Preliminary Estimation of Kappa Parameter in Croatia

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Abstract: Spectral parameter kappa κ is used to describe spectral amplitude decay "crash syndrome" at high frequencies. The purpose of this research is to estimate spectral parameter kappa for the first time in Croatia based on small and moderate earthquakes. Recordings of local earthquakes with magnitudes higher than 3, epicentre distances less than 150 km, and focal depths less than 30 km from seismological stations in Croatia are used. The value of kappa was estimated from the acceleration amplitude spectrum of shear waves from the slope of the high-frequency part where the spectrum starts to decay rapidly to a noise floor. Kappa models as a function of a site and distance were derived from a standard linear regression of kappa-distance dependence. Site kappa was determined from the extrapolation of the regression line to a zero distance. The preliminary results of site kappa across Croatia are promising. In this research, these results are compared with local site condition parameters for each station, e.g. shear wave velocity in the upper 30 m from geophysical measurements and with existing global shear wave velocity – site kappa values. Spatial distribution of individual kappa's is compared with the azimuthal distribution of earthquake epicentres. These results are significant for a couple of reasons: to extend the knowledge of the attenuation of near-surface crust layers of the Dinarides and to provide additional information on the local earthquake parameters for updating seismic hazard maps of studied area. Site kappa can be used in the re-creation, and re-calibration of attenuation of peak horizontal and/or vertical acceleration in the Dinarides area since information on the local site conditions were not included in the previous studies.

1. Introduction

Ground motion at the site is influenced by source, propagation path, and local site conditions, and is described using acceleration Fourier Amplitude Spectrum of shear waves. Spectral decay parameter kappa (κ) was first introduced by [1] to describe deviation at high frequencies between observed acceleration spectrum of shear waves (S) from seismograms and simple Brune source omega-square model [2]. Over the last three decades, the literature [e.g. 3 and references therein] is consistent that near site attenuation kappa or site kappa is affected primarily by site conditions, and source and path terms are regionally dependent.

This paper presents preliminary results the calculation of spectral parameter κ, for the first time, in Croatia at ten seismological stations. The objective of this study was to calculate κ from *S* wave acceleration spectrum using classical AH84 [1] approach for three component recordings of local earthquakes $M_L \geq 3$, epicentral distances $R_E \leq 150$ km, and focal depths $h < 30$ km. Full κ models as a

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function of a site and distance are proposed using horizontal components κ_{hor} and standard linear regression where site kappa was determined from the extrapolation of the regression line to a zero distance. The results are important for attenuation studies [4], re-creation, and re-calibration of attenuation of peak horizontal and vertical acceleration in the Dinarides area [5] and for updating seismic hazard maps of Croatia.

