Seismic microzonation study for two mining cities in the SW of Kyrgyzstan

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Abstract

Kyrgyzstan is an earthquake-prone country at the border of the Pamir Thrust, north of the active shortening structure of the Pamir Mountains and the intra-continental mountain belt of the Tian Shan further north. The region has had several M7 + damaging earthquakes, which have killed thousands of people. In the West, the country is cut through by the 700-km-long NW–SE Talas-Fergana active strike-slip fault system, where no major earthquakes have been observed in the last 250 years even though paleoseismic studies show the potential to produce M7.0 + events. This study is the second part of a project to estimate the potential damage and losses on residential buildings as well as critical infrastructures in the case of a large earthquake in the two mining towns of Kadamjay and Aidarken in the SW of Kyrgyzstan. Microtremors were recorded on 82 sites and analyzed with the Horizontal-to-Vertical Spectral Ratio (HVSR) method. For each site, we estimate the average frequency of the clearest peak and its amplitude in the HVSR spectra to produce microzonation maps, in terms of response frequency. We further used these data for the calculation of ground shaking using a set of six seismic scenarios based on the known faults around the two towns. This approach has proved to be efficient in a country where the resources and available data are limited and when the time of investigation is short. The Kadamjay and Aidarken cities have been divided into different zones with specific predominant resonance frequency ranges, which information is useful for risk analysis, mitigation and buildings retrofit. In Kadamjay, three regions dominate which are related to the history of alluvial deposition in a series of terraces. The more elevated terrace could be the place of seismic site amplification. Aidarkan is much more homogenous in terms of thickness and type of alluvial deposits.

Keywords Seismic microzonation · Kyrgyzstan · Earthquake scenarios · HVSR method

Introduction

This microzonation study is part of a wider project funded by MSF (Médecins Sans Frontières) Switzerland to estimate human losses due to earthquake shaking directly or indirectly by causing landslides, rock falls, lake outbursts and/or mudflows. A focus has been on estimating the damage and losses in the case of a large earthquake on residential buildings as well as critical infrastructure like schools, kindergartens and health centers in the district of Kadamjay,

in the SW of Kyrgyzstan. Here, MSF has offices (Fig. 1). The number of casualties which could occur in the epicenter area of any likely large ($M > 6$) future earthquake has been estimated in order to reinforce the emergency capacity of MSF in this region. This analysis required us to compile population and building data at the regional scale of the district, and to perform both local and individual surveys for residential and critical buildings, respectively (Rosset et al. 2020). Collected data were then entered into our loss estimating tool QLARM (Quake Loss Assessment for Response and Mitigation), a computer code with world data sets of population and building stock that calculates losses (building damage, injured, and fatalities) due to strong shaking in earthquakes (for details on QLARM refer to Rosset et al. 2021; Trendafiloski et al. 2009, 2011).

Kyrgyzstan is an earthquake-prone country in the north of the Pamir thrust and within the intra-continental mountain belt of the Tian Shan. According to Wyss et al. (2022), the

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reported death toll in Kyrgyzstan and the surrounding countries of Uzbekistan and Tajikistan is 708, 36,768 and 12,681, respectively (counting 6, 7 and 14 fatal earthquakes, respectively). The Kadamjay district, located in the SW of the Kyrgyz Republic, belongs to the Batken Province and covers an area of about 6100 km^2 with approximately 165,000 inhabitants (Fig. 1a). The town of Kadamjay (formerly called Frunze) is its administrative center and is located 105 km East of the provincial city of Batken. Its population is about 13,200 and the population of the province is estimated around 503,500 according to the 2017 census. It is located on the two sides of the Shakhimardan River in the north of a ravine cutting an EW-oriented mountainous area. This part of the valley is oriented NS at an average altitude of 1000 m and opens out to an alluvial basin (Fig. 1c).

The town of Aidarken (formerly called Khaidarkan), 45 km to the SW of Kadamjay, has a population of 11,400 (Fig. 1a). The Aidarken district is located along the southern border of the Fergana Valley close to the northern foothills of the Alai Range at an altitude of 1100–2000 m. The relief of the Aidarken Basin is relatively flat with small hills, composed mainly of loose deposits of the Quaternary period, including the debris cones of several rivers (see Fig. 1b). The town of Kadamjay hosts the 'Kadamjay Antimony Kombinat' (KSK mine) and Aidarken is the place of the mercury mine-smelter (KMP) (Fig. 2 in Torgoev and Aleshin 2009). The climate in Aidarken is less arid and hot than in Kadamjay because it is 1000 m higher in altitude.

This paper illustrates the use of a simple and inexpensive geophysical method to quickly established first-order seismic microzonation maps at a detailed level for two mining towns, Kadamjay and Aidarken. For that purpose, a campaign of ambient noise recordings has been conducted in both towns and records analyzed using the Horizontal-to-Vertical Spectral Ratio (HVSR) method. An attempt to correlate local history of deposition and the estimated resonance frequencies of the peak amplitude in the HVSR spectra and their associated amplitude helps to propose zones with similar
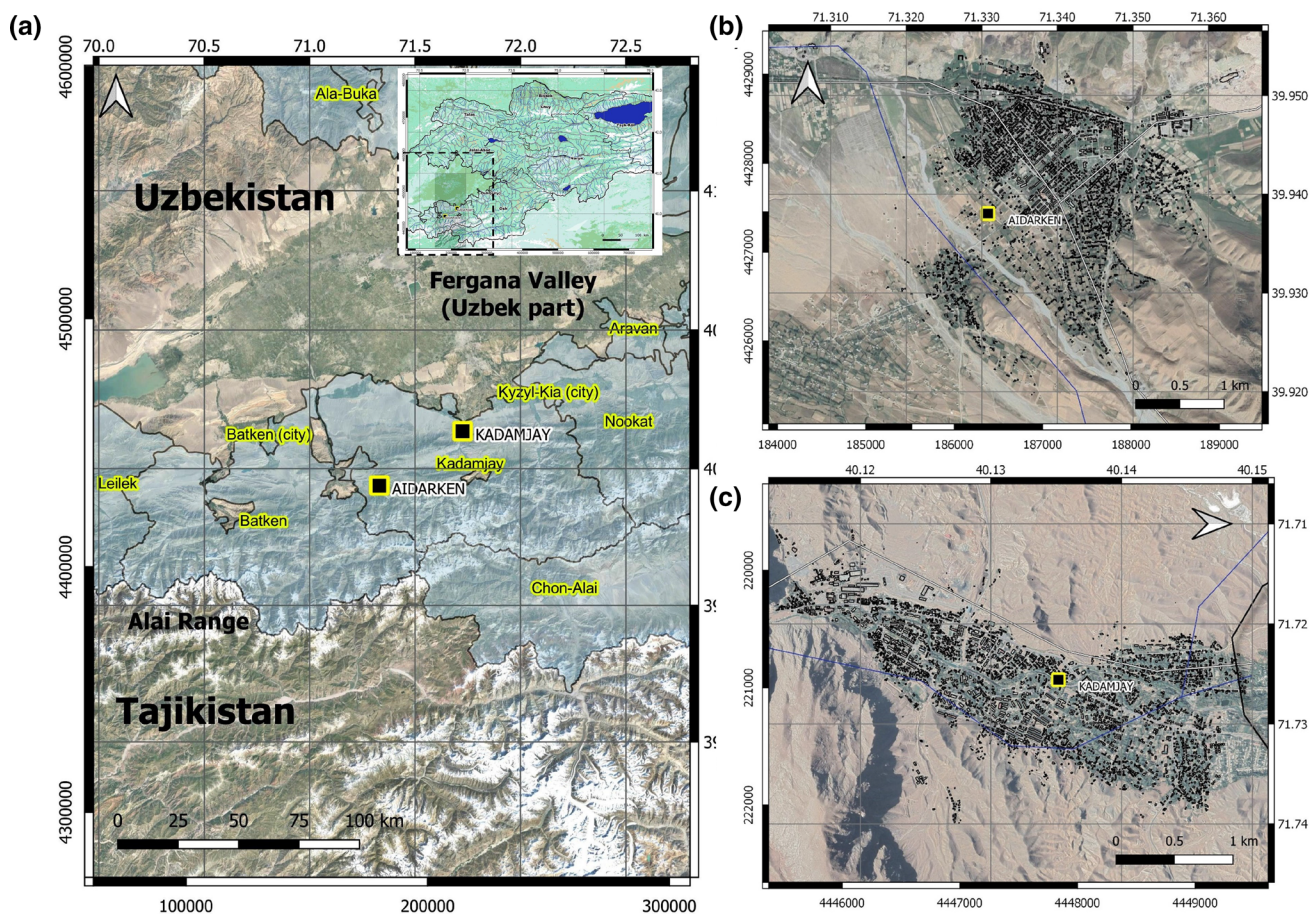
Fig. 1 Geographical context of the studied area. The Kadamjay and Batken districts are part of the Batken Province (map in **a**) is located in the SW part of Kyrgyzstan (black rectangle in the inset map). The Kyrgyz districts are contoured in black with the name highlighted in yellow. The mining towns of Aidarken (detailed map in **b**) and Kadamjay (detailed map in **c,** note 'North' arrow pointing to the right) are marked. The footprint of the buildings is in background of the maps b and c

