SEISMIC HAZARD MAPS FOR THE WESTERN BALKAN

KARTE POTRESNE OPASNOSTI ZA PODRUČJE ZAPADNOG BALKANA

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Abstract: *The Harmonization of Seismic Hazard Maps in the Western Balkan Countries Project (BSHAP) was funded for 7 years by NATO-Science for Peace Program to support the preparation of new seismic hazard maps of the Western Balkan Region using modern scientific tools. One of the most important outputs of the BSHAP is an updated and unified BSHAP earthquake catalogue that is compiled directly from the datasets of earthquake data providers of the region. In the framework of BSHAP, the regional free field strong motion network capacity was increased significantly by the purchased and installed recorders and the BSHAP strong motion database that includes both pre-BSHAP (mostly analog) and post-BSHAP (all digital) recordings was compiled. The BSHAP strong motion database is used for proper selection of the ground motion prediction equations (GMPEs) for the probabilistic seismic hazard assessment (PSHA) by comparing the compiled strong ground motions with the predictions of candidate global, European, and Euro-Med GMPEs in a systematic manner. BSHAP collected relevant knowledge about the geological structure of southwestern Balkans provided a better understanding of the prevailing stress regime in the region. The main output of BSHAP is the new probabilistic seismic hazard maps for Western Balkans, obtained by implementation of the smoothed-gridded seismicity approach. The results are expressed in terms of peak horizontal acceleration (PGA) for 95 and 475 years return periods aligned with Eurocode 8 requirements. The seismic hazard maps derived in this project are a good basis to characterize the seismic hazard of Western Balkans. They will help the national authorities, public and private institutions, civil emergencies agencies, etc., for urban planning, disaster preparedness, and seismic hazard mitigation.*
Keywords: *BSHAP, seismic hazard, Western Balkan.*

Sažetak: *Projekt usklađivanja karata seizmičke opasnosti za područje Zapadnog Balkana (BSHAP) financiran je 7 godina od strane NATO programa „Science for Peace" za pripremu novih karata seizmičke opasnosti za područje Zapadnog Balkana upotrebom modernih znanstvenih alata. Jedan od najvažnijih rezultata BSHAP programa je ažurirani i jedinstveni BSHAP katalog potresa direktno sastavljen iz baze podataka potresa iz pojedinih regija. U okviru BSHAP-a, znatno je povećana mreža „free-field" uređaja za snimanje jakog gibanja tla kupnjom novih i postojećih uređaja (akcelerografa), te je BSHAP baza podataka zapisa jakih (akcelerografskih) potresa sastavljena od prijašnjih (većinom analognih zapisa) prije BSHAP projekta, i novih digitalnih zapisa nakon i u toku BSHAP projekta. BSHAP baza podataka jakih gibanja koristi se za odgovarajući odabir relacija za procjenu gibanja tla (GMPE) za procjenu vjerojatnosti potresne opasnosti (PSHA) usporedbom prikupljenih zapisa jakih gibanja s GMPE relacijama na globalnoj, europskoj i Euro-Med razini. U okviru BSHAP-a, prikupljeno je relevantno znanje o geološkoj strukturi jugozapadnog Balkana koje je omogućilo bolje razumijevanje prevladavajućeg smjera napetosti u regiji. Glavni rezultat BSHAP-a su nove karte potresne opasnosti za područje zapadnog Balkana dobivene primjenom pristupa tzv. mreže izglađivanja seizmičnosti. Rezultati su izraženi preko vršnih horizontalnih ubrzanja (PGA) za povratne periode 95 i 475 godina usklađeni s zahtjevima Eurocode 8. Izrađene karte potresne opasnosti u ovom projektu dobra su osnova za opis potresne opasnosti područja zapadnog Balkana. One će pomoći nacionalnim vlastima, javnim i privatnim institucijama, civilnim agencijama za hitne slučajeve i sl., te za urbanističko planiranje, pripremu za prirodnu katastrofu i smanjenje seizmičke opasnosti.*
Ključne riječi: *BSHAP, potresna opasnost, zapadni Balkan.*

Received: 22.04.2017 / Accepted: 29.06.2017
Published online: 21.07.2017

Znanstveni rad / Scientific paper

1. INTRODUCTION

The Western Balkans is a seismically active region and characterized by significantly higher earthquake hazard and risk when compared to the rest of Europe. Local seismic design code regulations, seismic risk estimation, risk management and seismic safety improvements should be based on reliable hazard maps. However, relatively sparse seismological networks and limited cross-border seismic data exchanges restricted the adequacy of seismic hazard assessment and disaster management in the region. Minimizing of the loss of human lives and property damage, social and economical disruption due to earthquakes, essentially depends on reliable estimates of seismic hazard. The fact that current seismic provisions have been updated in early 1980-is (practically in all of participating countries) underlines an evident need to upgrade these technical norms. The foreseen logical step was harmonization with EU standards (EUROCODE 8), what impose the seismic hazard harmonization as the first step towards.

The Harmonization of Seismic Hazard Maps for the Western Balkan Countries Project (BSHAP) funded by NATO Science for Peace and Security Program was launched in 2007 and continued until the end of 2011 with the main objective of preparing new seismic hazard maps for the Western Balkan Region as an important step towards the seismic safety improvement and seismic risk management.

2. SUMMARY OF ACCOMPLISHMENTS

Development of the seismic hazard maps as a final project goal presedes an updated and unified earthquake catalogue, strong motion database compilation, proper selection of the ground motion prediction equations (GMPEs), compilation of all relevant regional geological knowledge and development of seismo-tectonic model.

2.1. Earthquake cataloque

One of the most important outputs of the BSHAP project is an updated and unified earthquake catalogue (Markušić et al. 2016). For this purpose, the national earthquake catalogues of 12 countries in the region; Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Hungary, Italy, Montenegro, Macedonia, Romania, Serbia and Slovenia were accessed and assembled together. The compiled catalogue is enriched with data from global catalogues, especially for large magnitude events. One of the biggest challenges was to build a standard data format due to the large number of events in the national and regional catalogues and variety of the data format.

The BSHAP earthquake catalogue (**Figure 1**) covers the geographic area limited by 38.0–47.5°N, 12.5–24.5°E and includes 26,118 earthquakes that occurred in the region between 510 BC and 2012.

