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A THREE-DIMENSIONAL REGIONAL-SCALE EARTHQUAKE GROUND MOTION SIMULATION FOR THE BENGAL BASIN

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Abstract

This study presents the initial results of a project with the goal of studying the ground motion characteristics of the Bengal basin region in Bangladesh, south Asia, through the simulation of a series of historical, recorded and scenario earthquakes. Bangladesh is one of the most densely populated countries in the world, with more than one thousand people per square kilometer, and several cities exceeding a few millions habitants. Most people in Bangladesh live in poorly constructed (often unreinforced) buildings. The country land is shaped by the Ganges delta, the largest delta system in the world, which rests over a sedimentary structure with thicknesses that can reach up to 20 km. The lithospheric structure is dominated by the different orogeny systems created by the collision between the Indian, Eurasian and Burmese tectonic plates. Depending on the geological setting, Bangladesh can be divided into three provinces: the stable shelf, which is part of the Indian continental plate at the northwest; the central deep basin, covering most of Bangladesh; and the Chittagong-Tripura fold belt at the eastern border, created by the oblique subduction of the oceanic crust under the Burmese plate. The region is bounded by the Dauki fault to the north and north-east, the Bogra fault on the stable shelf region, boundary thrust faults at Chittagong-Tripura fold belt region to the east, and the Madhupur fault and some other ambiguous faults inside the basin. These systems place Bangladesh under high seismic hazard, and given the population density and infrastructure conditions it is assumed the country presents elevated levels of seismic risk. This situation is worsen by the tremendous scarcity of seismic data, despite the significant seismic activity in the region. Under these conditions, simulations can provide valuable input to better understand the potential effects of a major earthquake affecting the Bengal basin. However, in order to perform ground motion simulations, the first step is to construct a reliable seismic velocity model for the region. Here, we present the initial version of a three-dimensional model built upon a geology-based representation of the geometry of the Bengal basin and simple approximations of the basin deposits, crustal, and background structures. We show results for a low-frequency ground motion simulation ($f \leq 0.5$ Hz) of the 10 September 2010 M_w 5.1 Chandpur earthquake and compare basic qualitative characteristics observed in the synthetics with a limited number of records available. The simulations are done using a finite-element parallel code. Using these initial results we investigate the influence of basic features such as fault boundaries and basin depth, and shed light over future steps necessary to better characterize earthquake ground motions in the region.

Keywords: Bengal basin; Bangladesh; deep basin effects; ground motion simulation, seismic velocity model

1. Introduction

Home to more than 160 million people, Bangladesh is the country with the highest population density in the world with about 1.2 thousand people per square kilometer, followed behind by Taiwan and South Korea with about half and less than half the number of habitants per unit of area, respectively. Given its density distribution and despite having a strong population presence in rural areas, Bangladesh is considered an urban country. According to the World Bank, about 34 percent of its total population live within major city limits. The metropolitan areas of Dhaka, the country's capital, and the seaport city of Chittagong, the second largest in the country, house near 16 and 4 million people, respectively.

These and other cities face significant seismic hazard. Chittagong and the northeastern city of Sylhet, for instance, are located in the vicinity of a complex subduction and folded-belt system of faults, and Dhaka is 200 km south of a thrust fault system. In fact, the whole country is surrounded by several fault systems. Just south of the Himalayan front, Bangladesh can be divided in to three major geologic units. The stable shelf at the northwestern part of the country, the Chittagong-Tripura folded belt at the eastern part, and the deep Bengal basin in the central region [1, 2]. The Bengal basin, which covers most of the country, and the country itself were formed by the collisions between the Indian and the Eurasian plates, and the Indian and the Burmese plates [3, 4]. The former defined the main Himalayan boundary thrust front and the Dauki fault to the north, and the latter defined the subduction zone of the Chittagong-Tripura folded belt to the east. The collisions between these plates also gave rise to the subjacent structure beneath the basin and other faults within it [5–7]. In turn, the sedimentary structure of the Bengal basin, which reaches a depth of about 22 km at its deepest point, was built by millions of years of deposition by the Ganges, Brahmaputra, and Meghna rivers, which together form the largest delta system in the world [2, 8].

The fresh flood-driven nature of the deposits on the Bengal basin makes Bangladesh one of the most fertile places in the world. Bangladesh remains, nonetheless, a developing country. Most of its population lives in poorly constructed—often unreinforced—buildings, and many suburbs rest on loosely deposited landfills prone to liquefaction during strong ground shaking [9, 10]. Historical evidence indicates that the country has seen several major earthquakes with magnitude greater than 7.0 in the last 150 years [11, 12], with some in the last 250 years exceeding magnitude 8.0, such as the 1762 Assam earthquake in the Chittagong-Tripura fault system and the 1897 Assam earthquake in the Dauki fault [11, 13].

Altogether, it is clear that Bangladesh is under conditions of elevated seismic risk. The country, however, lacks the appropriate monitoring infrastructure required for detailed seismic hazard analyses. To our knowledge, up until last year the country had but only a handful number of publicly accessible seismic stations, which has been recently increased to a total of 10 instruments [16]. While new instruments will surely offer interesting data in the future, in the meantime much can be done via alternative methods. In that regard, earthquake ground motion simulation offers a means to complement and substitute the current lack of data from past earthquakes, and serves as a tool to gain insight about the ground motion characteristics of the Bengal basin region.