responses in both towns. A specific zonation is proposed in Kadamjay combining microzonation and building types in terms of resonance frequencies for the risk estimate. The zonation is used for understanding potential site effects in the risk analysis presented in a companion paper by Rosset et al. (2020).

All presented maps in the figures have both WGS84 and UTM zone 43 N geographical coordinates projections in order to fulfill the needs of local experts.

Seismotectonic context

In Central Asia, because there are no seismograph networks dense enough to calculate epicenters to a few km accuracy, teleseismic epicenter estimates are prone to large uncertainties. Therefore, we base our understanding of the local epicenter accuracy (shown in Fig. 2) on our past experience of comparing teleseismic results with centers of strong shaking derived from intensity reports (Wyss et al. 2011). This comparison has shown that in Central Asia, epicenters are uncertain by 5–20 km, with 10 km being the most likely value.

The list of earthquakes with $M \geq 6$ and within a 250 km radius is extracted from the catalog compiled by the Central Asian Seismic Research Institute (CASRI) and shown in Table A1 (supplemental materials), ordered by increasing distance from Kadamjay. Earthquakes with $M > 7$ represent 8% of the list.

Molnar and Tapponier (1975), Allen et al. (1992) and Havenith et al. (2015), among others, describe the tectonics and related seismic and geological hazards of Central Asia, and thus also for the area of interest. In the region of the Kadamjay district, the seismicity diffuses with a major fault system marked by a strong earthquake activity along the Vakhsh Valley (Tajikistan), about 80 km south of Aidarken, striking ENE (Fig. 2).

In Central Asia, Abdrakhmatov et al. (2003), Bindi et al. (2012) and Ischuk et al. (2018) have mapped active faults. In the study area, two sources for faults are available; one from CASRI (in Abdrakhmatov, 2009) without references to the involved authors and another one from Mohadjer et al. (2016) available on the web with the authors cited. Although many faults are the same in both data sets, the number of faults in the CASRI data set near the two towns of interest is far greater. Thus, the faults in CASRI closer than 40 km
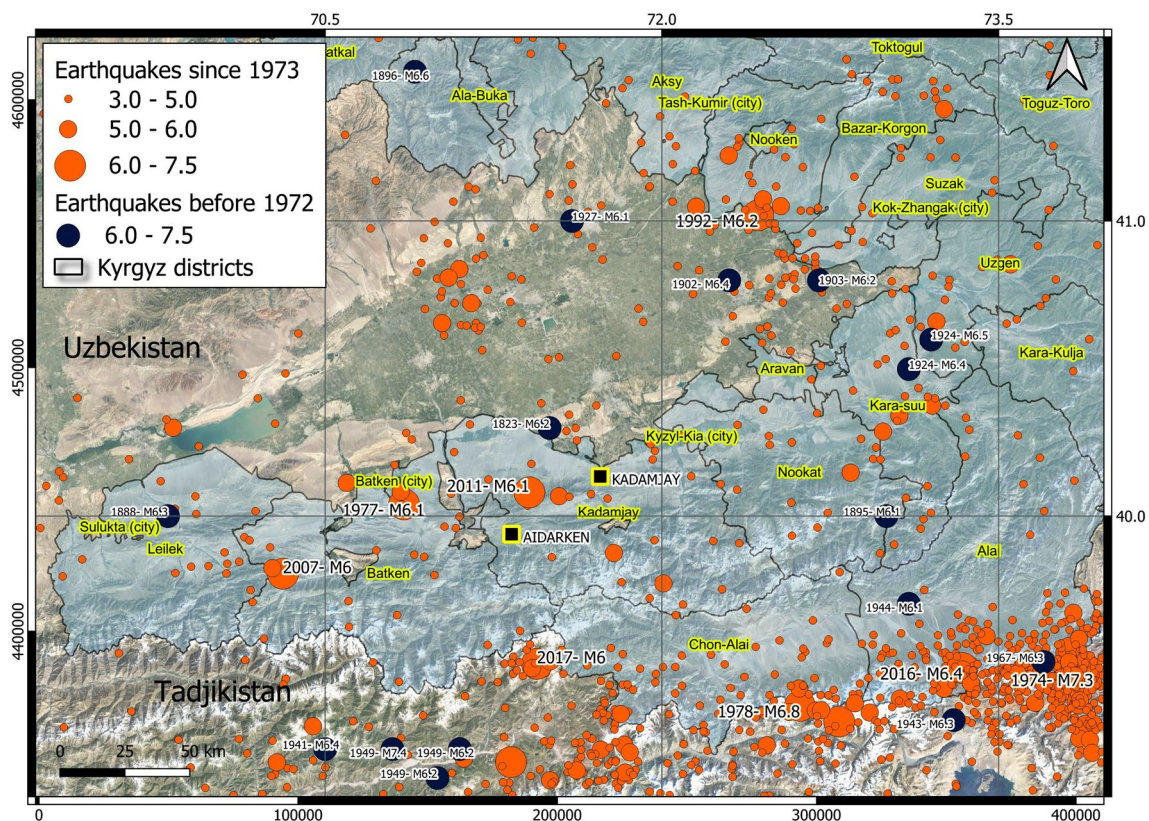
Fig. 2 Topographic map of the SE part of the Kyrgyz Republic showing historic and recorded earthquakes. Orange dots locate recorded earthquakes since 1973 and purple ones reported events since 1620. Year and magnitude of earthquakes with magnitude $M \geq 6$ are indicated. Yellow contoured rectangle locate the towns of Kadamjay and Aidarken. The Kyrgyz districts are contoured in black with the name highlighted in yellow

to our target area were selected as possible sources for earthquakes, which could strongly affect the study region.

Within a distance of 150 km around Kadamjay, the seismicity is diffuse, except for the region in the South, crossed by the Vakhsh Fault system that is outlined by strong earthquake activity about 80 km south of Aidarken, striking ENE (Figs. 1 and 3) and marked by the occurrence of the disastrous $Mw = 7.4$ Khait event in 1949 (in Tajikistan).

The slip rate across faults is of special interest because it allows an estimate of the approximate time it takes to accumulate the slip required for an M6 + earthquake. Considering the NS compression in all of Asia the annual rate is approximately 4 cm/year (e.g., DeMets et al. 2010). Half of this is taken up in the Himalaya and the other half in the Tien Shan (see GPS measurements analyzed by Abdrakhmatov et al. 1996) wider compression belt. The fact that approximately 2 cm/year of compression is distributed over numerous faults leads to the conclusion that only millimeters/year are available for single active faults (e.g., Zubovich et al. 2010; Thompson et al. 2002).