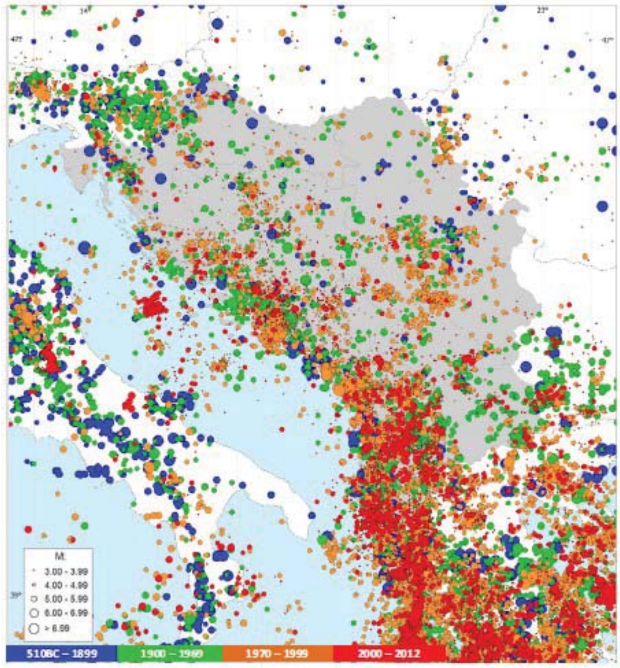


Figure 1. Spatial distribution of the earthquakes in the proposed BSHAP catalogue (earthquakes M ≥ 3.5 in the period 510BC–1969, and earthquakes M ≥ 3.0 in the period 1970–2012 (Markušić et al. 2016)

Since the primary objective was to provide input to the PSHA and seismic hazard maps, the M_w proxy is estimated for all entries in the BSHAP catalogue. Various magnitude scales, even from the same data provider, were assigned to the events in the compiled catalogue; therefore, separate empirical relationships between the local and other magnitude scales and M_W are developed for Albania, Croatia, Macedonia, Montenegro and Serbia using errors-in-variables regression technique (**Table 1**).

Table 1. Empirical relationships between moment magnitude M_W and local magnitude M_L (Markušić et al. 2016)

Agency	Regression equation Mw=b0+b1ML	Number of events	Determination coefficient, R2	SD of regression, s_e
Tirana	M_w=1.22+0.813M_L [a] (0.25) (0.056)	96	0.715	0.256
Podgorica	M_w=-0.01+1.028M_L [a] (0.16) (0.033)	75	0.930	0.184
Zagreb	M_w=-0.11+1.011M_L [a] (0.38) (0.080)	31	0.852	0.229
Belgrade	M_w=0.70+0.858M_L [a] (0.21) (0.049)	50	0.953	0.182
Skopje	M_w=0.56+0.913M_L [a] (0.48) (0.101)	28	0.773	0.267

[a] In the second rows, in parenthesis are given the standard errors of regression coefficients.

The data pairs collected from regional and global catalogues are employed in the regression analysis. The catalogue completeness thresholds are analyzed (**Table 2**) and incorporated into the seismotectonic model developed within the BSHAP Project. The unified and updated

BSHAP catalogue, as demonstrated, is fully compatible with the current well-established European and worldwide catalogues.

Table 2. Catalogue completeness intervals of BSHAP catalogue (Markušić et al. 2016)

Mw ≥	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
Complete From year	1982	1978	1965	1945	1900	1850	1605	1280

2.2. Fault plane solution (FPS) database

The BSHAP countries mostly lie in the Adria-Eurasia collision zone, characterized by great differences in seismicity rate, present-day stress direction, strain rate, and consequently in fault slip rate among neighboring regions.

To study dominant tectonic regime, we collected FPS database covering area bounded by 38-48° N and 12-24.5° E. Included are 714 FPS for M≥4.0 earthquakes that occurred between the years of 1909 and 2015 in this area (**Figure 2**). For 332 earthquake events FPS were analyzed by the project participants or gathered from data held by partner institutes (An updated Croatian FPS Database first described by Herak et al. (1995) – current version of which is presented in Herak et al. (2016), the updated Montenegrin FPS database (Kaluđerović 2015), and the FPS databases of Seismological Survey of Serbia and Institute of Geosciences, Energy, Water and Environment, Albania). All remaining FPS were collected from global resources.

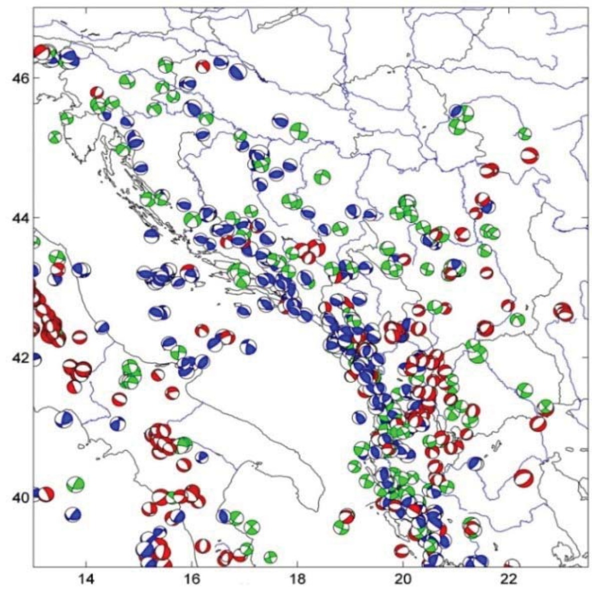


Figure 2. BSHAP FPS database, insert for the geographical area 13-23.5°E, 39-47°N. Color of symbols marks the FPS for different mechanisms: the blue, red and green symbols stand for the reverse, normal and strike-slip events, respectively (Mihaljević et al. 2017).