Much progress has been done in simulation of ground motions in the last decades and a variety of methods are available in the literature [15]. Among the alternatives, we are interested in using a deterministic, physics-based approaches to generating synthetic ground motions using numerical methods and three-dimensional (3D) models. These methods allow to solve regional scale wave propagation problems in heterogeneous media using parallel computers [16]. This paper presents our efforts on the development of an initial version of 3D velocity model for the Bengal basin, and the results obtained for the ground motion simulation of the 10 September 2010 M_w 5.1 Chandpur, Bangladesh, earthquake. We compare our simulation results with recorded seismograms and put emphasis in understanding the effect that the deep Bengal basin has on the ground motion. While much work remains to be done, our results reveal themselves as promising and constitute a solid first step in a long term effort to improve seismic hazard characterization in Bangladesh.

2. Tectonics, Seismicity, and Seismic Hazard

The tectonic setting of Bangladesh and the Bengal basin region is conditioned by the collision of the Indian, Eurasian, and Burmese plates. As it is well-known, sometime in the early Cretaceous, the Indian plate started rifting apart from the Antarctic plate and moving northeast. The encounter between the Indian plate and the Eurasian plate resulted in the rise of the Himalayan mountains, to the north of the Bengal basin, which was in turned formed by this and the additional collision of the Indian plate with the Burmese plate to the east [3, 4, 17, 18]. This process gave origin to a rich and complex set of seismotectonic faults, the most prominent of which being the main Himalayan boundary thrust, the Dauki fault, the Chittagong-Cox's Bazar (CCB) fault and the Chittagong-Tripura fold belt (CTFB), and the Kaladan and Kabaw faults, shown in Fig. 1.

As the Indian plate traveled, sediments deposited on the northeast corner of the plate and a portion of the oceanic crust was pushed back and trapped between the three plates, and now lies under continental land and beneath the deepest portion of the Bengal basin. A major feature of the basin itself is its depth. The Bengal Basin is well known for the development of a thick—as deep as 22 km—Early Cretaceous-Holocene sedimentary succession [19, 20]. As shown in Figs. 1 and 2, to the northwest the basin is delimited by the Rajmahal Hills (Traps), which are composed of lower Jurassic to Cretaceous trap basalts of the upper Gondwana system; to the north, it is bounded by the Garo, Khasi and Jayantia hills (west to east) [21]; the far northeast is delimited by the Shillong and Assam plateaus; and to the east and southeast, it is bounded by the Chittagong-Tripura folded belt, which is composed of Paleocene-Pliocene age sediments of the Siwalik system (the Himalayan fore-deep basin sediment system) [22].

The transitions between the oceanic and continental crusts and the geology of Bangladesh, in general, are marked by the presence of two distinctive high-gravity signatures: (i) the Calcutta-Mymensingh hinge zone, which differentiates the basin from the stable shelf region to the far east; and (ii) the Barisal-Chandpur gravity high, which indicates the transition between the continental and the oceanic crust [2]. Both of them are shown in Fig. 1 (top view), and the cross north-south and east-west sections in Fig. 2 illustrate the progression of continental crust into the oceanic crust and the attenuating crustal thickness, as well as the contrast with the Shillong plateau and the Himalayan front. (Note that the sediment thickness in the basin is nearly as much as the crustal thickness.) The ongoing orogeny further compresses the sediment deposit and creates different sections within the sedimentary deposit, such as the Faridpur and Sylhet troughs [8].

Altogether, these conditions provide for a very rich seismic environment. Fig. 3 shows the seismicity of the region of interest for historical and instrumental events between 1500 and 2015, including some highlighted events and various events with magnitudes greater than 7. It is clear that the proximity of the country to the Himalayan main thrust, which runs about 100–300 km away from the northern border of Bangladesh, poses a high level of seismic hazard for the country. So do the Dauki fault, right on the northern border, and the CCF and CTFB fault systems in the subduction zone to the east (see Fig. 1 for reference). These have also been the source to several major damaging earthquakes.

Historical accounts show that Bangladesh has witnessed the occurrence of several M > 7 earthquakes in the last 150 years and a few M > 8 earthquakes in the last 250 years. The Dauki fault—which is formed due to the uplifting of the Shillong plateau—ruptured in 1897 with an estimated magnitude of 8.2±1, prompting the occurrence of liquefaction and causing devastation all over the country [13]. This event is still considered as the major reference earthquake when estimating seismic hazard for the region [12]. Other significant earthquakes include the 1762 Arakan earthquake, with epicenter in the Chittagong-Tripura folded belt and an estimated magnitude of up to 8.8 [23], the 1869 M 7.39 [24] Cachar earthquake near Sylhet basin [11], the 1918 M_s 7.6 Srimongal earthquake near Sylhet [25], and the 1930 M 7.1 Dhubri earthquake in the Dauki fault [25]. The potential for devastation is such, that the Arakan earthquake is believed to have shifted the Brahmaputra river from its original course to its current one. There are studies that indicate this earthquake changed the geography of the country, caused liquefaction and triggered a tsunami [26]. Table 1 lists these and other earthquakes and their epicentral location, estimated magnitude, and depth.

