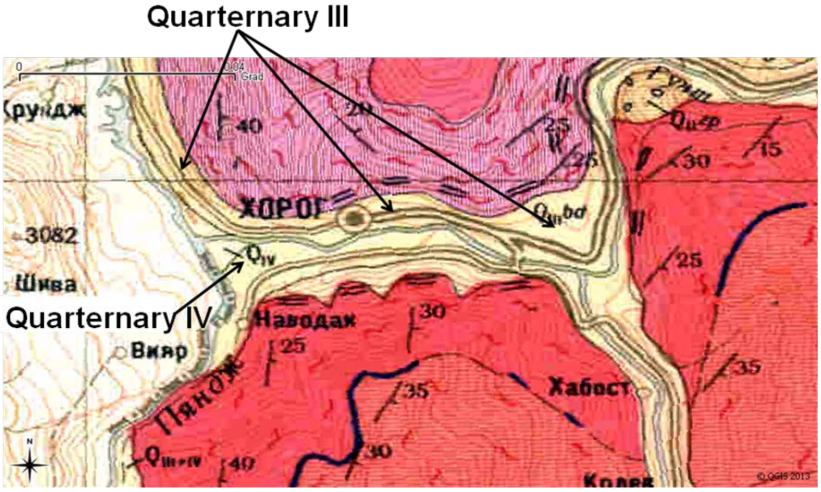

Figure 3: Surface geology around Khorog. The river valleys (yellow) are filled with Quaternary sediments.

In summer 2012, a network of 12 short period sensors was installed in the city which operated continuously for more than 3 months between 10 July and 17 October 2012. Additionally, two array measurements have been carried out. During the installation period, around 100 events were recorded, many of which occurred at local and regional distances. Additionally, eight teleseismic events were recorded. Following standard analysis procedures, earthquake H/V spectral ratios have been calculated (see Figure 4). However, no SSR analysis could be carried out due to the unavailability of a proper reference site.

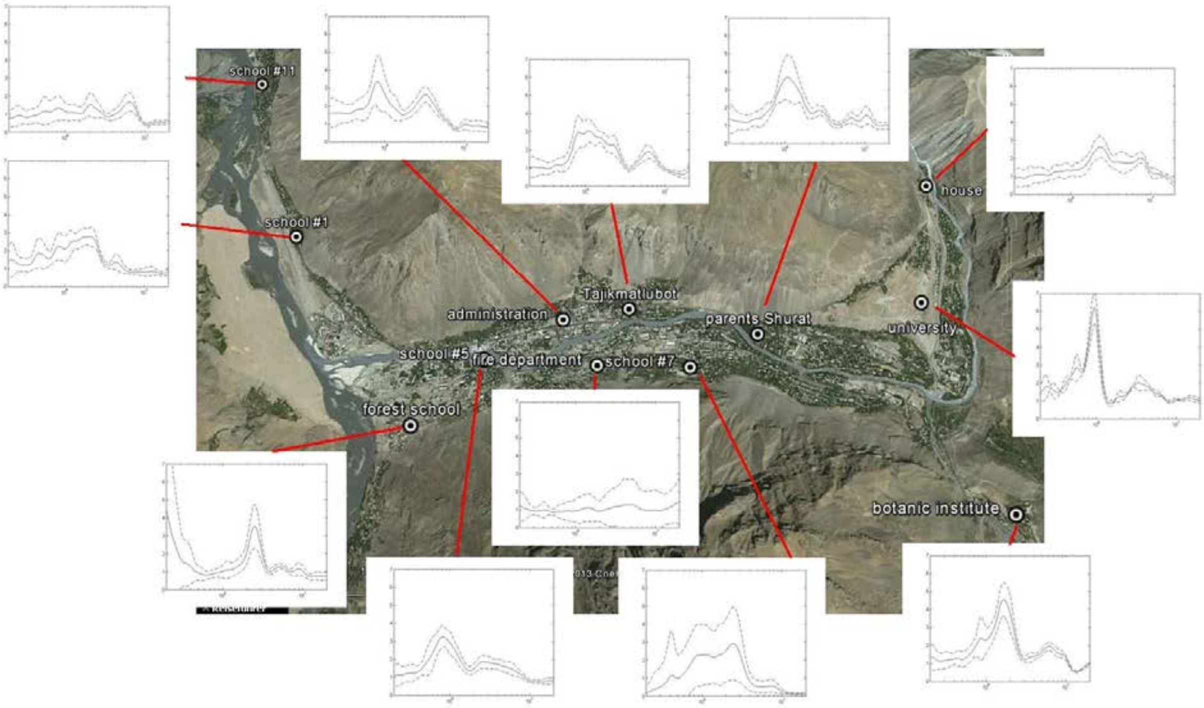

Figure 4: Network layout (white dots) in the city of Khorog. Horizontal-to-vertical spectral ratios for earthquakes plus/minus one standard deviation are shown for all network sites.