The general pattern of the FPS indicates that the majority of the earthquakes observed along the coastlines of Croatia, Montenegro and Albania have reverse mechanism, correlated to the thrusting in the most part of the External Dinarides and Albanides. Tectonic compressions are directed in SW–NE direction in the southern and eastern parts and in S–N direction in the northern and western parts of the coastline. Moving away from the coast towards inland, the faults are active as strike-slip to oblique strike-slip or even as reverse faults. This distribution reflects the counter-clockwise motions of Adria and its compression against the Dinarides. In the Albanides, the boundary between normal faulting to east and thrust faulting to west runs through central Albania. The extension is observed in eastern Albania and Macedonia

2.3 Seismic source characterisation (SSC)

It is well known that hazard results are sensitive to the seismic sources comprised within as well as outside the area of calculation. Thus, the broader area 12-24.5°E and 38-48°N has been considered in SSC modelling. To develop the SSC models we used the uniform and updated BSHAP earthquake catalogue (Markušić et al. 2016) while utilizing relevant knowledge about the geological and seismotectonic structure of Western Balkans as well as the stress information indicated by the BSHAP FPS database. Additionaly, sets of sensitivity analyses are performed to support final estimates of some models' parameters (Mihaljević et al. 2017).

The super zone model (SZM) (**Figure 3**) consists of seven larger and two smaller zones that were delineated based on the seismotectonic characteristics. The purpose was to avoid undue fluctuations in the recurrence model parameters (b-value, mean annual rate of earthquake occurrence, etc.) that are commonly present when addressing smaller areas - particularly in the zones of low seismicity.

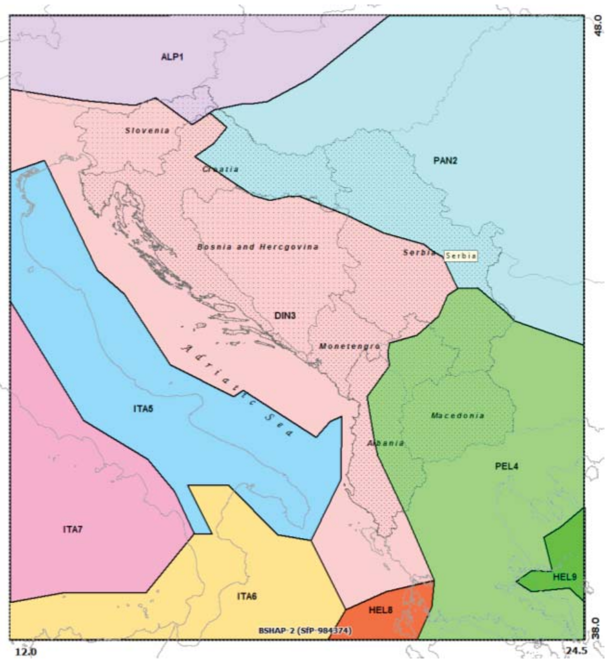


Figure 3. Super zone model (SZM) is defined for influence area covering 12-24.5°E and 38-48°N. (Mihaljević et al. 2017)

Since the BSHAP earthquake catalogue - for the out of BSHAP countries (**Figure 3**) zones strongly depends on the global catalogues, the completeness levels of the catalogue show a large temporal and spatial variability. Completeness time intervals of the BSHAP earthquake catalogue in each super zone are estimated for different magnitude of completeness Mc (**Table 3**). Considering that spatial variability of Mc-the smallest value of magnitude at which the catalogue is thought to have included all seismic events, can lead to erroneous results of the seismicity reccurence parameters, the minimum magnitude (m_0) is set to 4.0 for all super zones.

Table 3. Completeness of the BSHAP earthquake sub-catalogues over magnitude classes (Mihaljević et al. 2017)

Complete-ness (Mc) / Complete from year	[4.0, 4.5)	[4.5, 5.0)	[5.0, 5.5)	[5.5, 6.0)	[6.0, 6.5)	6.5, 7.0)	[7.0, 7.5)	[7.5, 8.0)
ALP1	1958	1935	1920	1900	1640	1300	1300	1300
PAN2	1965	1915	1880	1835	1565	1300	1300	1300
DIN3	1965	1955	1905	1830	1600	1400	1250	1100
PEL4	1932	1908	1870	1820	1760	1400	1400	1400
ITA5	1960	1930	1850	1750	1650	1360	1360	1360
ITA6	1945	1910	1895	1840	1780	1650	1650	1650
ITA7	1930	1910	1850	1740	1640	1300	1300	1300
HEL8	1950	1902	1870	1825	1770	1625	1625	1625
HEL9	1975	1960	1940	1908	1590	1300	1300	1300

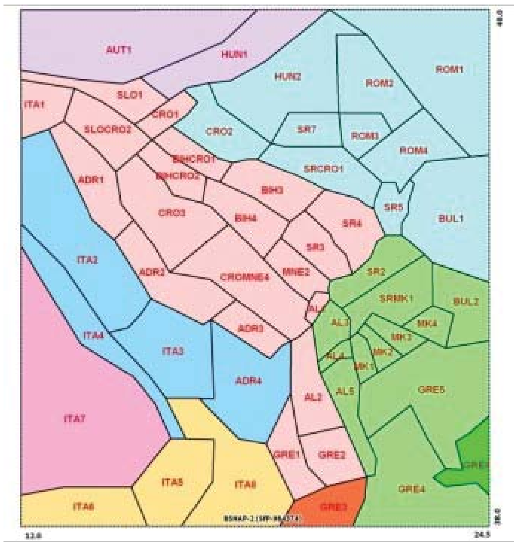
For each super zone, b-value was calculated using the maximum likelihood estimation (MLE) that considers unequal completeness intervals for different magnitude ranges (Weichert 1980) and the MLE procedure developed by Kijko and Sellevoll (1992, KS-92). The magnitude recurrence parameters (b, m_{max}) estimated by the KS-92 procedure are compared to the relevant values from the MLE approach defined by Weichert (1980) (**Table 4**), as well as to the relevant estimates obtained in the framework of the SHARE project for the areal source model (AS Model, Basili et al. 2013).

Two alternative estimates for the b-value are used for each source zone: (1) the average value of the relevant estimates derived using the super zones sub-catalogs, considering the variable magnitude completeness MLE (Weichert 1980) and the estimates obtained using the Kijko and Sellevoll (1992) approach on the same sub-catalogs; and (2) b=1.0 for all the source zones, as comparable to the AS model of the SHARE project (Giardini et al. 2013).