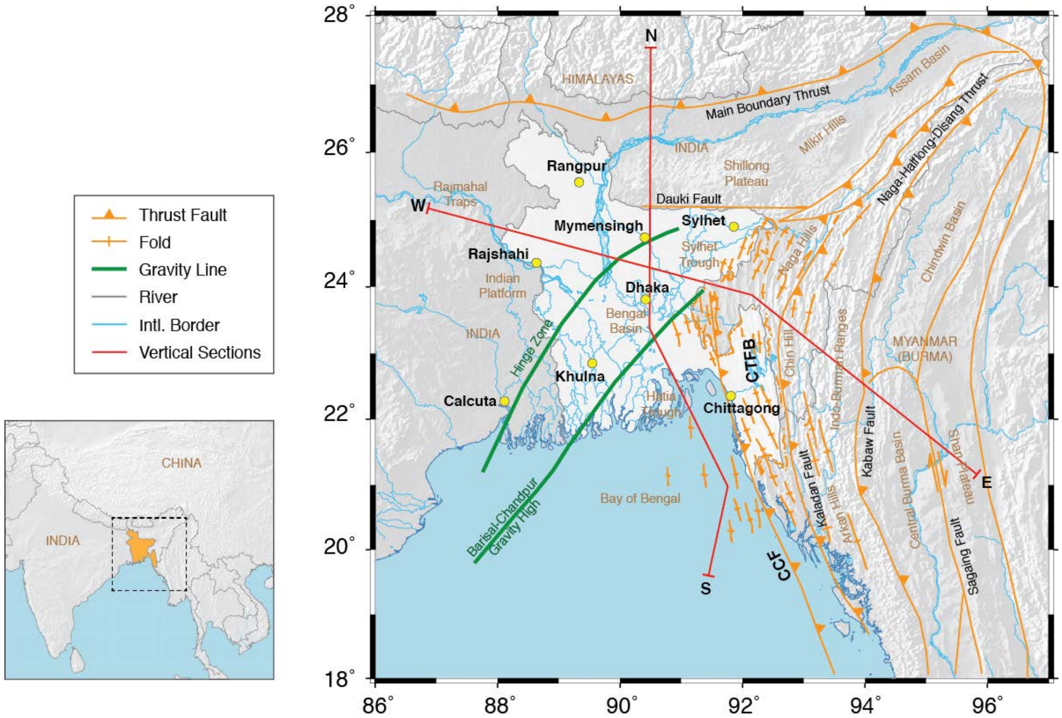

Fig. 1 – Map of Bangladesh and surrounding countries with major seismic fault systems, and gravity lines. The dark orange lines indicate the profiles shown in Fig. 2. This figure was digitally enhanced and modified based on original images by [2] and others cited therein.

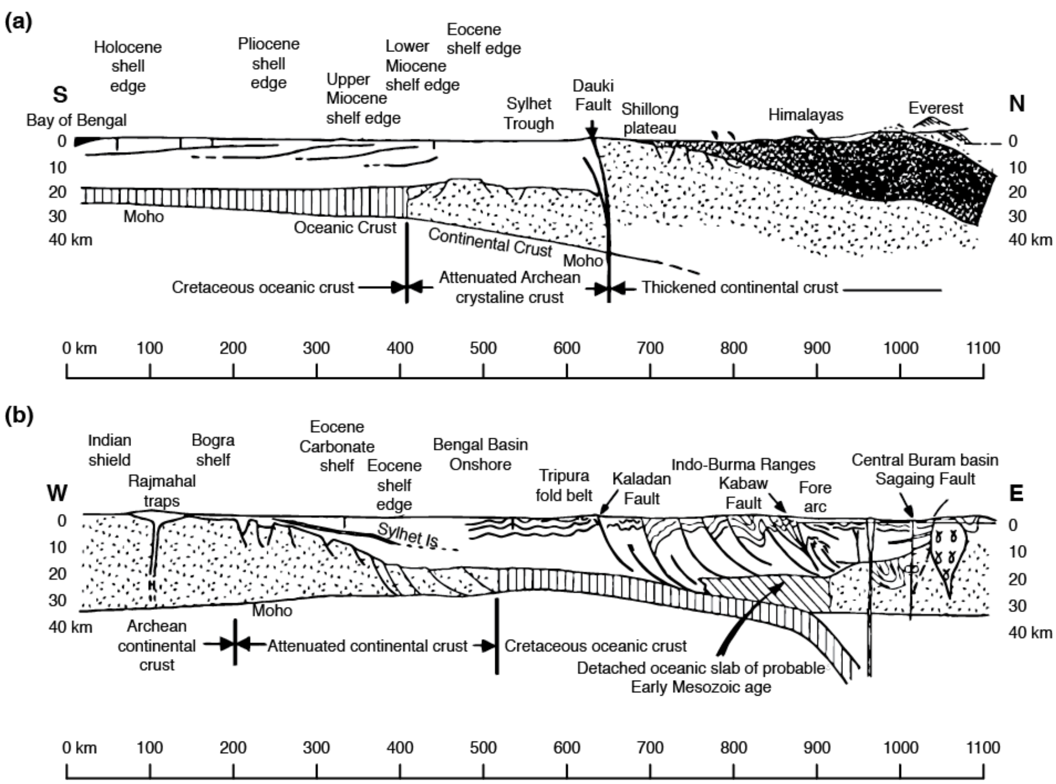

Fig. 2 – Details of the (a) north-south and (b) east-west crustal cross sections through the Bengal basin indicated in Fig. 1. Modified after [2] and others cited therein.