Most of the network sites not only show a single peak for the H/V spectral ratios, but also amplification over a broad intermediate-frequency range. The fundamental frequency of ~1 Hz might be associated with a deep impedance contrast with the bedrock, while the first higher mode, ~5 Hz, might be linked to a shallow impedance contrast at the gravel layer. As shown in Figure 4, the S-wave velocity-depth profiles at the array sites also suggest the presence of two impedance contrasts at depths of around 50 m and 80 m.

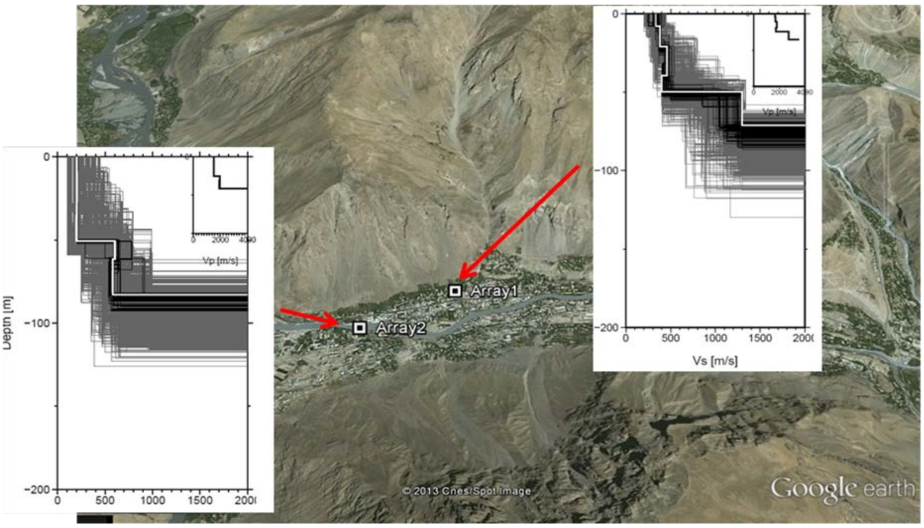

Figure 5: Array measurement sites and shear-wave velocity profiles obtained by the joint inversion of dispersion curves and H/V spectral ratios. Thin gray lines show all tested models. The white line represents the minimum cost model and the black lines indicate all models lying inside the minimum cost +10% range.

Interestingly, since the interstation distances between the stations of the temporary network are rather small (on average less than 1 km) a clear trend can be identified for the peak amplitudes. Whereas the H/V spectral ratios around the fundamental frequency for the stations in the west do not show high amplitudes, much higher values (and small standard deviations) can be found for the ratios in the eastern sites. This might indicate a comparatively higher impedance contrast at depth moving west to east. A possible explanation for this pronounced difference might be a higher compaction of the sediments in the eastern parts of the studied area.

On the other hand, multi-dimensional effects are also likely to occur in the narrow valley of the Gunt River around Khorog. Whereas the fundamental resonance frequency varies between 0.8 Hz and 1.8 Hz, no significant lateral variations can be observed for the frequency of the first higher mode. Peaks in the observed Fourier spectral ratios also suggest that edge-generated surface waves are contributing to amplification at higher frequencies. So, in this case, the interference of surface waves with vertically propagating waves might give rise to the evolution of a 2D resonance pattern for such deep valleys.

Remarkably, rather high amplitudes for the H/V spectral ratios, which provide only a lower bound in terms of site amplification, are found in the eastern parts of Khorog. This indicates that high amplification over a broad frequency range might occur. Unfortunately, the area of

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highest amplification corresponds exactly to the zone in which building densification and the completion of the new university is expected in future, therefore exposing the structures to a high level of hazard. Preventative measures are therefore indispensable to mitigate against potential earthquake-induced damage.

Summarizing, all investigations carried out in this work showed that site effects have a considerable influence on earthquake ground motion in the city of Khorog. However, we can also be better armed in assessing the physical and socioeconomic impact of earthquakes by a proper allocation of resources towards the mitigation of these impacts. The extensive research being carried out in the close cooperation between GFZ, CAIAG and AKDN on the development of earthquake risk assessment methodologies will guide our efforts in the future.

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