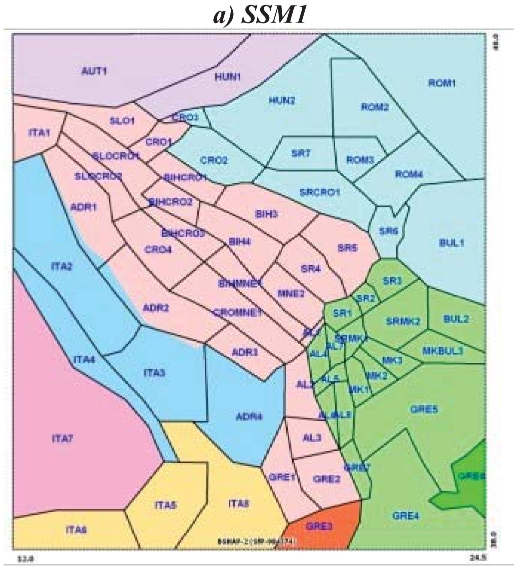
While the super zone model has been implemented with the purpose of estimating statistically-stable b-values, other parameters of the SSC model (m_{max}, dominant style of faulting and fault directions) were estimated for smaller areas, delineated within two alternative zonation models. Seismic source 1- SSM1 and Seismic source 2 - SSM2 (**Figure 4**) representing the local tectonic features provided input data for the two-stage (circular and elliptical) smoothing procedure.

Table 4. The recurrence parameters for the super zones (Mihaljević et al. 2017)

	MLE ($M_W \geq 4.0$)				KS-92 ($M_W \geq 4.0$, R=30km)		
	# Ev.	b-value	$m_{max\ obs}$	m_{max}	# Ev.	b-value	m_{max}
ALP1	11	0.79	6.54	6.75	38	–	–
PAN2	56	0.83	6.50	6.75	197	1.02	6.20
DIN 3	1505	1.00	7.37	7.65	1935	1.09	7.98
PEL4	1659	1.16	7.51	7.75	1751	1.02	7.59
ITA 5	195	0.68	6.95	7.15	143	1.03	6.84
ITA 6	111	0.77	6.95	7.15	250	1.00	7.17
ITA 7	35	0.68	6.54	6.75	515	0.98	7.23
HEL8	386	1.10	7.40	7.65	185	1.09	7.55
HEL9	186	1.34	7.16	7.45	391	1.10	7.64



a) SSM1



b) SSM2

Figure 4. Geographical partition of SSM1's and SSM2's zones and their position vs. super zone model. (Mihaljević et al. 2017)

In Western Balkans, SSM1 and SSM2 were delineated considering a detailed analysis of tectonic settings, known active faults, activity rates, observed magnitudes, and foci depths. Zones covering the neighboring (out-of-BSHAP) region are preserved in both models and were delineated considering SHARE project (Basili et al. 2013; Giardini et al. 2013), and according to Vamvakaris et al. 2013. Borders of the source zones are mostly consistent with the borders of the super zones since the b-value estimated for the corresponding super zone is directly implemented for the zones of SSM1 and SSM2. Each zone is attributed by a zone ID, covered area, maximum observed magnitude, average foci depth, and sets of weighted parameters: b-value, m_{max}, style of faulting and fault strike angle. To assign the weights related to tectonic information, faults were grouped based on the mechanism and the median strike azimuth. Their weights were calculated based on measured length of the (grouped) faults (Poljak et al. 2000). In SSM1 and SSM2, the m_{max} for each source zone was chosen by considering the largest observed magnitude in the zone. Taking into account the uncertainties related to this parameter - two alternative estimates of m_{max} are included by adding 0.25 and 0.5 magnitude units to the largest observed magnitude in each zone. We assumed that the minimum m_{max} value in any zone cannot be lower than Mw=6.0 even if largest observed magnitude is much smaller.

Conditioned by the lacking of sufficient data to define a fault-based model for BSHAP region, we decided to use the seismicity-based background models in the hazard calculations. The overall method for modeling background seismicity is based on the spatial smoothing approach (Frankel 1995; Lapajne et al. 1997, 2003), whereby the rate of past earthquakes and a regionally consistent MFD are used to forecast the rate of future earthquakes. To smooth the annual rates of earthquake occurrence (λ-grid) in each grid cell, a two-stage spatial smoothing method is used. Sets of sensitivity analyses are performed to support final estimates of some models' parameters affecting the smoothed seismicity rate (Mihaljević et al. 2017).

For the adopted BSHAP seismic source characterization models incorporated epistemic uncertainties associated with construction of the seismic source models (uncertainty of the b-value, choice of SSM, maximum magnitude), type of smoothing and ground motion prediction equations are provided in the logic tree scheme (**Figure 9**).

2.4. Strong ground motion database

In the framework of BSHAP project, the regional free field strong motion network capacity was significantly increased by deployed recorders. During the implementation of BSHAP project, 46 in total strong motion stations were deployed in the territories of participating countries (Albania, Croatia, Macedonia, Montenegro and Serbia). As shown in **Figure 5**, newly installed stations have significantly increased the available regional strong motion network capacity (Šalic et al. 2016).

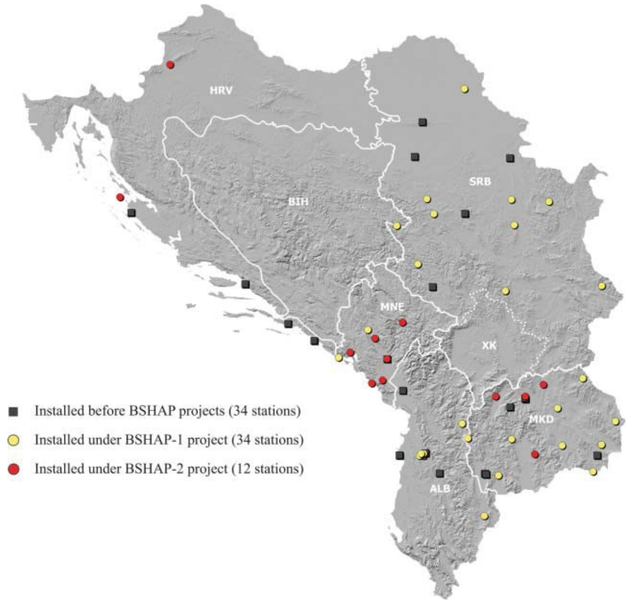


Figure 5. Geographic distribution of the digital strong motion stations deployed before and during the course of BSHAP Project (Šalic et al. 2016)

One of the main goals of this project was to provide a reliable and uniformly processed strong motion database that contains all of the available regional free field strong motion data. Therefore, all free field strong motion data found in the archives of Albanian, Croatian, Macedonian, Montenegrin, Serbian, and Slovenian seismological networks were collected (**Table 5** and **Table 6**). In total BSHAP strong motion database consists of 672 three-component accelerograms from 358 earthquakes recorded (**Figure 7**) at 121 strong motion stations (**Figure 6**). After the initial strong motion database was compiled, the waveform quality of all ground motion recordings was checked and some recordings were eliminated from the dataset due to non-standard errors (Douglas 2003). Remaining recordings in the database were associated to the earthquakes in the BSHAP earthquake catalogue (Markušić et al. 2016) and the moment magnitude (M_w) values from the catalogue were directly adopted.