The map of Fig. 3 shows the main supposedly active faults of the study region where slip could be accumulated. The closest faults with calculated slip rates are located about 300 km ENE of Kadamjay and show a different tectonic setting (Thompson et al. 2002) predominantly marked by thrust fault mechanisms. The results of Thompson et al. (2002) and Coddington and Burgette (2018), who mapped faults south of Bishkek in the same tectonic province, measured slip rates between 0.1 and 3 mm/year, which are representative of slip rates along faults in the study area.

The use of horizontal-to-vertical spectral ratio (HVSR) method in Kadamjay and Aidarken

In order to assess the influence of the soil on seismic waves, a campaign of ambient noise recording was carried out and the data analyzed using the Horizontal-to-Vertical Spectral Ratio (HVSR) method. This method is considered
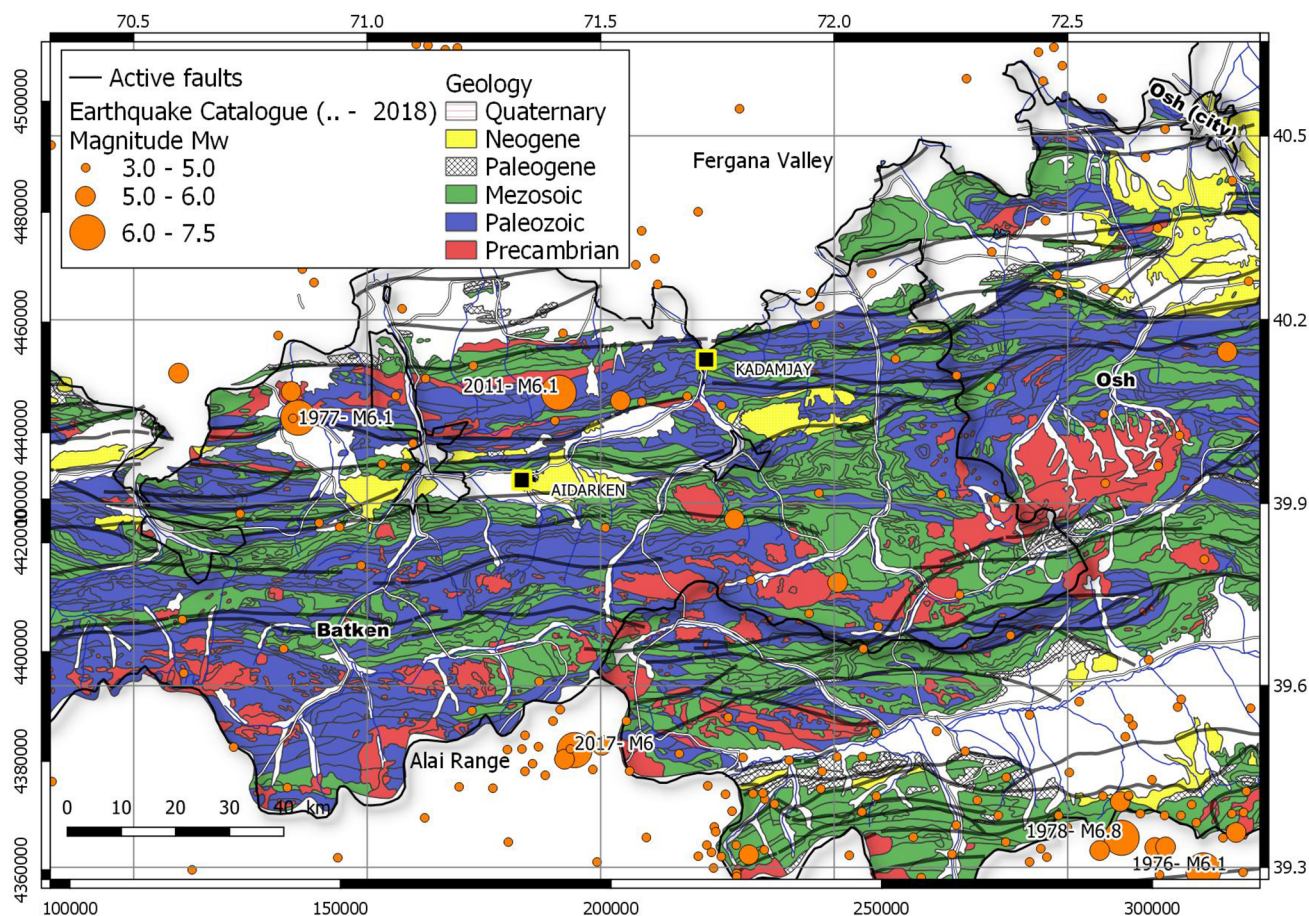
Fig. 3 Seismotectonic map of the Batken region in Kyrgyzstan (not available for neighboring countries at this scale). The map locates earthquakes, with year and magnitude for those with magnitude higher than 6. The main geological layers as well as identified faults from CASRI catalog are indicated. Note: most faults are thrust faults in this area, some are strike-slip faults but existing maps do not specify which ones

as one of the cheapest, fastest and most suitable method to estimate the fundamental resonance frequency of a site, which is linked to the ground geological conditions. For example, a dominant frequency of microtremor higher than 5 Hz is an indicator of a thin layer of soft soil, while lower frequencies indicate thicker and probably looser or softer sediments. The method is described in detail in the state-of-the-art paper of Molnar et al. (2018) and has been widely used for the last 30 years (e.g., the review by Lunedei and Malischewsky, 2015). We use the Geopsy software (Wathelet et al. 2020) to analyze the signal and follow the standard procedure described in the SESAME project (Bard et al. 2008). Ambient noise was recorded during 20 min after setting up the Tromino© sensor in a flat and quiet zone. The majority of the sites were on soil and a few were on concrete or asphalt. The ratio STA/LTA (Short Time Average over Long Time Average) was fixed between 0.2 and 2.5 in order to select windows without energetic transients and to avoid abnormally low amplitude signals. STA is the average level of signal amplitude over a short period (here fixed at 1 s) and LTA the average level of signal amplitude over a long period (here fixed at 30 s). A minimum of 10 windows of 20 s were selected in order to have a reliable number of cycles. For that, an overlap of the windows by 10% was chosen in order to increase the number of windows when transients are important. The signal saturation was avoided by smoothing windows when the peak amplitude exceeded 90% of the raw signal. The conservative Konno and Ohmachi (2000) filter with a bandwidth coefficient of 30 within a range from 0 to 100 was selected to smooth the Fourier spectra windows.

Kadamjay is located on the two flanks of the Shakhimardan River (Fig. 1c)The eastern flank of the town has the highest peak around 1640 m and is composed of limestone and conglomerates of Carboniferous ages (360–295 Ma) with a steep dip westward. The western flank is occupied by the KSK antimony mining site and cut by a perpendicular valley. Rocks are shale of Silurian age (443–419 Ma). Alluvial terraces are covering both flanks and are more prevalent in the eastern part. The terraces are made of a mix of layered dense sand, gravel and boulders with a limestone matrix as shown in the photograph of Fig. 4 taken close to the site KDJ034 (red colored dot in the map). In Kadamjay, the survey was carried out to cover the terrace, the flanks and the alluvial valley. A total of 43 sites have been investigated using the HVSR method as shown in Fig. 4.

Aidarken is located on a flat EW deposition cone created by alluvial material coming from mountains in the south by the Gavian River (Fig. 1b). The alluvial deposits are composed of boulder, gravel and sand of different levels of compaction as shown in the photograph of Fig. 5. The eastern part of the town is built on loess deposits

(Neogene period) which are progressively eroded by seasonal streams as shown in the photograph of Fig. 5. High mountains surround the valley to the south and north. For this town, 39 sites were investigated using the HVSR approach with the same protocol. The map of Fig. 5 shows the location of the ambient noise recording sites.