Most of the shallow earthquakes in the region have depths from 15 to 40 km, which indicates all the earthquakes are occurring in the crust below the sediment deposit. There are few deep earthquakes on the southeastern border but they do not pose seismic threat. The first seismic hazard map elaborated for Bangladesh was published in 1993 [29] and divided Bangladesh in three major seismic zones: a high risk zone enclosing the cities of Sylhet and Mymensigh and other provinces in the northeast, a medium risk zone across a northwest-southeast corridor, and a low risk zone in the southeast. The map was later updated in 2005 (with minor changes) and more recently in 2014 [30, 31]. The 2014 version now divides the country in four zones and increased the maximum considered peak ground acceleration (PGA) on rock in the high-hazard zone from 0.25g to 0.36g. Both the original 1993 and the current 2014 seismic zoning maps are shown in Fig. 4.

Table 1 – List of major historical and instrumental notably damaging earthquakes in and around Bangladesh.

Name	**Date**	**Epicenter Location**		**Magnitude M_w**	**Depth (km)**
		Lat.	**Long.**		
Arakan Earthquake	2 April 1762	22.00°N	92.00°E	≤ 8.8*	–
Great Bengal Earthquake	14 July 1885	24.70°N	89.55°E	6.5–7.0*	72
Great Indian (Assam) Earthquke	12 June 1897	25.84°N	90.38°E	8.1–8.3*	60
Srimangal Earthquake	8 July 1918	24.25°N	91.80°E	7.6*	14
Dhubri Earthquake	3 July 1930	25.95°N	90.04°E	7.1	60
Mikir Hills Earthquake	8 July 1945	25.80°N	92.30°E	6.7	–
Moheshkhali Earthquake	22 July 1999	21.61°N	91.96⁰E	5.1	10

* Approximate estimation

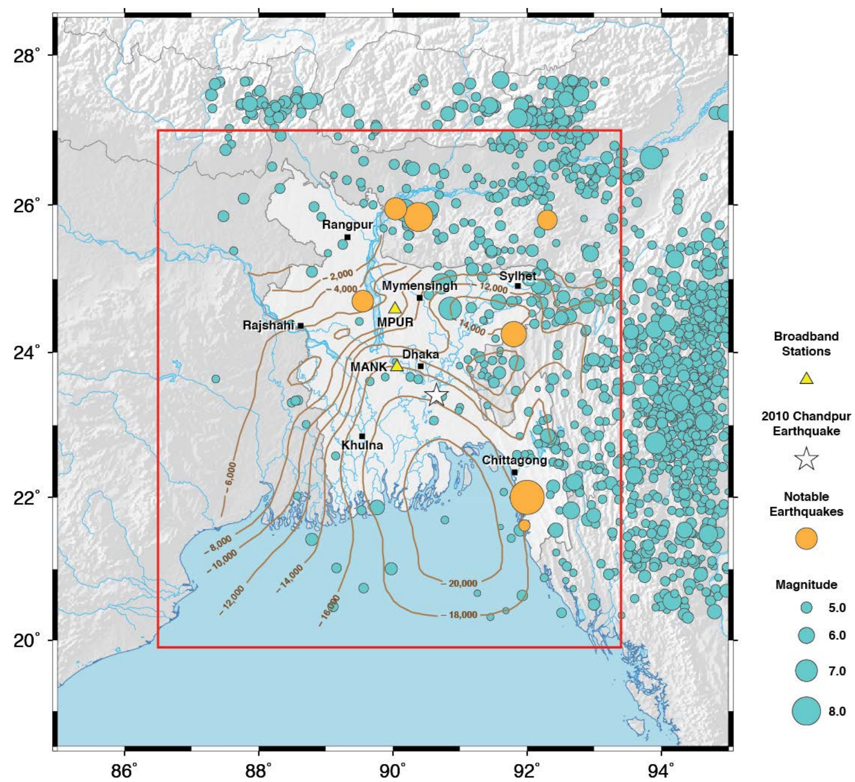

Fig. 3 – Instrumental and historical seismicity of the region of interest and simulation domain boundaries. Notable historical and other recent damaging earthquakes described in Table 1 are highlighted. The star indicates the location of the epicenter of the earthquake selected for initial simulation testing of the velocity model in development. Yellow triangles indicate the location of the broadband stations that recorded the event. The brown contour lines correspond to those obtained from [27, 28].