Table 5. General statistics of the digital portion of the BSHAP strong motion database (Šalic et al. 2016).

Country	No. of Records	Mw	Hypocentral depth (km)	Repi (km)	Period (year from-to)	No. of records used in the analysis
Albania	163	3.70–6.10	0.0–24.0	2.2–500.0	2003–2015	155
Croatia	3	4.73–5.10	5.2–21.9	55.8–62.1	2003–2005	3
Macedonia	37	3.00–5.20	0.0–21.0	11.4–301.3	2013–2014	0
Montenegro	50	3.07–5.50	0.0–33.0	15.9–180.1	2009–2012	33
Serbia	24	3.50–5.50	1.0–15.0	16.9–137.9	2006–2013	3
Slovenia [a]	21	2.92–5.64	7.0–18.3	4.0–103.5	1998–2011	1
Total	**298**	**2.92–6.10**	**0.0–33.00**	**2.2–500.0**	**1998–2015**	**195**

[a] Slovenia was not directly part of NATO SfP-983054 (BSHAP-1) and NATO SfP-984374 (BSHAP-2) project. Data provided was courtesy of ARSO (Dr. Mladen Zivcic).

Table 6. General statistics of the analogue portion of the BSHAP strong motion database (Šalic et al. 2016).

Country	No. of Records	Mw	Hypocentral depth (km)	Repi (km)	Period (year from-to)	No. of records used in the
Albania	1	5.91	5.0	14.8	1998	1
Croatia	36	3.20–5.99	1.1–16.4	4.6–157.2	1986–1996	19
Macedonia [a]	337	2.10–7.40	0.0–94.0	0.9–527.4	1975–1994	235
Total	374	2.10–7.40	0.0–94.0	0.9–527.4	1975–1998	255

[a] Provided data from Macedonia are related to the territories of all former Yugoslavian Countries (By alphabetic order: Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia and Slovenia.

After the strong motions were collected, earthquake metadata information of the strong motion database was enriched with the fault plane parameters based on the fault plane solutions (FPS) of the earthquakes gathered either from the relevant global resources (e.g. Global Centroid Moment Tensor Project) or the FPS analysis performed by the project participants (Mihaljević et al. 2017) using different softwares (developed within the institutions or commercial). Unfortunately, for the majority of the data (64 %), any information regarding the fault plane parameters still does not exist in the BSHAP database. Using the M_w values and double-couple solutions, the style-of-faulting of each event was determined by P- and T- angle definitions given in Boore and Atkinson (2007) and the source-to-site distance metrics (epicentral distance: R_{epi}; hypocentral distance: R_{hyp}; Joyner–Boore distance: R_{JB}; rupture distance: R_{rup}) were computed using the procedure described for Reference Database for Seismic Ground-motion in Europe (RESORCE; Akkar et al. 2014).

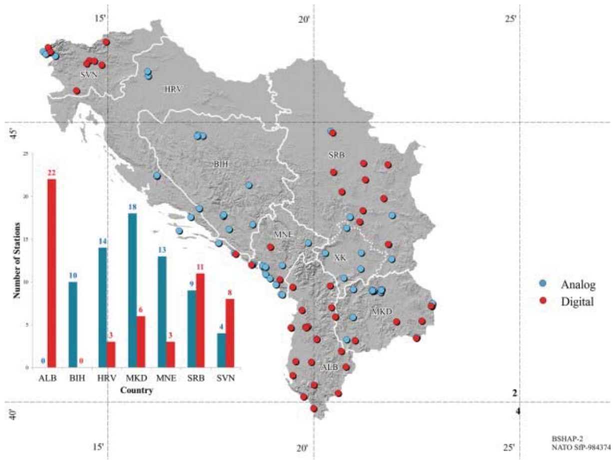


Figure 6. Geographic distribution of the free field strong motion stations related with the records in the BSHAP strong motion database (Šalic et al. 2016)

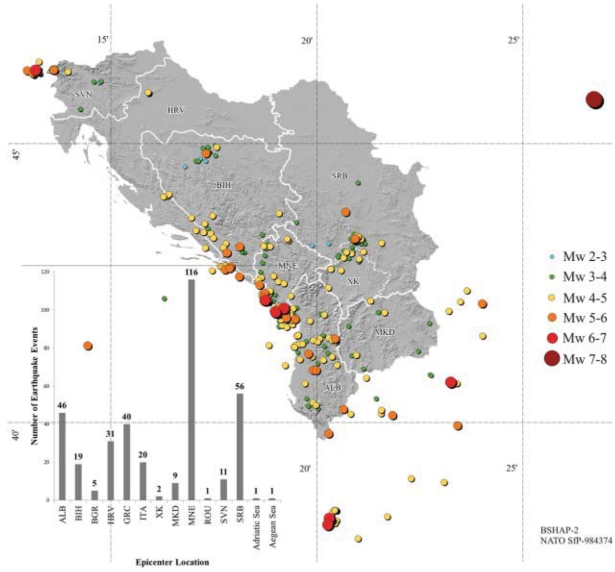


Figure 7. Geographic distribution of the earthquake events in the BSHAP strong motion database (Šalic et al. 2016)

All digital records in the BSHAP database were processed by uniform processing technique for the elimination of high and low frequency noise. Processing of the digital records was performed using the USDP (Utility Software for Data Processing) (Boore et al. 2011) and the analog waveforms were processed using the standard CALTECH procedure, modified due to use of different type of data processing equipment (Petrovski and Naumovski 1979; Petrovski et al. 1982). Details are presented in Šalic et al. (2016).

2.5. Selection of ground motion models

The established strong motion database is used for selection of the ground motion prediction equations (GMPEs) to be employed in the probabilistic seismic hazard assessment by comparing the compiled strong ground motions with the predictions of candidate global and Euro-Mediterranean GMPEs in a systematic manner (Šalic et al. 2016).