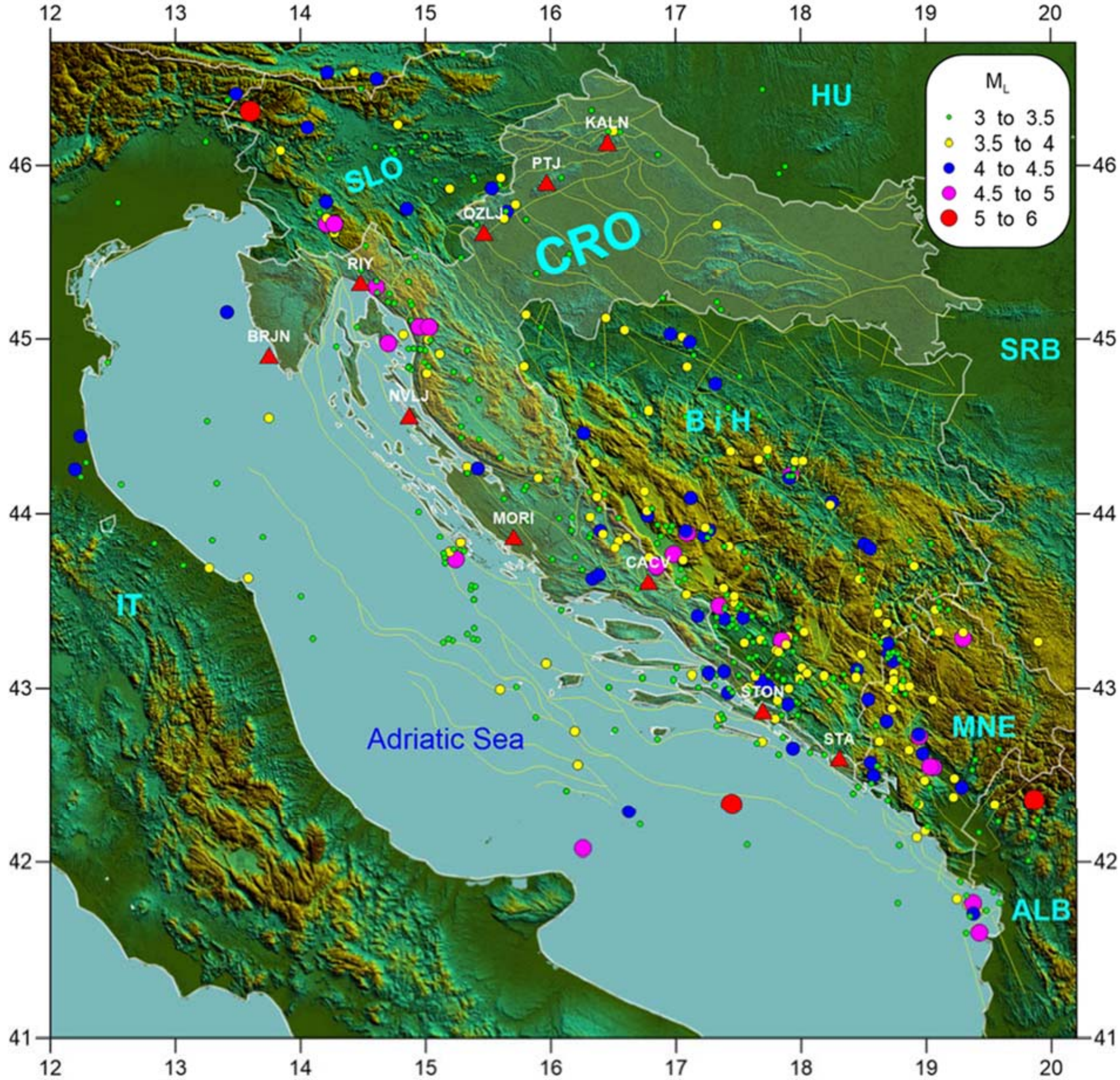

Figure 1. Map of earthquake epicentres (2002-2016) used in this study ($M_L \geq 3$, $R_E \leq 150$ km, and $h < 30$ km). Locations of seismic stations are marked with red triangles. Yellow lines represent known surface faults in Croatia and Bosnia and Herzegovina [6]

2. Study area and data

The study area shown in Figure 1 covers the interaction of the Pannonian basin in the north of Croatia and Dinarides extending from west to southeast of Croatia [7-9]. The extensive description of the geology of the study area can be found in [9-12]. Highest seismicity in this area exhibits the south-eastern part of Croatia, around Dubrovnik [6]. Except for recorded data, historical data shows that this area was repeatedly hit by strong earthquakes [13].

For the purpose of this study, we have used only seismograms (2003-2016) of local earthquakes $M_L \geq 3$ (max $M_L = 5.7$), epicentral distances $R_E \leq 150$ km, and focal depths $h < 30$ km recorded at ten stations: Kalnik (KALN), Puntijarka (PTJ), Ozalj (OZLJ), Rijeka (RIY), Brijuni (BRJN), Novalja (NVLJ), Morići (MORI), Čačvina (CACV), Ston (STON) and Stravča (STA). Since the kappa at stations is attributed to be the site-specific attenuation parameter influenced by local soil conditions [1,14], we performed geophysical measurements (S waves Refraction Tomography, for details about method look in [15]) to estimate shear shear wave velocity in the upper 30 m (V_{S30}) at the locations seismological of stations. By authors knowledge, no reliable information regarding V_{S30} at the seismological stations exist up to now. In Table 1 we listed some analyzed earthquakes for certain period, peak ground accelerations for the return period of 95, 200 and 475 years (PGA_{YRP}) and V_{S30} for each station. The information about V_{S30} is valuable since site kappa estimates from κ_0 - V_{S30} relationships are developed in various studies [3,16], and our results can be compared to the existing one.

Table 1. A number of analyzed earthquakes, peak ground accelerations (PGA_{YRP}) for the 95, 200, 475, years return period (YRP) and V_{S30} for each station. *Approximated as a soil category *A* from the EC8 [17] due to terrain features to conduct geophysical measurements (KALN and PTJ) and research permits at National Park Brijuni (BRJN).