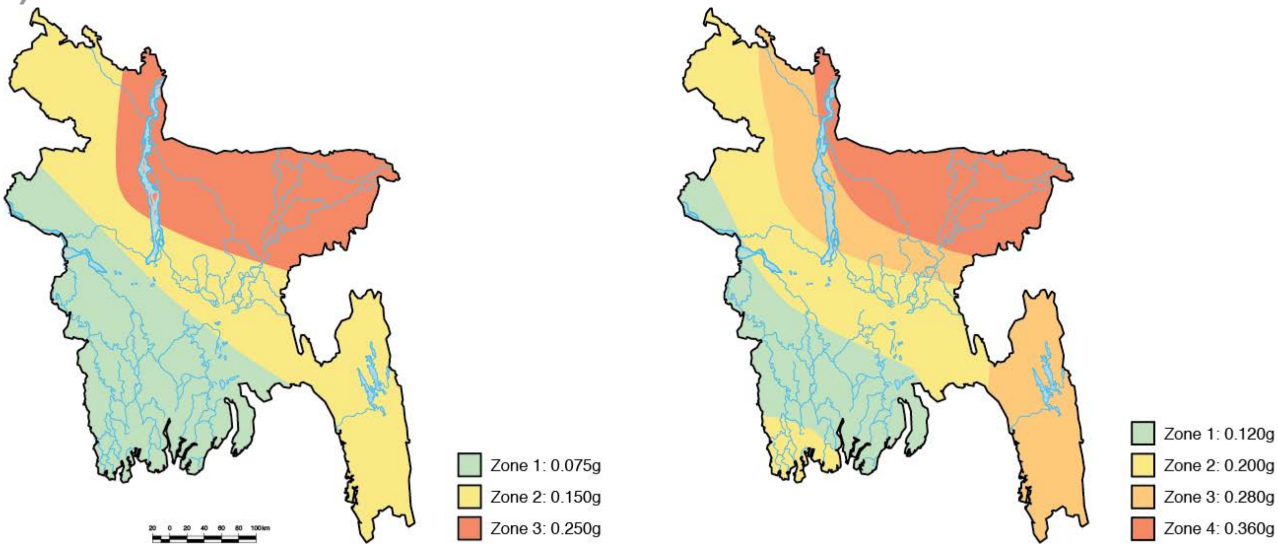

Fig. 4 – Seismic hazard map of Bangladesh according to the 1993 (left) and 2014 (right) national building codes [29, 31]

3. Simulation Domain and Velocity Model

We consider a simulation domain with a surface area of 760 km × 780 km, and 50 km in depth. This domain covers all of Bangladesh, the continental section of the Bengal basin and part of the offshore section under the Bay of Bengal, as well as territories of the adjacent countries and some of the major faults in the region (Fig. 3). The domain also covers the Shillong plateau and part of the Assam, the Dauki fault and a portion of the Himalayan belt, which together mark the northern edges of the basin; and the folded belt at the eastern boundary. While there is no major fault structures west of the basin, the model extends in that direction to include the boundary of the Ganges basin on the stable continental shelf (see the Rajmahal traps in Fig. 1).

A necessary component for 3D ground motion simulations using deterministic, numerical approaches is the availability of a seismic velocity (or crustal structure) model to characterize the geometry and material properties in a given simulation domain for a chosen region of interest. Such a model was not available for Bangladesh or the Bengal basin region. Therefore, we built a model using available information from the literature. Our approach to this task consisted of defining the depth of the basin, or depth to the oceanic and continental crusts under the basin, and then building a rule-based seismic velocity model using simple one-dimensional depth-dependent profiles for the background structure and mantle, the crust and the basin. Although we recognize this is a rather simplistic approach, the main objective here is to construct a first version of a velocity model for the region which we use here for initial simulations but plan to refine and test more thoroughly in the future.

In that order of ideas, our first step was to digitize information available on the depth of the basin. Fig. 4 shows the depth contour lines taken from [27, 28] within the simulation domain, and Fig. 5a shows our digitized version of these contours augmented and extended to cover all the simulation domain and to consider other features such as the Ganges river basin and Rajmahal traps, and the back of the Shillong plateau and the Assam basin, as mentioned before.

Upon digitizing and complementing these data, we generated a surface using the *griddata* function of MATLAB. The result of this process is shown in Fig. 5b. This surface map shows the depth of the basin or depth-to-crust within the simulation domain. Once the surface was obtained we used it as reference to define a 20 km thick crust below, and used the normalized profiles shown in Fig. 6 to define the properties within the basin, in the crust, and in the mantle or background models. As a first approximation and as it can be seen in the figure, in all three cases we assumed a linear gradient for the values of P- (V_P) and S-wave (V_S) velocities and density, increasing with depth. The top and bottom reference values of the profiles were defined based on published data [32–34].