Guidance provided by the recent world-wide projects (such as SHARE-Seismic Harmonisation in Europe and GEM-Global Earthquke Model) was followed in addition to the well-known criteria proposed by Cotton et al. (2006) and Bommer et al. (2010) for building the list of candidate models. Therefore, the set of candidate models chosen by the BSHAP working group (**Figure 8**) was quite similar to the candidate list of Delavaud et al. (2012) and Stewart et al. (2015) except that the updated versions of the NGA-W1 and European models were included in this study (Abrahamson et al. 2014; Boore et al. 2014; Campbell and Bozorgnia 2014; Chiou and Youngs 2014; Akkar et al. 2014; Bindi et al. 2014 and Cauzzi et al. 2015).

On the other hand, provided is a comprehensive methodology for testing the applicability of candidate GMPEs for the PSHA studies in the Western Balkan area based on the collected BSHAP ground motion database. Our approach combines the residual analysis methods, evaluation of the median predictions for the scaling and functional form of candidate GMPEs, and recently published quantitative model-data comparison methods (Scasserra et al. 2009 and Gülerce et al. 2016). Four GMPEs (2 global NGA-West-2 models and 2 recently published European models) are selected based on the behavioral analysis i.e their satisfactory fit in the BSHAP strong motion dataset with these approaches. Accordingly selected are: [BSSA14] Boore et al. (2014), [CY14] Chiou and Youngs (2014), [Aetal14] Akkar et al. (2014) and [Betal14] Bindi et al. (2014).

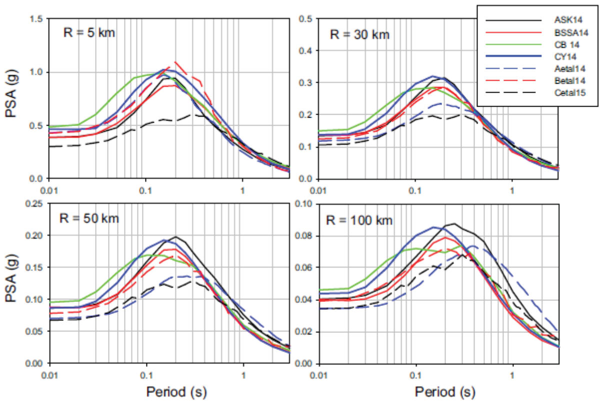


Figure 8. Comparison of the median predictions of the candidate GMPEs for EC site class A (VS_{30} = 800 m/s, Faulting style: SS, Earthquake size: Mw = 7.5 (Šalić et al. 2016)

In **Table 7** are presented calculated and combined (EDR, LLH) weighting factors as well as the adopted ones employed in PSHA calculations. The procedure used, allows that weighting factors are calculated based on either EDR (Kale and Akkar 2013) or LLH (Scherbaum et al. 2009) method, in which cases either LLHi=1 or EDRi=1, respectively.

Table 7. EDR and LLH scores of the selected GMPEs and calculated/adopted logic tree weights (Šalić et al. 2016).

GMPE	Period	EDR Score	LLH Score	Rank (EDR) SR	Rank (EDR) GR	Rank (LLH) SR	Rank (LLH) GR	Logic Tree Weights (w) Calculated	Logic Tree Weights (w) Adopted
BSSA14	**PGA**	1.485	2.647	2		1			
	0.2s	1.500	2.687	1	(1)	1	(1)	0.28199	**0.30**
	1.0s	1.275	2.249	1		2			
CY14	**PGA**	1.425	3.320	1		4			
	0.2s	1.439	3.038	1	(1)	4	(4)	0.25022	**0.30**
	1.0s	1.256	2.469	1		4			
Aetal14	**PGA**	1.644	3.227	4		4			
	0.2s	1.543	2.878	2	(4)	3	(3)	0.23516	**0.20**
	1.0s	1.415	2.289	4		2			
Betal14	**PGA**	1.641	3.120	4		3			
	0.2s	1.777	3.008	4	(4)	4	(3)	0.23262	**0.20**
	1.0s	1.261	2.111	1		1			

The calculated logic tree weights (**Table 7**) are much more in favor of EDR than LLH scoring scheme, attributing larger weights of 0.25 - 0.28 to CY14 and BSSA14, respectively, than to Aetal14 and Betal14 being of ~0.23. While the subsequent PSHA analyses could incorporate the epistemic uncertainty by using the calculated logic tree weights, the consensus decision of the BSHAP team was to additionally stipulate the CY14 and BSSA14 GMPEs attributing them the equal weights of 0.3 in respect to Aetal14 and Betal14, being de-stipulated to weights of 0.2.

2.6. Seismic Hazard Assessment

Conditioned by the lacking of sufficient data to define a fault-based model for BSHAP region, we decided to use the seismicity-based background models in the hazard calculations. The overall method for modeling background seismicity is based on the spatial smoothing approach (Frankel 1995, Lapajne et al. 1997, 2003), whereby the rate of past earthquakes and a regionally consistent MFD are used to forecast the rate of future earthquakes. The method accounts for the spatial variability of seismicity rate, and is used for areas where faults are not known or cannot be parameterized. A grid with the dimensions of 10 km by 10 km is superimposed on the region (12.0-24.5°E, 38.0-48.0°N). In methodology applied - the areal seismic sources are modelled as set of the grid points included within the relevant SSMs' polygons (zones). Earthquakes with Mw ≥4.0 that passed the completeness test of BSHAP catalogue are counted in each grid cell. Then, the annual rate of earthquakes occurrence is computed by maximum-likelihood (Weichert 1980) method - using the b-value from the corresponding super zone and the number of the events in the cell - adjusted to account for the magnitude completeness levels. Finally, a two-stage spatial smoothing method is used to smooth the annual rates of earthquake occurrence (λ-grid) in each grid cell. At first, the two-dimensional isotropic Gaussian smoothing (Frankel 1995), hereinafter circular smoothing (CS), is applied to smooth the λ-grid. In the second stage, the fault-oriented smoothing (Lapajne et al. 1997, 2003), hereinafter elliptic smoothing (ES) that employs the seismotectonic knowledge in the relevant source zones of SSM1 and SSM2 (main directions and types of the tectonic structures, as well as m_{max}) is used to model smoothed seismicity rates.