STATION	STA	STON	CACV	MORI	NVLJ
Period	2005-2016	2003-2016	2007-2016	2011-2016	2002-2016
Nr. EQs	157	222	132	51	107
PGA-95	0.137	0.180	0.161	0.095	0.078
PGA-200	0.199	0.254	0.230	0.135	0.105
PGA-475	0.295	0.367	0.338	0.198	0.146
***VS30* (m/s)**	≈ 1280	≈ 1390	≈ 1050	≈ 1280	≈ 1270

STATION	BRJN	RIY	OZLJ	PTJ	KALN
Period	2009-2013	2006-2016	2011-2016	2005-2016	2010-2016
Nr. EQs	33	60	35	70	24
PGA-95	0.036	0.093	0.103	0.137	0.087
PGA-200	0.047	0.13	0.146	0.202	0.128
PGA-475	0.064	0.184	0.208	0.302	0.191
***VS30* (m/s)**	*EC8-A	≈ 900-1000	≈ 800-900	*EC8-A	* EC8-A

3. Kappa (κ) AH84 calculation method and results

The basic observation from AH84 method [1] is that, at high frequencies, the spectrum of ground acceleration falls off exponentially with frequency:

$$A(f,t) = A_0 e^{-\pi f \kappa} \quad (1)$$

In the classical AH84 [1] method, κ is estimated from the high-frequency part (Δf) of the acceleration spectral amplitude of S waves above certain corner frequency (f_c) where spectrum start to decay rapidly (f_{max}) up to noise floor (f_2). Individual κ for a given earthquake record at some distance from the source is calculated from the slope of FAS in the linear-logarithmic space as:

$$\Delta \ln(A) = -\pi\kappa\Delta f\,,\; f_1\,(>f_c) \leq f_{max} \leq f_2\,(noise) \quad (2)$$

$$slope = \frac{\Delta \ln(A)}{\Delta f} \Rightarrow \kappa = -\frac{slope}{\pi} \tag{3}$$

The example of kappa calculation using AH84 method separately for three components (*E, N, and Z*) seismogram recorded at the station RIY for an event that occurred on 16th June 2013 at 20:04, M_L=3.8, R_E=56 km is displayed in Figure 2. High-frequency part Δf from which kappa is calculated is handpicked from range f_1-f_2 with a variation of $\Delta f \sim$ 8-15 Hz, among records, and f_{max} is picked as the frequency at which FAS starts to decay rapidly. In most cases, f_1 is picked as a lower bound of the high-frequency slope before FAS start to decrease rapidly (slightly lower than f_{max}) and after f_c to exclude source contribution on the kappa value, whereas f_2 is the frequency at which noise is present in the FAS as an upper bound (except in cases where high resonance peaks are present). Local site conditions control frequency f_{max}, and it acts as a low-pass soil filter [1,18,19] on the FAS of S waves propagating through the ground. Each FAS was checked to have Signal-to-Noise-Ratio SNR>3. Spectrums which contained deviations from exponential decay trend at high frequencies (e.g. flat spectrum), broadband site resonance and noise effects were not used in kappa calculation [1,14].