Results of the HVSR analysis

The procedure described in Sect. "The use of horizontal-to-vertical spectral ratio (HVSR) method in Kadamjay and Aidarken" is applied to ambient noise recorded in both towns of Kadamjay and Aidarken. Examples of HVSR spectra in Fig. 6 show the calculated individual spectra from the different windows in thin colored lines, the average spectrum in bold lines and the standard deviation calculated with individual spectrum in dashed lines. For each site, the average frequency of the clearest peak f_0 as well as the standard deviation $Stdv(f_0)$ was estimated, as shown in Fig. 6 by the vertical gray bar. The amplitude of the HSVR curve at the average frequency A_0 was also measured as an indicator of the reliability of the estimate and of the impedance contrast. In addition, a qualitative rate of the HVSR curve was expressed by a value ranging from 1 to 4, the latter being the most accurate one. Rate 1 is given to spectra with low amplitude values, rate 2 to spectra with multiple peaks of the same amplitude, rate 3 to spectra with two clear peaks at different frequencies f_0 and f_1 and rate 4 to spectra with one single clear peak of significant amplitude. Each case is illustrated in Fig. 6.

The maps in Figs. 7 and 8 locate the sites investigated in Kadamjay and Aidarken, respectively, and groups them in terms of estimated f_0 value and quality rate. The f_0 and A_0 values are written close to the site. Two pdf files in the Supplementary Material compile the spectra for all the sites in both towns (HVSR_KDJ and HVSR_ADK for Kadamjay and Aidarken, respectively).

The Table A2 of the Supplementary Information lists the sites, their location, the date of measurements and the parameters described above for both towns. The collected data are used to propose a zonation based on the geology and the estimated resonance frequencies.

Seismic zonation for Kadamjay and Aidarken

In Kadamjay, the amplitude of the *H/V* peaks is low indicating a relatively small impedance contrast, i.e., an expression of the variation of shear wave velocity between the two layers generating peaks. The HVSR analysis for sites in the base of the valley shows clearly a rock response, with flat,
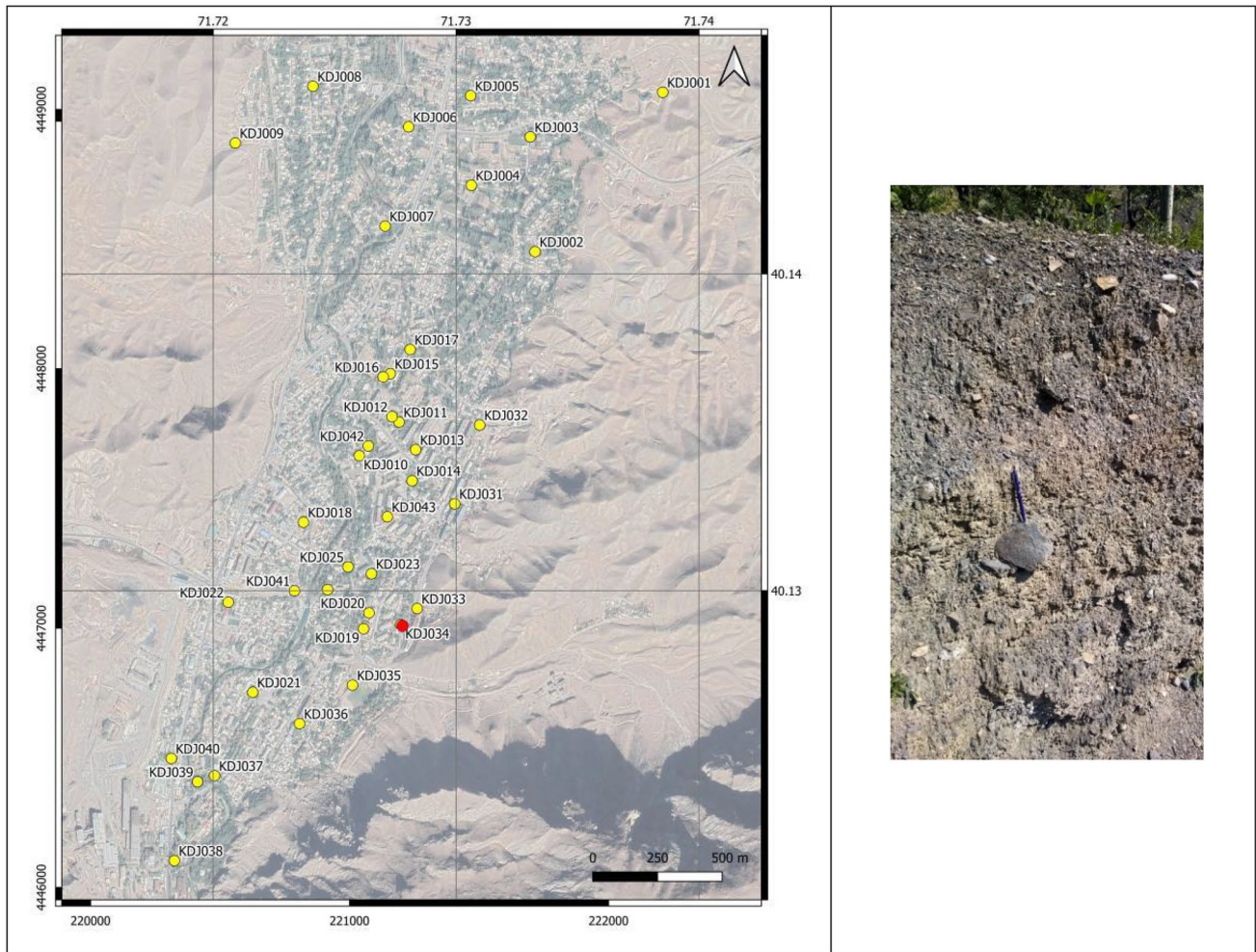
Fig. 4 Location of the HVSR sites in Kadamjay. Yellow dots locate the sites. The photograph on the right shows the typical deposits of the terrace in the eastern flank of the valley at the site KDJ034 colored in red. A pen of 14 cm length makes the scale

low amplitude spectra without a clearly identified peak or a high frequency amplitude peak. This region is divided in three zones (numbered 7–9 in Fig. 7) based on the types of buildings (single-family houses and multi-story buildings). In the eastern and western part of the town, the soil response is influenced by the altitude and thickness of the terraces. The western flank shows a low amplitude peak at frequencies varying from 6 to 10 Hz. This flank is divided in three zones (numbered 4–6) based on their altitude. On the eastern flank, the site response is inversely correlated with the elevation of the terraces, and frequencies varying from 4 to 9 Hz from the top to the bottom (zones numbered 1–3, respectively). The map of Fig. 7 shows the zones in different colors and their range of f_0 values.