The PSHA analysis indicate that the choice of seismicity smoothing methods has significant influence on seismic hazard estimates. To evaluate the effects of spatial smoothing, alternative seismicity smoothing methods are investigated. Based on the sensivity analysis we decided to use the circular spatial smoothing (CS) with a correlation distance of 30 km, as well as both the circular and elliptic smoothing which also considers the rupture directions in the seismic source zones, based on the seismotectonic data. Spatial smoothing approach is considered as a branch in the logic-tree structure describing the epistemic uncertainties associated with construction of the seismic source model. We assign the same weight (0.5) to both CS and CES smoothing approaches.

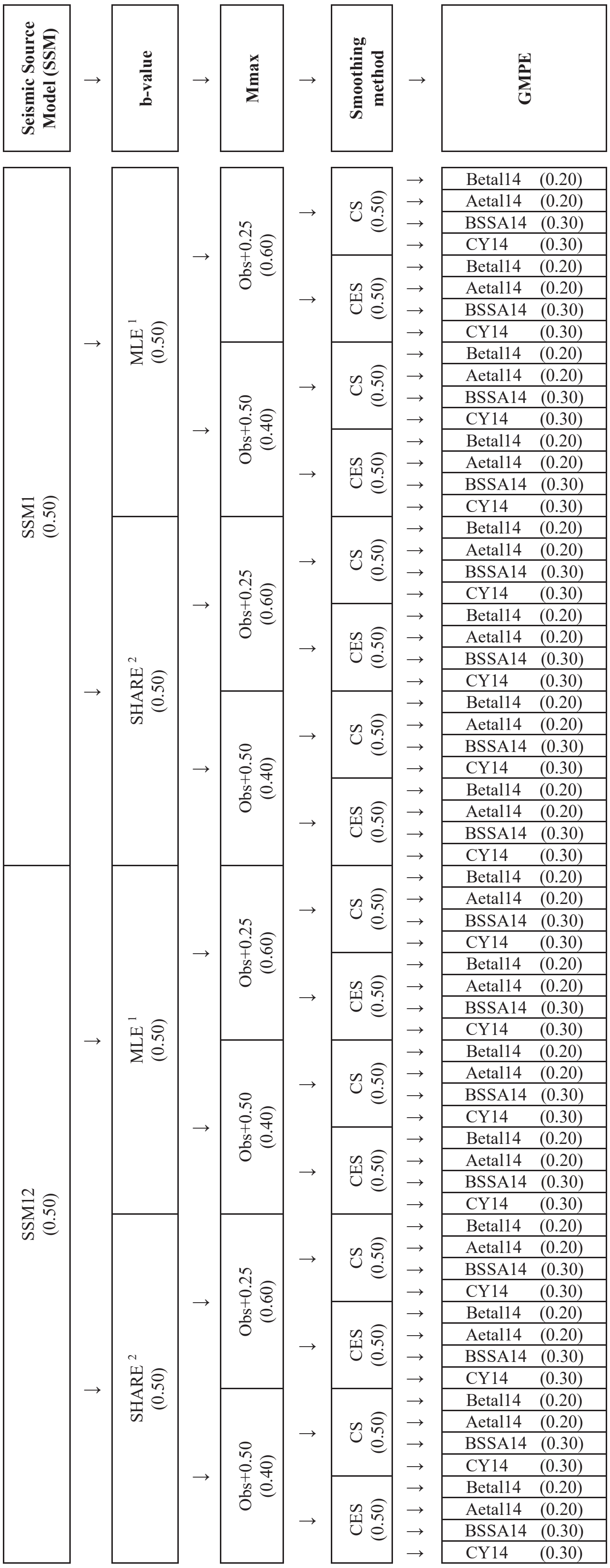


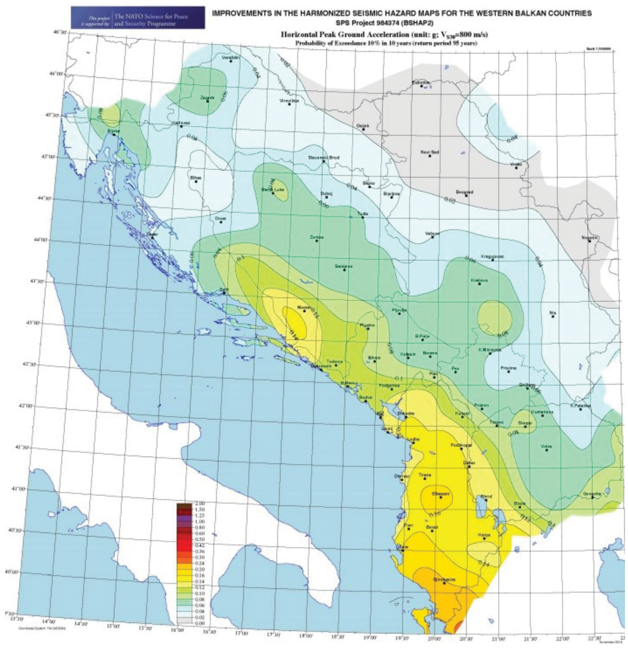
Figure 9. Logic-tree for the seismicity based background source model in the Western Balkans. Assigned branch weights shown in parentheses.

1) Average value of Weichert and KS-92 MLE, 2) AS denotes Areal Source model of SHARE ***(Kuka et al. 2017)***

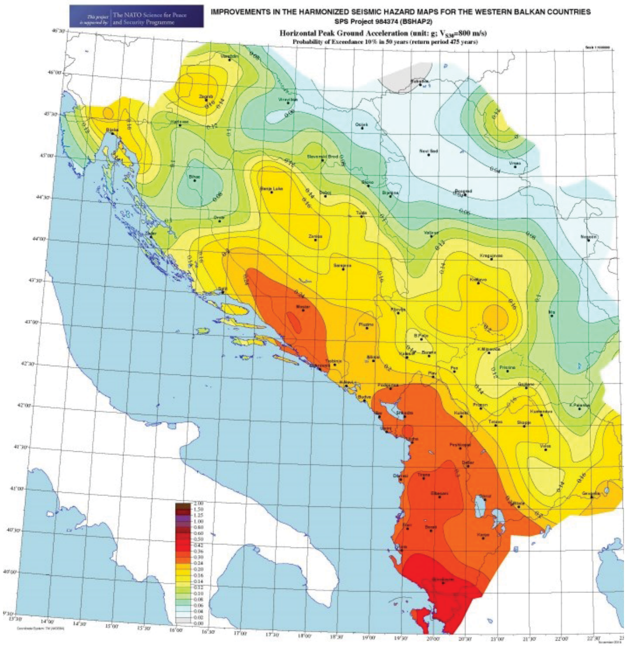
It is evident the prehistoric and historical earthquakes in each source zone provide a lower bound on m_{max}. That is, m_{max} must be at least as large as the largest observed earthquake. We cannot know, however, if the largest observed earthquake is the largest possible earthquake. We represent the uncertainty in m_{max} by assigning weights to two alternative estimates. For each source zone, two alternative estimates for m_{max} are considered adding an increment of 0.25 and 0.50 magnitude units, respectively, to the maximum magnitude observed in the zone. To the both branches is assigned the same weight, 0.5.