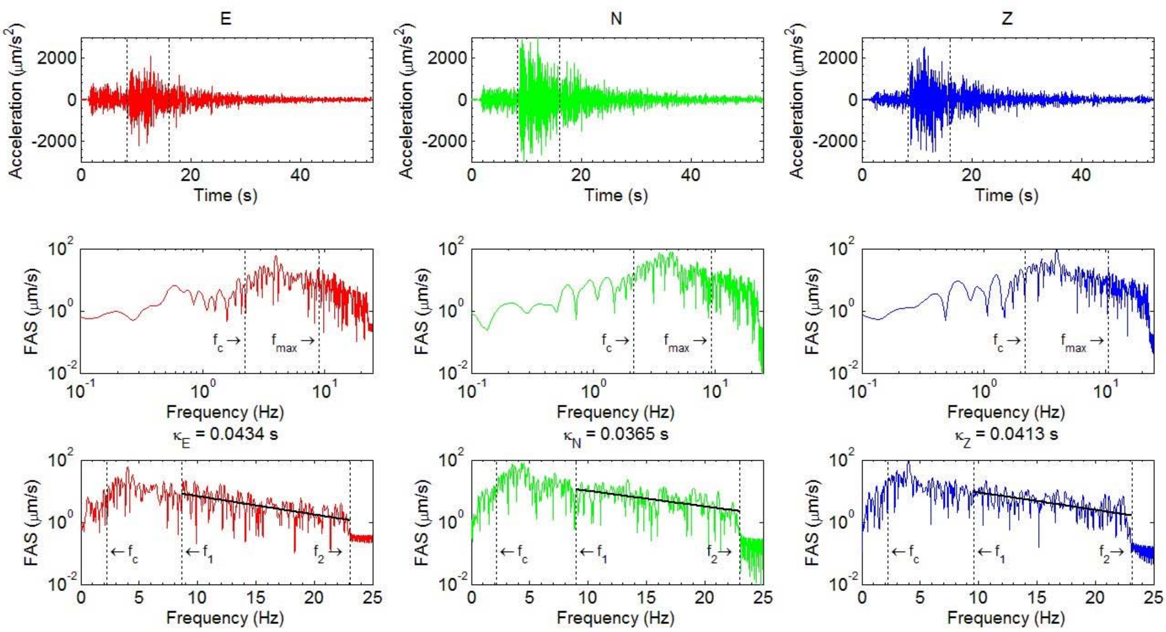

Figure 2. Example of kappa calculation using AH84 method for three components (E, N, and Z) seismogram. Station RIY, earthquake event on 16th June 2013 at 20:04, M_L=3.8, R_E=56 km

AH84 κ-model proposed a linear formulation of calculated κ and epicentre distances (R_E) that treated this parameter as an arbitrary function of distance:

$$\kappa = \kappa_0 + \kappa_R \cdot R_E \tag{4}$$

where the explanation of κ tends toward finite values (κ_0) as R_E approaches zero to be the characteristic of the local geological structures below and near the site and path effect as the regional component attributed to the gradually increase with distance described by the slope of linear function κ_R.