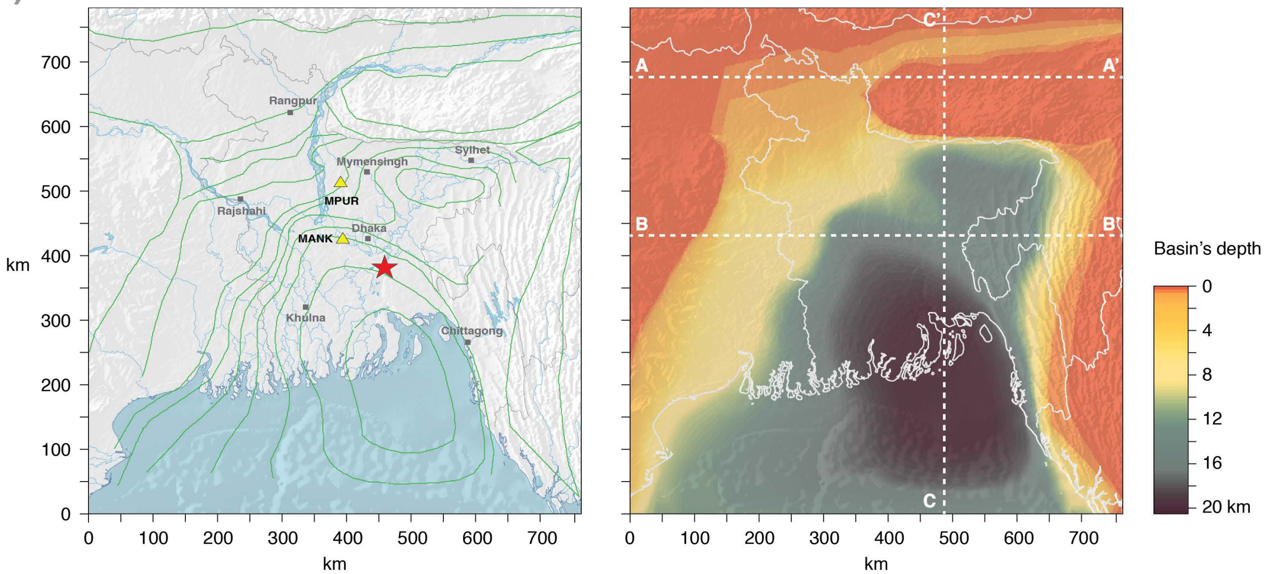

Fig. 5 – Simulation domain (left) and basin depth (right) as implemented in the velocity model built for the region. Green contour lines on the left correspond to the digitized and complemented basin depth model built upon the original contours shown in Fig. 3. White dashed lines on the right are used for reference in Fig. 7.

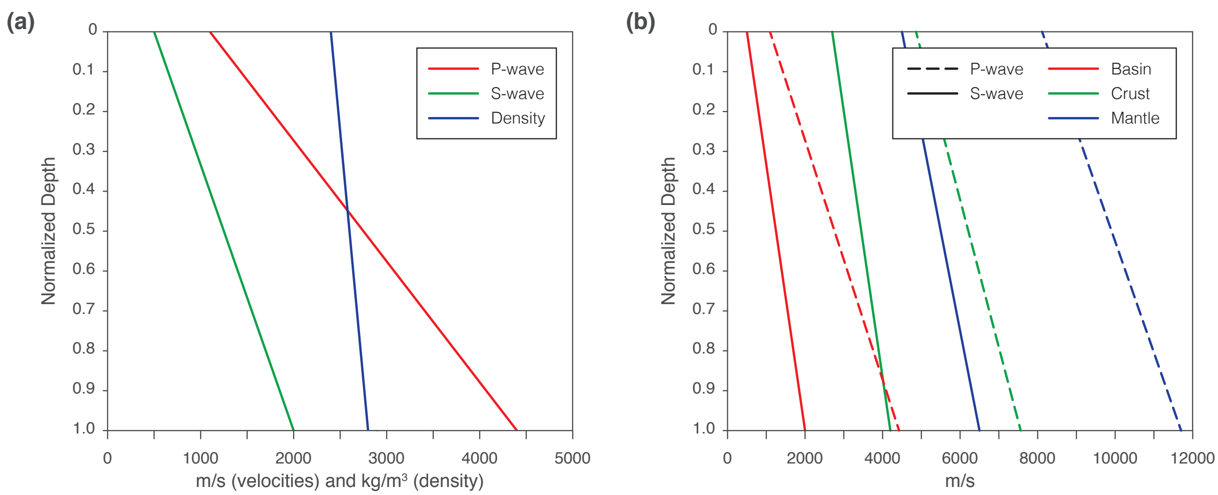

Fig. 6 – Normalized model profiles of *P*- and *S*-wave velocities and density. (a) Profiles inside the basin. (b) Comparison for *P*- and *S*-wave velocities between the basin, crust and mantle/background models.

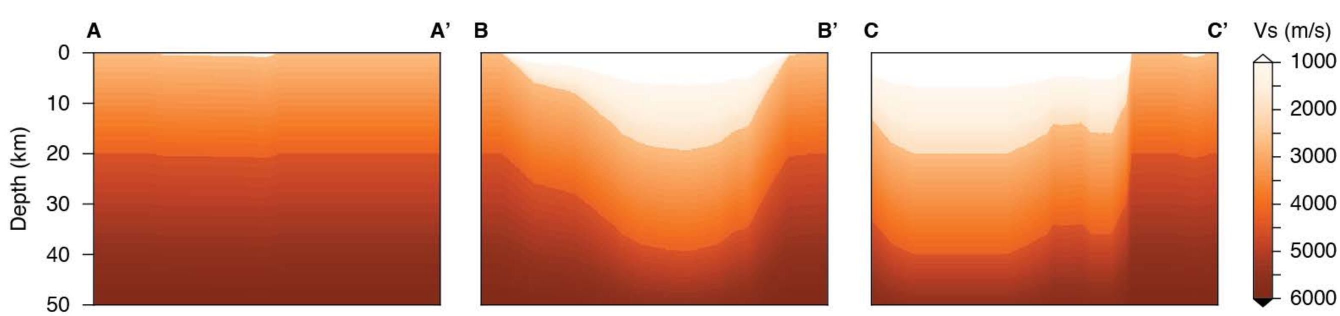

Fig. 7 – Cross sections of the velocity model (S-wave) along the lines AA', BB' and CC' shown in Fig. 5b.