For Aidarken, the zonation is influenced by the deposition history of eroded deposits from the high mountains carried down by the southeastern streams and by seasonal flooding. Seasonal precipitation erodes the important loess formation in the eastern part of the city (zone 9 in the eastern part of the map in Fig. 8). The zones 2 and 3, which were not investigated since they are not urbanized, correspond to the massive part of the loess deposit. The proposed zonation of Fig. 8 considers these different sources of deposition which correlate relatively well with the obtained value of predominant frequency f_0 from the HVSR analysis. The zones numbered 7, 8 and 10 are the ones where we could expect the largest thickness of alluvial deposits considering the low value of f_0 and the proximity with the River. In the northern
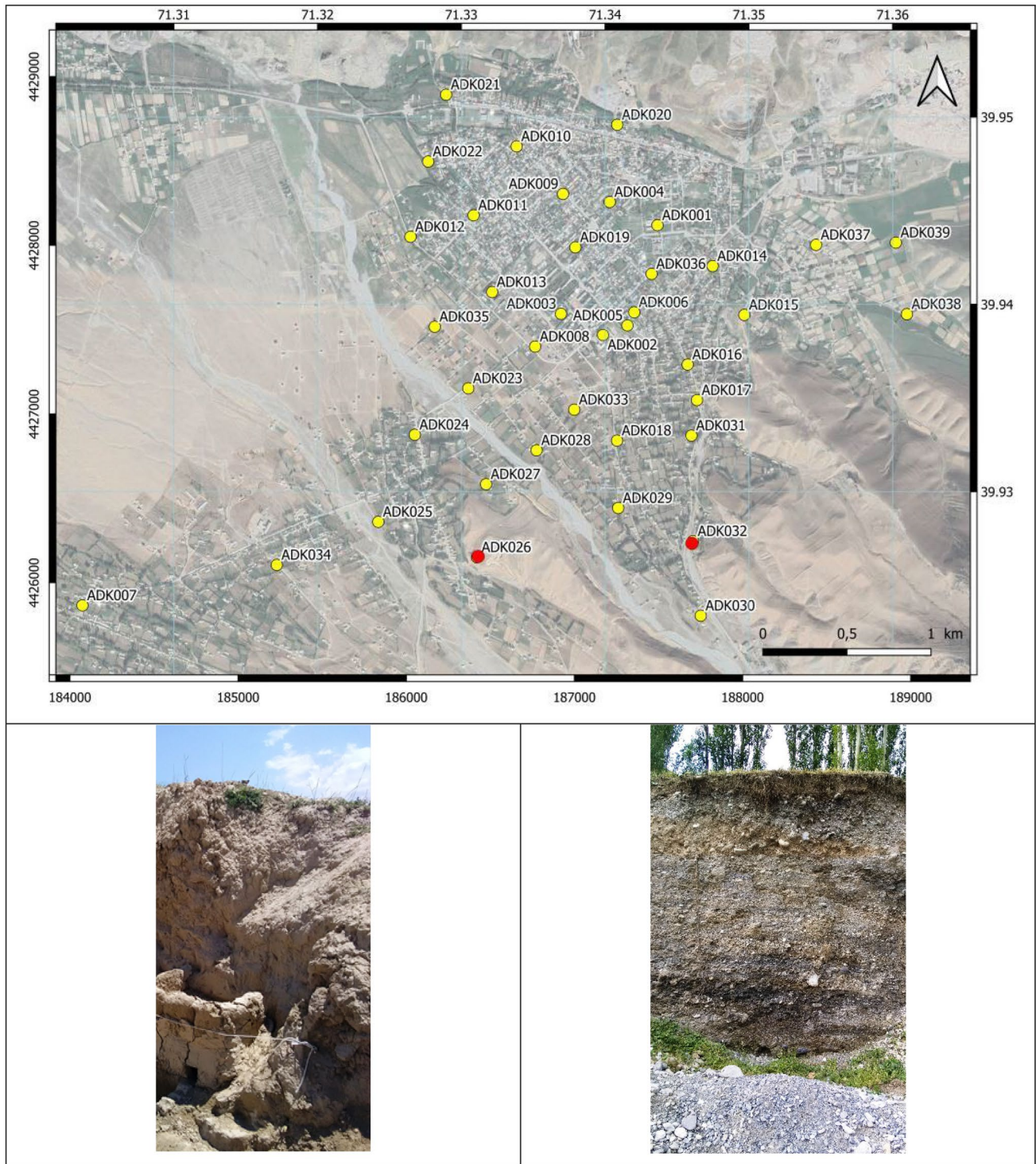
Fig. 5 Location of the HVSR sites in Aidarken. HVSR sites are located by the yellow dots labeled as in Table 2 of the Annex. The photograph on the left shows loess deposits (red point labeled ADK026) and the right one shows river deposits (red point labeled ADK032). The thickness of soil in both photographs is around 3 m
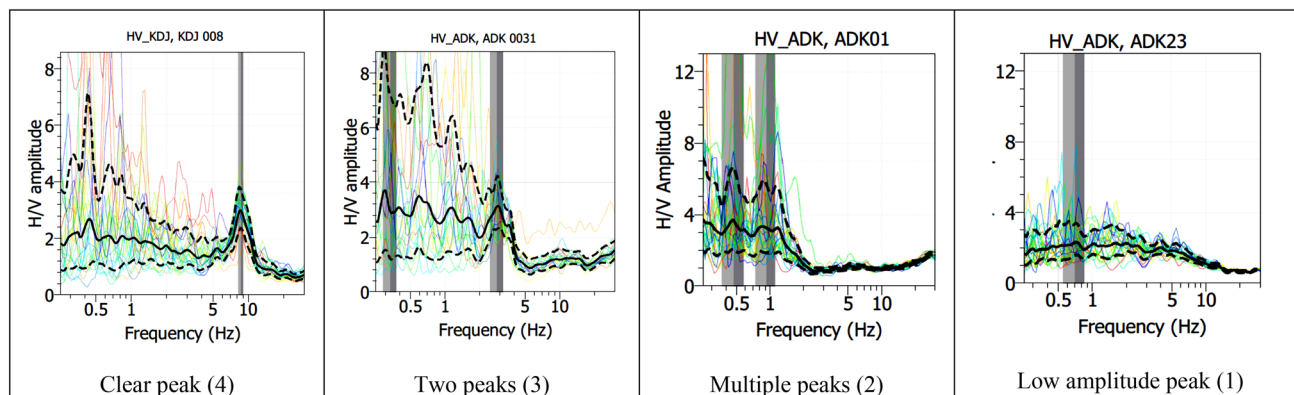
Fig. 6 Four types of HVSR spectra. The rate from 1 to 4 is indicated in brackets

part of the town, the outcropping bedrock is delimited by the zone 1. Two zones southward have high values of f_0, which could be correlated with a thin layer of alluvial deposits (zones numbered 5 and 6 in Fig. 8). A zone (numbered 3) in the right bank of the present river shows resonance frequency around 3–4 Hz, which could be explain by a lower thickness of deposit than the areas further downstream. The map of Fig. 8 shows these zones in different colors and their range of f_0 values.

Use of the microzonation maps for seismic risk analysis

For this seismic microzonation project, only the HVSR approach has been selected because the time in the field (3 days per city) and the budget were limited. Most of the investigated sites in both towns have a clear peak amplitude often accompanied by a second peak with lower amplitude (true for 70–80% of the investigated sites). The signature of rock sites is confirmed by flat HVSR spectra in Kadamjay and in Aidarken. Where the extent of the alluvial deposits is large, a single clear peak at low frequency is observed in 46% of the sites. The first estimate of the resonance frequency of the investigated sites is in accordance with what we know from the limited geological data and from the observations and deposition history. In Kadamjay, the resonance frequency decreases with the elevation of the alluvial terraces mostly present in the eastern part of the city indicating an increase in the thickness of the deposits (Fig. 7). In Aidarken, the frequencies are higher in the eastern flank of the alluvial cone than in the center, where the city is located, suggesting a thicker layer of more ancient deposits (Fig. 8).

The information of the zonation maps proposed in Figs. 7 and 8, for Kadamjay and Aidarken, respectively, were included in the calculation of the ground motion model (in terms of intensity) used for risk estimate for the six different seismic scenarios presented in a companion paper (Rosset et al. 2020). In both towns, a building footprint database using satellite photographs and a field survey at the scale of individual blocks were conducted. The most typical buildings were visited in order to count and distribute the footprints dataset by construction types in terms of the six EMS-98 classes (Gruenthal 1998) of decreasing vulnerability, from A to F, as detailed in the companion paper of Rosset et al. (2020). Building properties in conjunction with site response characteristics allowed the division of Kadamjay into three zones (Fig. 9) as follows:

- Zone 1 includes the northern part of Kadamjay with HVSR resonance frequency f_0 higher than 8 Hz and mainly built up with single-family houses.
- Zone 2 the southern part with f_0 higher than 6 Hz but with a mixture of single-family houses and multi-floor buildings.
- Zone 3 is located inside Zone 2 in the eastern section of Kadamjay with f_0 between 4 and 5 Hz (the light blue zone in the map of Fig. 7).