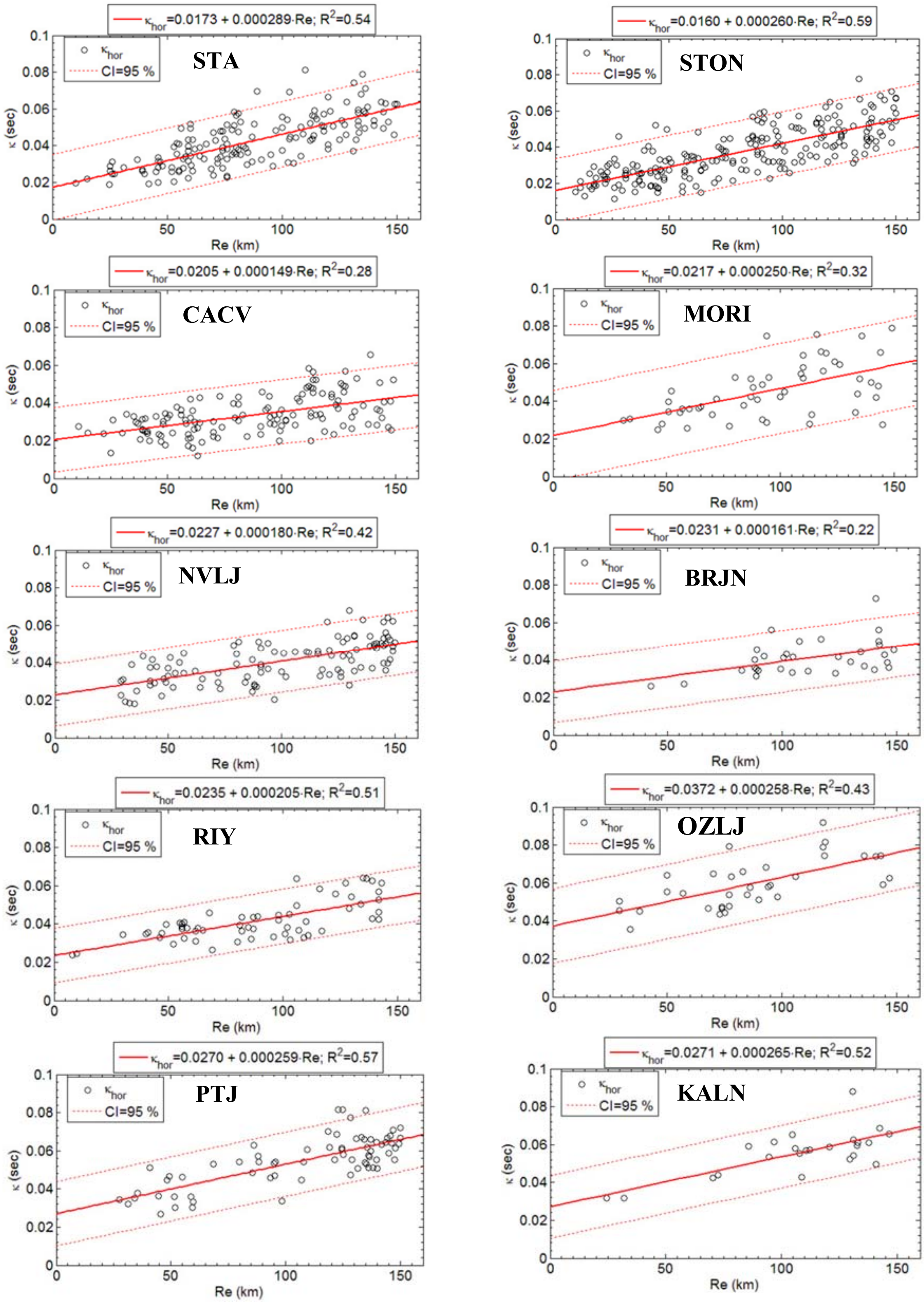

Figure 3. κ_{hor} model for Croatia as a function of a site (seismic station) and epicentre distance using standard linear regression (thick red line) with confidence interval (CI) of 95% (dashed line). Regression line equation (3) in term of κ_0 as zero R_E intercept and slope of regression in term of $\kappa_R{\cdot}R_E$ with a coefficient of correlation R^2 is shown in legends.

Calculated horizontal kappa's (E and N) were averaged and in some cases where they differ significantly (> 25 %) were rejected [3,14,20]. In Figure 3 we present first preliminary results of κ models for Croatia as a function of a site and epicentral distance using only horizontal components κ_{hor} and standard linear regression. The linear form of κ-R_E correlation can be visual in all cases. Site kappa (κ_0) for each station is determined by the extrapolation of the regression line to a zero distance.

4. Discussion

Since the literature, e.g. [1,3] about site kappa (κ_0) origins is consistent with local site conditions influence, particularly below and around the station. The general trend in published V_{S30}- κ_0 correlations [3,16,20] follow the rule of lower κ_0 - higher V_{S30}, but large scatter of observed correlations exists. In Table 2 we compare our results with published global V_{S30}- κ_0 correlations. Site kappa (κ_0) and V_{S30} values estimated for each station are comparable with global values, particularly for the $V_{S30} \geq 1000$ m/s.

As it were observed in Figure 3, the coefficient of correlation $R^2 > 0.50$ is observed for the stations with a higher number of data (STA, STON, RIY, and PTJ) situated in the seismically active regions. Other stations show $R^2 < 0.50$ indicating a low correlation between κ-R_E. The reason for this could be the number of analyzed data per stations and scatter of κ-R_E data (MORI, BRJN, OZLJ). The other effect on the low κ-R_E correlation, particularly for the CACV and MORI could be the geo-location of the stations and fault structure (Figure 1). To better perceive this effect, in Figure 4 we present spatial κ_{hor} distribution for the individual κ values for each earthquake recorded at stations. From the presented spatial κ_{hor} distribution for each station site, several observations can be drawn. Spatial κ-R_E distribution/correlation at stations STA, STON, RIY, and PTJ confirm that path effect as the regional component is attributed to the gradually increase with distance described by the slope of linear function κ_R. Stations BRJN, OZLJ and KALN have a lack of data, but preliminary results are promising. Stations CACV and MORI indicate that potential earthquake azimuthal dependence and fault structure directions could affect the individual κ calculations due to local scattering. Although this effect is not observed at other stations, and similar observations regarding azimuthal influence on κ calculation [14] imply that orientation of the data sets does not have an effect on the κ results, further study is needed.

In the literature within the context of seismic hazard [21,22] areas with low κ values correspond to seismograms with much high-frequency energy and are expected to produce larger ground motion and vice-versa. If PGA_{YRP} from Table 1 is compared with κ_0 values from Table 2, higher seismicity PGA_{YRP} follow lower κ_0, but no clear correlation is observed, and further study is needed.