The results of using these profiles to compose the 3D velocity model is shown in Fig. 7 for the cross-sections indicated in Fig. 5b. Together, Figs. 5–7 give a good idea of the shape of the basin and the composition of the model. As mentioned before, the most distinctive feature of the Bengal basin is its depth. At the deepest part of the basin, marked by the combined estuary of the Ganges, Brahmaputra and Meghna rivers, the deposits in the basin reach thicknesses of about 22 km. Most other basins in the world are no deeper than 10–12 km, and the vast majority of basins are under 5 km of depth. Another relevant feature captured in our extended model is the presence of the Dauki fault and Shillong plateau, and the subsidence due to the uplifting of the plateau.

4. Simulation Method and Parameters

We simulate the ground motion within the region of interest using a physics-based, deterministic approach. This approach entails the solution of the wave equation in 3D models such as the one we developed for this study (described in the previous section). This, in turn, implies the use of numerical models which, because of the large-scale (regional) nature of the problem, are often addressed with the aid of high-performance, parallel supercomputers.

There are multiple methods and implementations available for this, including the finite difference, spectral element, and finite element methods, e.g. [35–38]. In this study we use a parallel computing software called *Hercules*, which implements the finite element method and uses an octree-based modeling approach [38]. Hercules relies on a standard Galerkin method for discretizing the equations of elastodynamics in space, and advances the solution of the resulting system of ordinary differential equations explicitly in time to obtain the next-step state of nodal displacements. The code uses first-order backward and second-order central differences to approximate the velocity and acceleration terms [39], a viscoelastic model to represent the effects of intrinsic attenuation in the material [40], and a plane wave approximation to absorb outgoing waves at the boundaries of the truncated simulation domain.

Hercules has been used in multiple ground motion simulation studies before, including the verification of large scenario earthquakes and the validation of simulations of past earthquakes, e.g. [41–43]. Such studies have shown that the code is a reliable tool for ground motion simulation. Table 2 summarizes the simulation parameters used this study.

5. The 2010 Chandpur Earthquake

As a first approximation to testing the velocity model developed for the region and begin the process of understanding the characteristics of the ground motion in the Bengal basin region, we select the 10 September 2010 M_w 5.1 Chandpur earthquake as our study case.

The 2010 Chandpur earthquake was a moderate event with epicenter south of Dhaka and near the city of Chandpur (Figs. 3 and 5). Despite its moderate magnitude, according to local news outlets, the earthquake was felt vigorously in both cities and other nearby urban centers, where it caused considerable damage. We model the rupture within the simulation domain using a kinematic (double-couple) point source model. The centroid moment tensor (strike, dip and rake) solution used to define the double-couple was taken from the U.S. Geological Survey website and contributed by the U.S. Global CMT project of the Lamont-Doherty Earth Observatory. Although the primary reported solution located the hypocenter of the earthquake at 18.4 km depth, other solutions situated the event at 10 and 14.4 km under the surface. We opted for using a depth of 14.4 km in our simulation, as a middle-point alternative. These and other relevant parameters are included in Table 2.

Two seismic monitoring stations in Bangladesh recorded this event, the station MPUR southwest from the city of Mymensingh, and the station MANK west from Dhaka (Figs. 3 and 5a). We obtained the corresponding seismograms (broadband channel) from the Data Management Center (DMC) of the Incorporated Research Institutions for Seismology (IRIS) for these two stations and use them for reference to qualitatively validate our results.

Table 2 – Simulation and source parameters.

Domain size	760 km × 780 km × 50 km
Domain bottom-left corner	86.5°E, 19.9°N
Domain top-right corner	93.4°E, 27.0°N
Vs_{min}	500 m/s
f_{max}	0.5 Hz
Points per wavelength	10
Time step size	0.01 s
Simulation time	150 s
Qs	$0.1Vs$
Qp	$2Qs$
Epicenter coordinates	90.648°E, 23.407°N
Hypocentral depth	14.4 km
Magnitude (M_w)	5.1
Strike/Dip/Rake	149°/77°/171°

6. Simulation Results

Fig. 8 shows the response of the ground for 150 s of simulation along the surface lines BB' and CC' (shown in Fig 5b) in terms of the surface particle velocity, and Fig. 9 shows a comparison of synthetics with respect to data recorded at the MANK and MPUR stations. This being the first simulation ever done using a 3D model for the region of the Bengal basin, there is still much to be done before meaningful analysis of the ground motion can be done. For the time being, however, there are a few noteworthy characteristics captured by the synthetics and their comparison with respect to the data.

First, from Fig. 8 we note that the synthetics offer an interesting view into the different phases of the wavefield within the simulation domain. *P*, *S*, and other wave types are easily identified. This is in part due to the simplistic representation of the basin so far captured by the model. Unfortunately, at this point we do not seem to capture the effects of the basin very well. We do not observe any reflection from the basin's edge, nor do we observe a clear amplification or longer duration within the basin other than the amplification due to the proximity to the source.

This is corroborated by the comparisons with data shown in Fig. 9, where we note that the synthetics attenuate much faster than the data. This is likely not to an overestimation of the attenuation effects but more due to the fact that the profiles we chose (Fig. 6) are too smooth to effectively amplify and trap waves within the basin, as obviously the data suggest is not the case. It is nonetheless remarkable to have both the data and the synthetics plotted within the same order of magnitude, and despite some early arrival of the synthetics, to have them with some level of good agreement on the phases of the first arrivals. It must be noted that in our experience it usually takes several attempts and significant effort to obtain synthetics within the same order of magnitude when comparing simulations with data. Here, the results presented in Fig. 9 are, on the contrary, the very first attempts at simulating the ground motion for the region of interest. This gives us confidence and we hope to obtain much more meaningful results in the future as we improve the model to properly represent the general characteristics of the basin and its effect on the ground response.