The resonance frequency of the sites f_0 was compared with the average resonance frequency of the buildings F_0 in the three different zones. For the rough estimation of the fundamental frequency F_0 of the buildings of interest, the empirical equation given in the Eurocode 8, Sect. 4.3.3.2.2 (EN 1998-1 2004), that follows has been used.
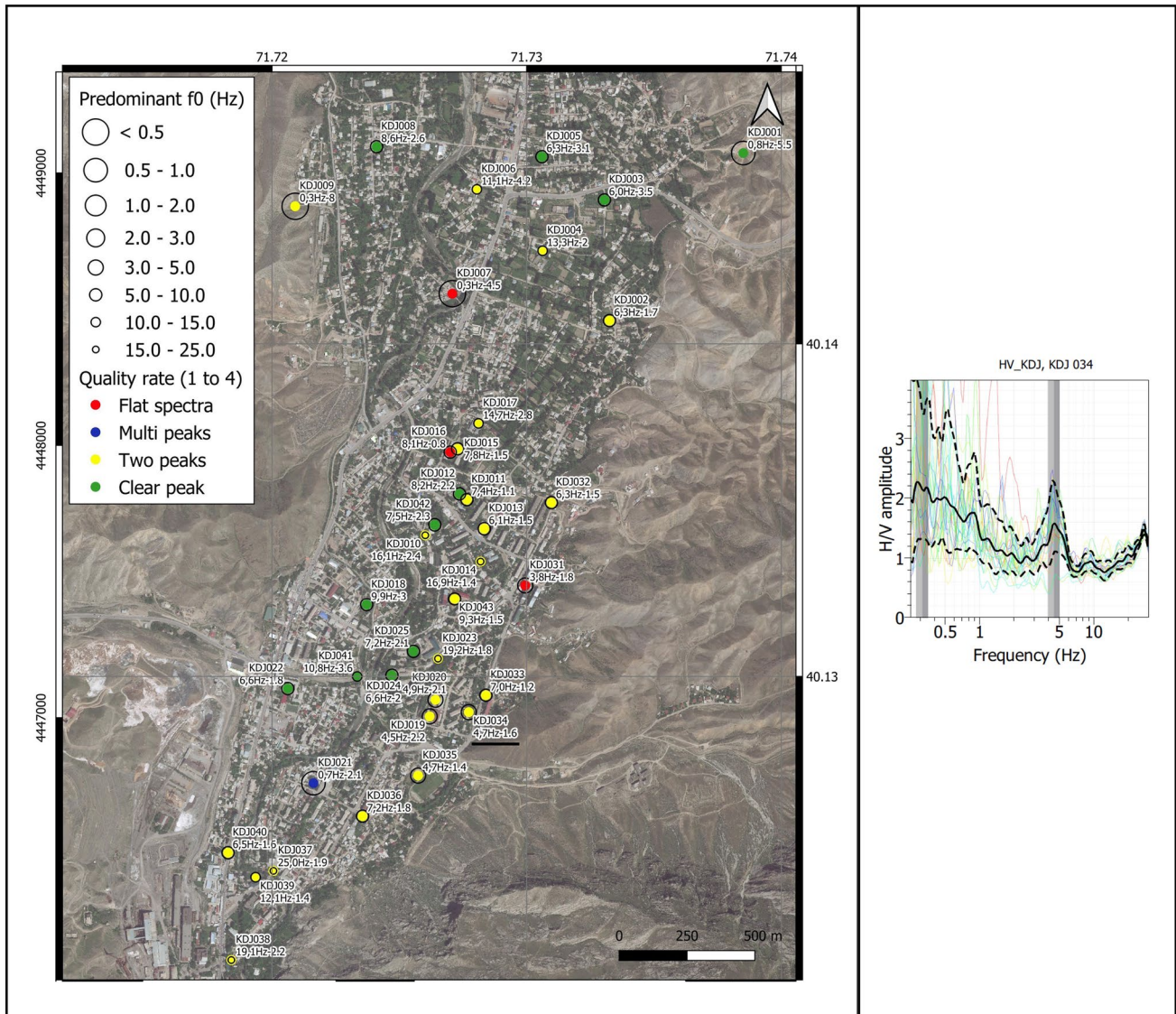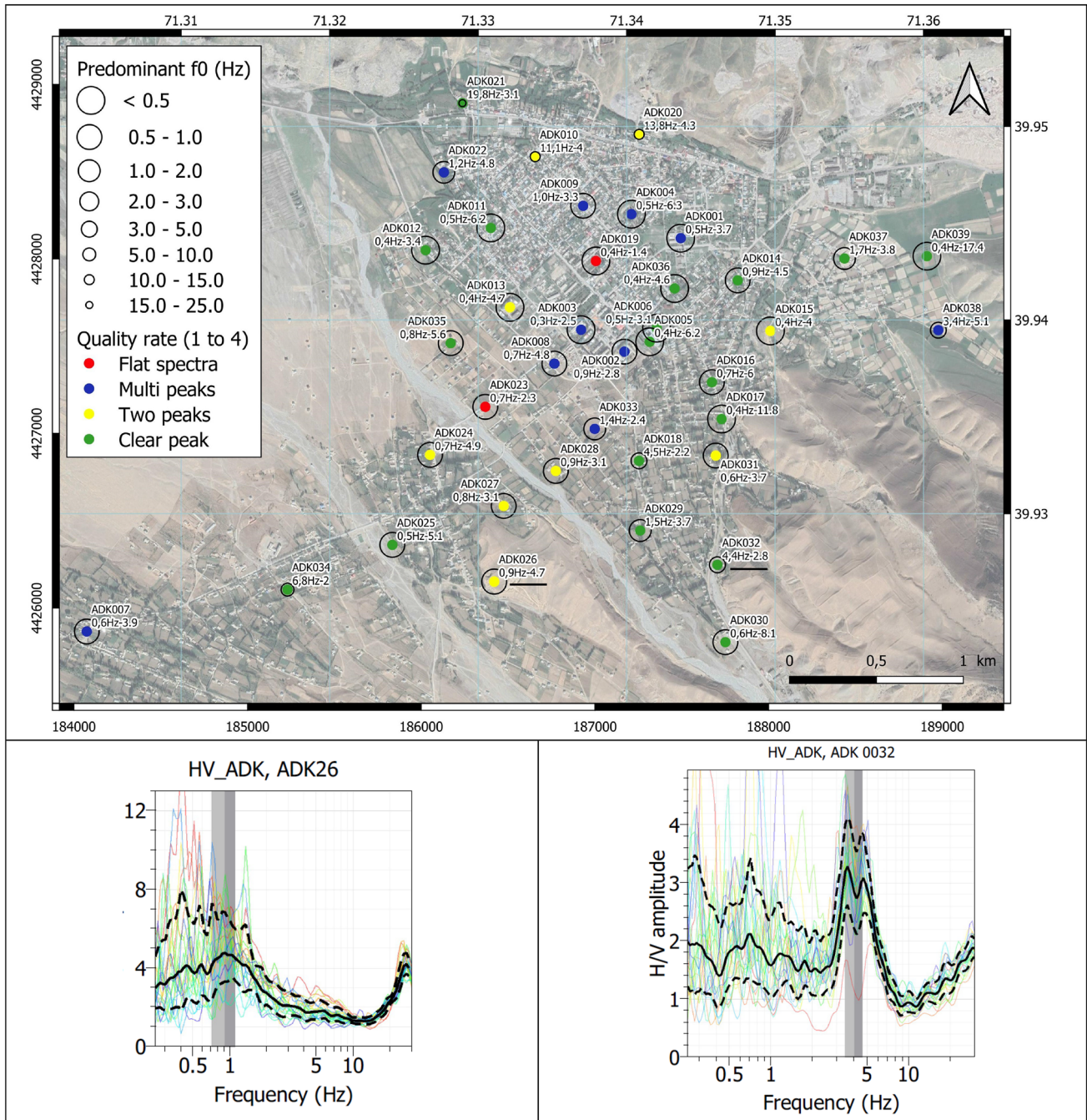
Fig. 7 Results of the HVSR method for sites in Kadamjay. Colored dots locate the sites. The sizes of the circles are inversely proportional to the value of f_0. Colors indicate the qualitative rate given to the HVSR curve. Name of the site, predominant frequency f_0 (in Hz) as well as the amplitude of the main peak A_0 are written close to the site. The HV spectrum on the right shows the typical response for deposits of the terrace in the eastern flank of the valley at the site KDJ034 underlined in black

$$F_0 = \frac{1}{CH^{\frac{3}{4}}}, \tag{1}$$

where C equals 0.075 for reinforced concrete buildings and 0.050 for masonry buildings, and H is the height of the building from its foundation. The height of a typical floor is assumed as 3 m where relevant data were not available (Figs. 10, 11).