The preliminary result presented in this study are going into a good direction regarding developing full κ models for Croatia. Further work is expected to be performed. The plan is to complete geophysical measurements (terrain features, permits, etc.) for all seismic stations in Croatia to estimate V_{S30} parameter. In some recent studies [23], κ correlation with soil resonant frequency and amplification is proposed. Site resonant frequency (f_{res}) and site amplification can be estimated from Horizontal-to-Vertical-Spectral-Ratio (HVSR) from ambient noise measurements [24]. In this preliminary study, we did not use vertical κ component. Although we calculated it, little to none literature [25] present and develop κ_{ver} models, we plan to try to develop κ_{ver} models and compare them to κ_{hor} models.

Typically, the whole path degree of seismic attenuation [26] is separated into two parameters: frequency dependent quality factor (Q) as a crustal attenuation and high-frequency spectral parameter kappa (κ_0) as a near site attenuation. Assuming an average crustal shear wave velocity, frequency independent Q can be estimated from the slope κ_R as some studies suggested [23], [26] and compared with frequency-dependent Q from attenuation studies in the region [e.g. 4]. This comparison of the trade-off between Q and κ could help us to identify how deeper regional structures influence κ calculation, but detailed study comparison is required to provide some reasonable conclusions.

Table 2. Comparison of Croatia - κ_{hor} model with published V_{S30}- κ_0 correlations

#	Region	V_{S30} (m/s)	κ_0 (s)
CROATIA	**STA**	**1280**	0.0173
	STON	**1390**	0.0160
	CACV	**1050**	0.0205
	MORI	**1280**	0.0217
	NVLJ	**1270**	0.0227
	BRJN	***EC8-A**	0.0231
	RIY	**900-1000**	0.0235
	OZLJ	**800-900**	0.0372
	PTJ	***EC8-A**	0.0270
	KALN	***EC8-A**	0.0271
[27]	CNA & ENA	2800	0.003-0.006
	WNA	700	0.066
		650	0.073
		700	0.069
		1200	0.002
	Sino-Korean	1200	0.019-0.039
	Paraplatform	1500	0.014
	South China Fold	1500	0.018-0.027
	System	650	0.040-0.045
	Australia	2350	0.011
		480	0.069
	Southern Iberia	530	0.067
	NE Japan	480	0.081
	Taiwan	850	0.040
	Generic Rock	620	0.070
	Apennines, Italy	620	0.045
	Northeastern Italy	650	0.056
	Southern California	850	0.040
	Iceland	700	0.048
	NEHRB Site Class C	1000	0.04
		740	0.05
[25]	France	Soil sites	0.0270
		Rock sites	0.0207
[28]	France	500	0.010-0.036
		1000	0.008-0.028
		1500	0.005-0.018
		2000	0.008-0.012
[26]	Switzerland	525	0.020-0.023
		760	0.016-0.021
		1070	0.013-0.018
		1500	0.010-0.014
		2000	0.0074-0.010
[28]	Japan/California/Taiwan	0.042	0.042
		0.029	0.029
		0.020	0.020
		0.014	0.014
		0.010	0.010
[16]	Northern California	525	0.048
		760	0.032
		1070	0.022
		1500	0.015
		2000	0.011
[23]	Northern Greece (EUROSEISTEST)	EC8: C (180-360)	0.025-0.08
		EC8: B (360-800)	0.018-0.055
		EC8: A (> 800)	0.016-0.024
[20]	New Zealand	400-800	0.04-0.05
		800-1100	0.025-0.040