Logic tree with 64 branches (**Figure 9**) has been designed for deriving the hazard maps of the Western Balkans using the seismicity-based background source model. The logic tree includes two background-seismicity source models (SSM1 and SSM2), two alternative estimates for the b-value, two alternative estimations of the maximum magnitude for each source zone, two alternative algorithms for smoothing of the seismic rates (CS with 30 km correlation length, and CS+CES), and four GMPEs (Aetal14, Betal14, BSSA14 and CY14) for ground motion prediction. Hazard calculation for each branch of logic tree are performed using the computer code OHAZ (Zabukovec and Kuka et al. 2007), jointly developed by ARSO (Slovenian Environment Agency) and IGEWE (Institute of GeoSciences, Energy, Water and Environment, Albania), and recently updated and improved by Kuka (OHAZ 2015) to fulfil requirements of the BSHAP project.

Hazard assessment is applied for firm rock conditions, with 800 m/sec shear-wave velocity in the upper 30 m of the soil section (CEN, 2004). Based on the hazard results taken according to the above mentioned procedure, the probabilistic seismic hazard maps that characterize the spatial variability of maximum horizontal acceleration (PGA) were compiled. In compliance with EC8 standards, the hazard was calculated for two characteristic return periods: 95 (Figure 10a) and 475 years (**Figure 10b**), which correspond to the exceedance probabilities of 10% in 10 years and 50 years, respectively.



a) Seismic hazard map of Western Balkans showing peak ground acceleration for 10-percent probability of exceedance in 10 years (RP 95 years).



b) Seismic hazard map of Western Balkans showing peak ground acceleration for 10-percent probability of exceedance in 50 years (RP 475 years).

Figure 10. Seismic hazard maps of Western Balkans showing peak ground acceleration for VS30 site condition of 800 meters per second (Kuka et al. 2017).

3. CONCLUSIONS

One of the most important outputs of the BSHAP is an updated and unified earthquake catalogue that is compiled directly from the datasets of earthquake data providers of the region. New magnitude conversion equations for various local magnitude scales of the data providers are developed with the aim of having homogeneous moment magnitude estimates. Completeness time intervals for the catalogue data are provided as inputs to the seismic source models for updated seismic hazard of Western Balkan Region. The unified and updated BSHAP catalogue is found to be compatible with the current well-established European and world-wide catalogues and represents a sound basis for analysis of the seismicity of this region.

BSHAP collected relevant knowledge about the geological structure of southwestern Balkans. Database of focal plane solutions, held by BSHAP partners, provided a better understanding of the prevailing stress regime in the region. Entire influence area covered by earthquake catalogue data is represented by logic-tree branches of seismic source models: each model is composed of full set of seismogenic zones (groups of cells with the same attributes that are grouped into regions). The weighted b-values are adopted from the Super zone model and using MLE (Weichert 1980) and Kijko and Selevoll (1992) approaches and in accordance to estimates of SHARE Area Source model (Basili et al. 2013). Presented Seismic source models SSM1 and SSM2 - represented by its geometry, seismicity and seismotectonic information is provided as the input to perform the spatial smoothing of seismic activity rates for the hazard calculations.

In the framework of BSHAP, the regional free field strong motion network capacity was increased significantly by the purchased and installed recorders and the BSHAP strong motion database that includes both pre-BSHAP (mostly analog) and post-BSHAP (all digital) recordings was compiled. The BSHAP harmonized strong motion database includes the uniformly processed strong motions along with the related earthquake metadata and station information; therefore, it provides a solid background for the ground motion characterization studies in the surrounding region. The BSHAP strong motion database is used for proper selection of the ground motion prediction equations (GMPEs) for the probabilistic seismic hazard assessment (PSHA) by comparing the compiled strong ground motions with the predictions of candidate global, European, and Euro-Med GMPEs in a systematic manner.

The main output of BSHAP are the new probabilistic seismic hazard maps for Western Balkans (Figure 10), obtained by implementation of the smoothed-gridded seismicity approach. They are prepared based on the BSHAP earthquake catalogue, selected GMPEs and developed seismotectonic model. Hazard calculations are carried out following a logic-tree structure with 64 branches describing the epistemic uncertainties associated with construction of the seismic source model, and of the GMPEs selected for ground motion prediction. The results are expressed in terms of peak horizontal acceleration (PGA) for 95 and 475 years return periods. The assessment has been carried out for rock conditions with average velocity of shear waves $V_S \geq 800$ m/sec in the upper 30 meters of soil section (classified as soil type A according to Eurocode 8 soil definitions). Thus, obtained results are in full agreement with the Eurocode 8 standard for seismic zonation and aseismic design. The seismic hazard maps derived in this project are a good basis to characterize the seismic hazard of Western Balkans. They will help the national authorities, public and private institutions, civil emergencies agencies, etc., for urban planning, disaster preparedness, and seismic hazard mitigation.

4. ACKNOWLEDGMENTS

This work is funded by NATO SpS Program under: "Improvements in the Harmonized Seismic Hazard Maps for the Western Balkan Countries Project" (NATO SfP Award Number: 984374). BSHAP participants are indebted to the institutions/data providers for positive cooperative attitude in data releasing and continuous support. We, the BSHAP Projects teams and authors of this paper, do expect that NATO, Public Diplomacy Divisions' expectations and policies are meet, in terms of technical and synergic achievements, and that BSHAP's results justify granting that we highly acknowledge.

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