In Zone 3, most of the buildings are a mix of unreinforced masonry, reinforced masonry and reinforced concrete structures with 4–6 floors. The estimated response frequency f_0 of the soil varies between 4 and 5 Hz, values which are close to the dominant frequency of the buildings in this zone. In order to consider possible damaging resonance effects between soil and structure responses, the calculated intensity was increased by adding 0.2 units. This value, which is an

Fig. 8 Results of the HVSR method for sites in Aidarken. Colored dots locate the HVSR sites. The sizes of the circles are inversely proportional to the value of f_0. Colors indicate the qualitative rate given to the HVSR curve. Name of the site, predominant frequency f_0 (in Hz) as well as the amplitude of the main peak A_0 are written close to the site. The HV spectra on the left are for loess deposits and the right one for river deposits (sites ADK026 and ADK032 underlined in black, respectively)

empirical expert estimate independent of the level of shaking, should be verified by dynamic structural analyses in a future stage.

On July 19, 2011, an earthquake occurred in the Kadamjai region, with magnitude $M = 6.2$, called Kan earthquake (Kamchybekov et al. 2013). The epicenter of this event was
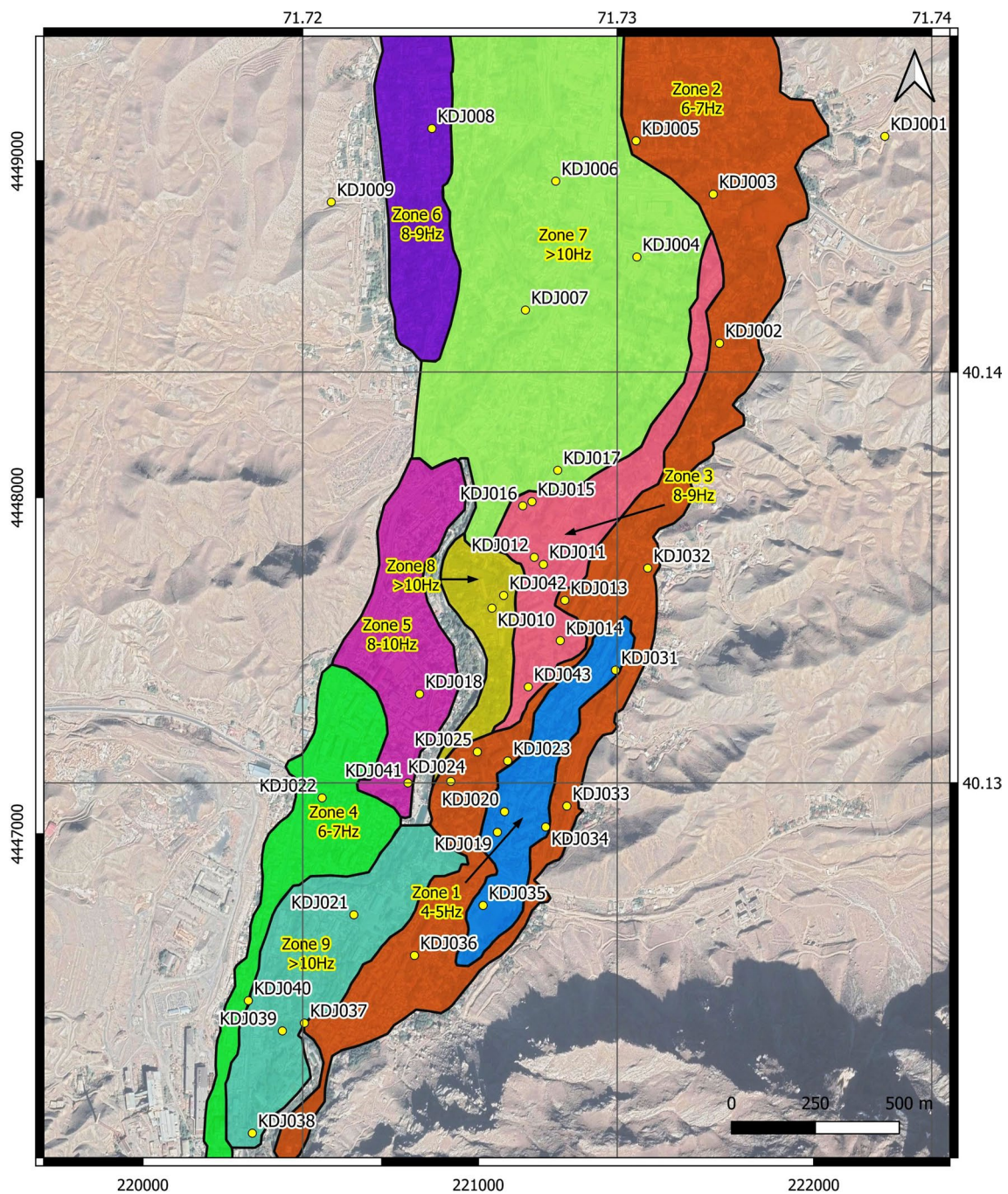
Fig. 9 Zonation map for Kadamjay in terms of resonance frequency f_0. Ranges of f_0 values defines each colored zone and are written in black and highlighted in yellow. The yellow dots locate the investigated sites

located 40 km to the west of Kadamjay (40.13 N, 71.435E and depth between 7 and 20 km). According to the Kyrgyz Ministry of Emergencies, more than 60 social facilities and about 800 private houses were affected, more than 200 of which being completely destroyed. In Kadamjay City, 107 apartments in six multi-story houses were damaged and
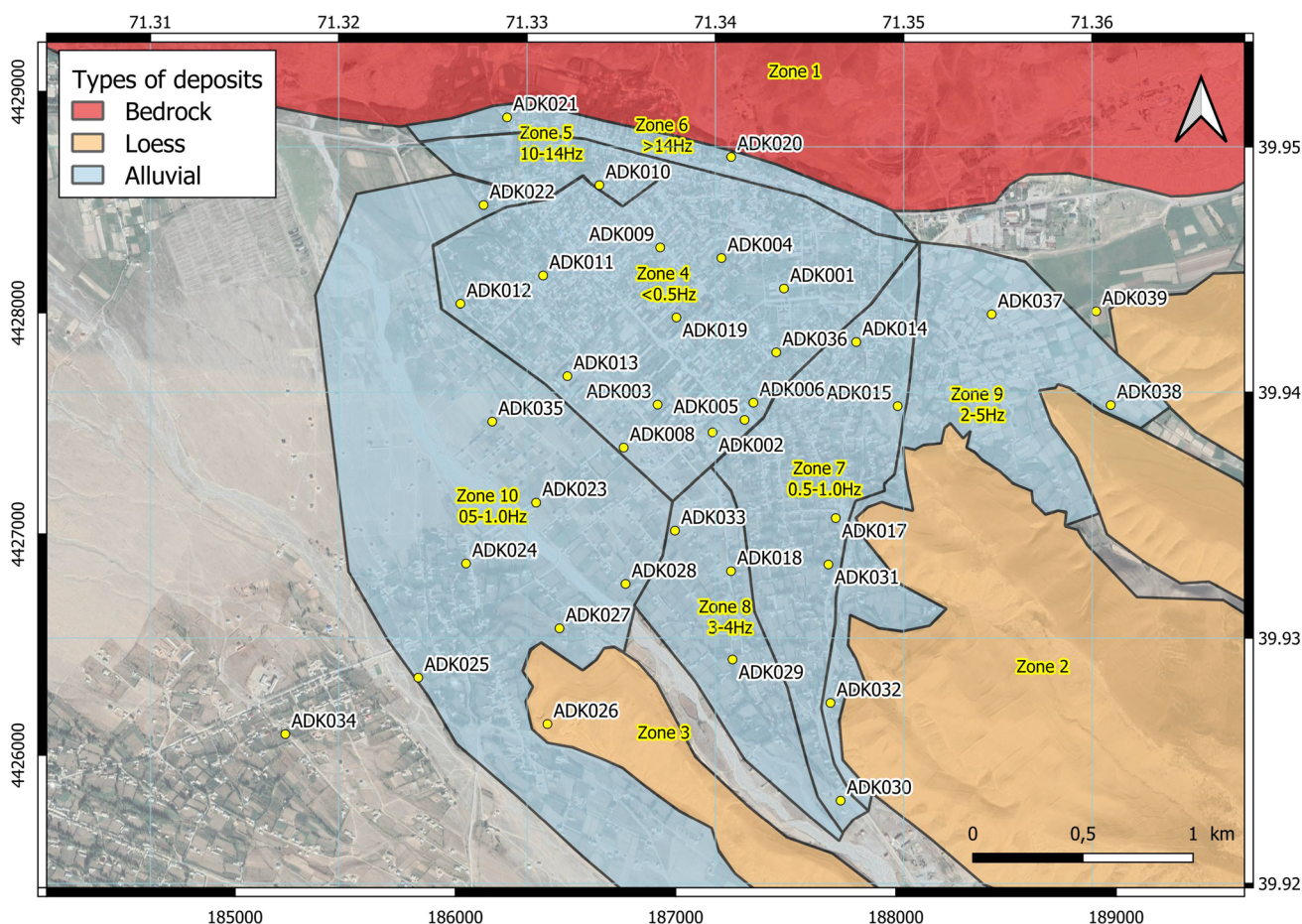
Fig. 10 Zonation map for Aidarken in terms of resonance frequency f_0. Zones in the alluvial deposits are defined by their range of f_0 values (written in black and highlighted in yellow). Dots locate the sites