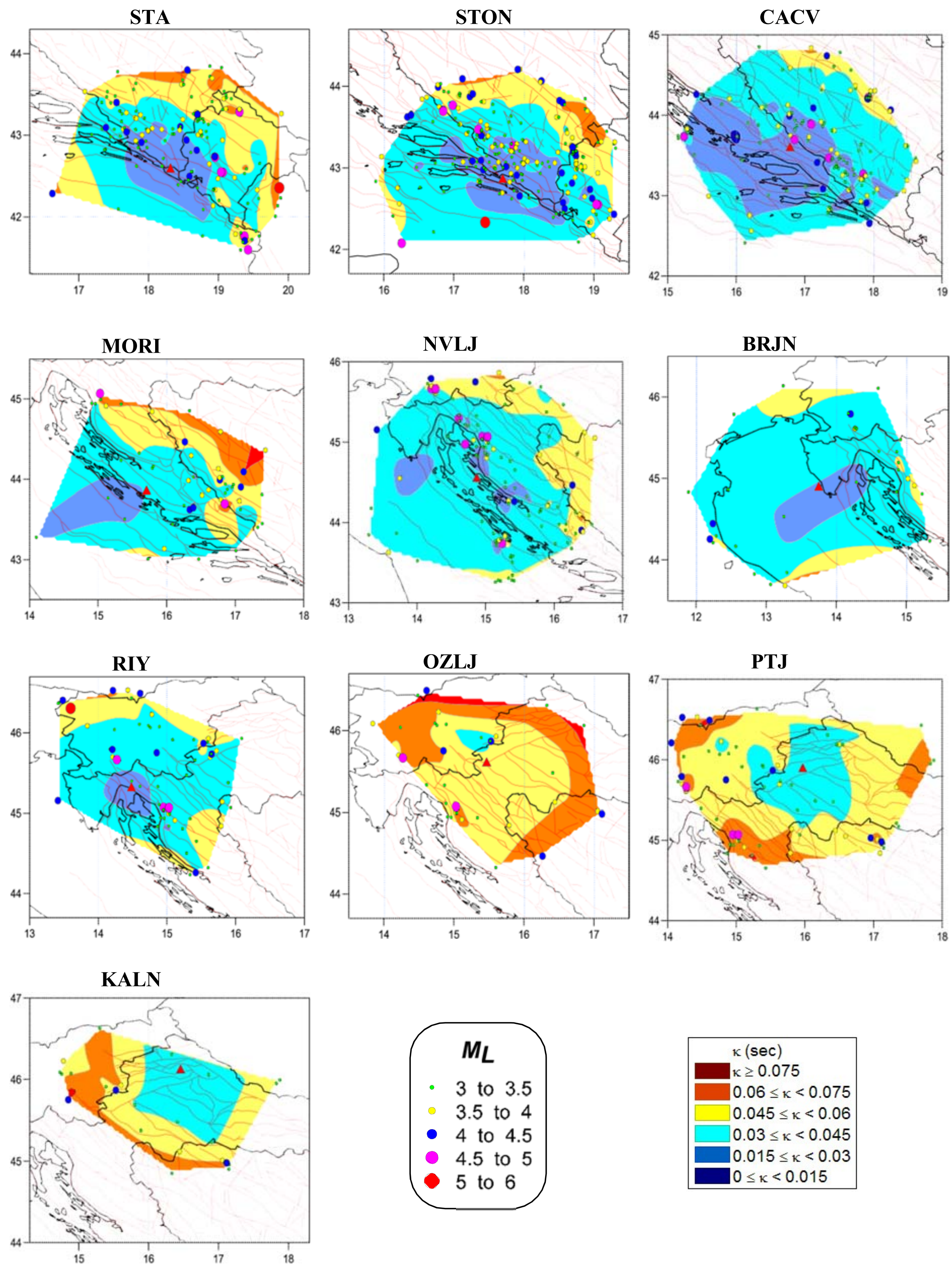

Figure 4. Spatial κ_{hor} distribution for seismic stations used in this research

5. Conclusion

In this paper, we present for the first-time estimation of spectral parameter κ in Croatia. Parameter κ is calculated from S wave acceleration spectrum using classical AH84 approach for recordings of local earthquakes $M_L \geq 3$, epicentral distances $R_E \leq 150$ km, and focal depths $h< 30$km. The original AH84 model proposed κ as distance-dependent parameter divided into the regional path and site component. The linear form of κ-R_E dependence is observed, and we used standard linear regression. Preliminary κ_{hor}-models in Croatia are derived for each seismic station. Site kappa (κ_0) and V_{S30} values estimated for each station are comparable with global values, particularly for the $V_{S30} \geq 1000$ m/s. Spatial κ-R_E distribution/correlation confirms that path effect as the regional component is attributed to the gradually increase with distance described by the slope of linear function κ_R, but potential earthquake azimuthal dependence and fault structure directions could affect the individual κ calculations due to local scattering.

Although this first preliminary results of kappa estimation and κ_{hor}-models derived for Croatia are promising, more data at some stations and detailed study comparison with attenuation studies and local geology in the area are required to provide reasonable conclusions. Near site attenuation κ_0 is one of point source seismological model input parameter [19] and the κ results are important for future work, e.g. attenuation studies, updating seismic hazard maps, re-creation, and re-calibration of attenuation of peak horizontal and vertical acceleration relations in the Dinarides area [5].

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