evacuated. Most of them were located in multi-story buildings in Zone 3 of the microzonation map.

In Aidarken, significant differences in resonance frequencies of buildings and site were identified; therefore, no subdivision in zones was considered pertinent for the risk analysis.

Conclusions

The resonance frequency f_0 derived from the HVSR analysis for 82 ambient noise recorded sites give a first estimation of the thickness of the soft soils, able to amplify seismic waves, underlying harder deposits. In Kadamjay, values of f_0 are relatively high suggesting a thin layer of alluvial deposits under the bedrock, which thickens toward the East to form the different terraces. In this zone, additional seismic measurements should be planned in future to better constrain their

potential influence on the seismic waves. In 2011, during the Kan M6.1 earthquake, buildings in this area suffered more damage than in the other part of the city.

In Aidarken, f_0 values are very low in most of the alluvial cone of deposition of the Gavian River and other streams, suggesting a thick layer of alluvial deposits. The low amplitude of the HVSR frequency peak could be an indication of a low velocity contrast between the alluvial deposits (mainly compacted boulders and gravels) and the underlying bedrock. In this case, the amplification effects on seismic waves could be limited. In the Eastern part of the cone at the contact with the loess, the peak frequency is around 4 Hz suggesting a looser or a softer soil layer. Since this zone is not urbanized, no further investigation is currently needed.

Based on this new study and re-evaluated information on multi-hazard risk of direct and induced effects of large earthquakes in the region of Kadamjay and Aidarken, MSF
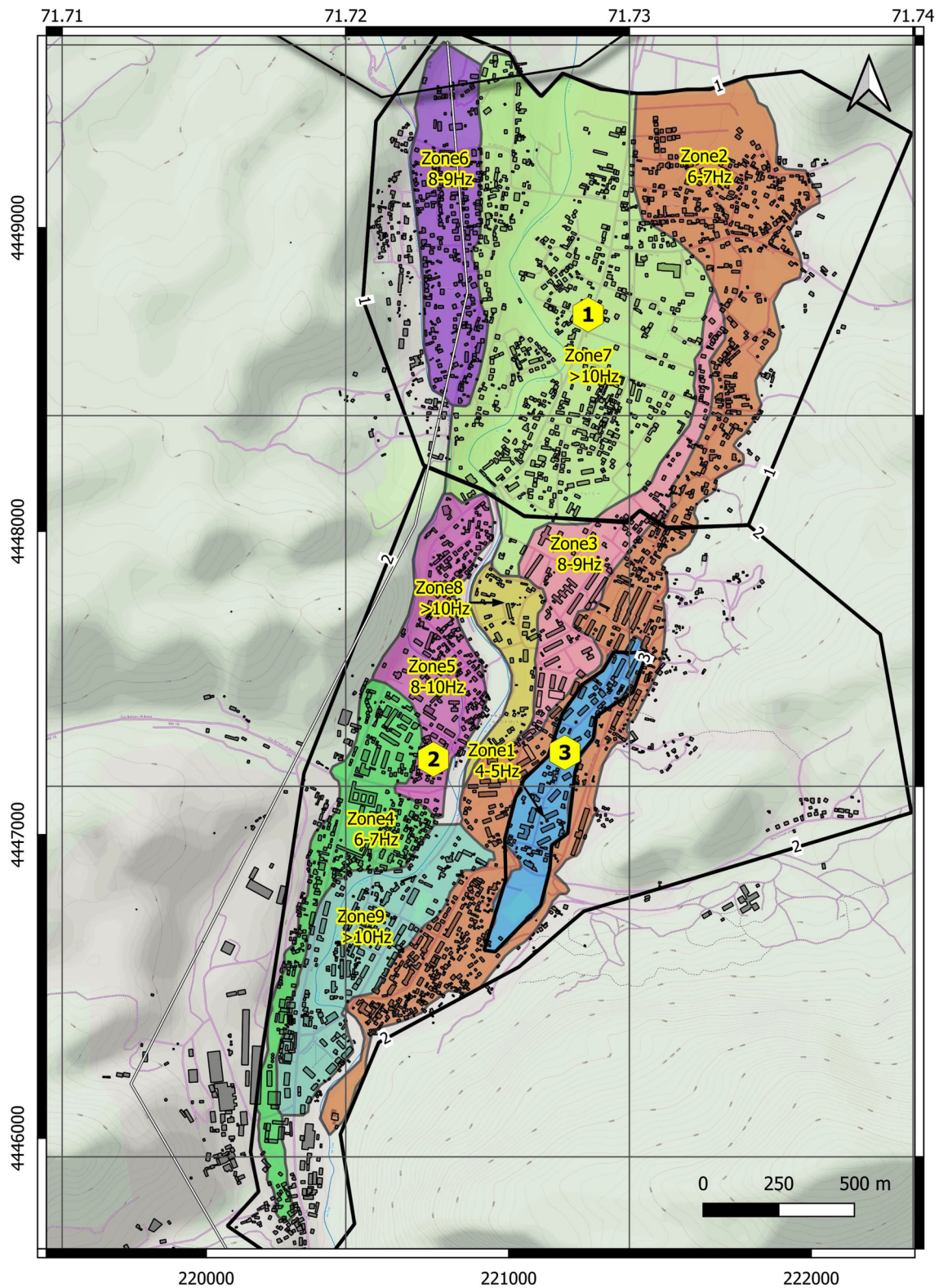
Fig. 11 Zonation map for Kadamjay in terms of resonance frequency f_0. The black lines are the contours of the three zones 1, 2 and 3 mentioned in the text. Gray polygons are the footprint of the buildings

developed a new program to better plan their crisis and disaster management program in terms of human safety. It includes the logistic means to rescue people in the towns and villages of the region. The vulnerability assessment provided for critical facilities such as schools, kindergartens and health centers for different scenarios has shown the needs to retrofit most of such buildings (Rosset et al. 2020).

Author Contributions MW and PR contributed to conceptualization, PR contributed to methodology, formal analysis and validation; PR contributed to field investigation; PR contributed to writing—original draft preparation; all authors have read and agreed to the published version of the manuscript.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article. For this type of study, formal consent is not required. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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