7. Final Remarks

In this study we briefly review the tectonics and seismicity of Bangladesh and the Bengal basin, and present the first version of a three-dimensional velocity model developed for the region. Using this model, we conduct a physics-based, deterministic earthquake simulation for a recent moderate magnitude earthquake and compare results with data. The long term objective of this work is studying the region's ground motion characteristics and the effects of the unique Bengal basin on the surface response in an area under high seismic hazard and elevated levels of seismic risk. While such an effort is still in its infancy, we found our first approximation to the problem to be promising. We obtained synthetics that were comparable in amplitude to observations and it seems very likely that given this head-start we will be able to make positive progress in the near future, when we will attempt to validate simulations of recent earthquakes with some of the scarce data available for the region and, more important, conduct simulations of scenario events that will contribute synthetic results to a region in need of reliable estimates of expected ground motions, which can meaningfully help reduce seismic risk.

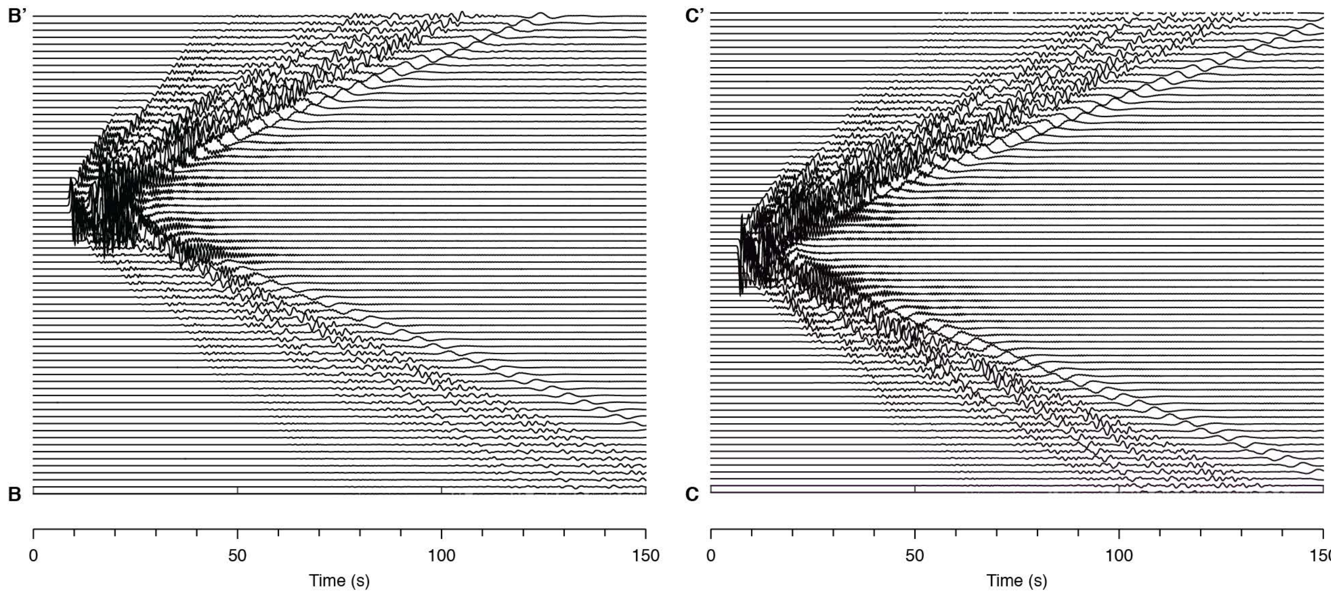

Fig. 8 – Ground motion response during 150 s of simulation in the EW component of motion along the surface lines BB' and CC' shown in Fig. 5b.

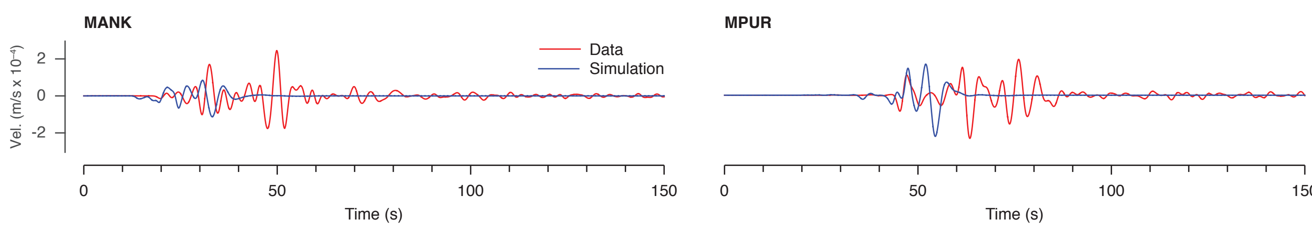

Fig. 9 – Comparison of synthetics with data for the EW component of motion at the MANK and MPUR stations.

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9. References

[1] Alam M (1972): Tectonic Classification of the Bengal Basin. *Geological Society America Bulletin*, **83**, 519–522.

[2] Alam M, Alam MM, Curray JR, Chowdhury MLR, Gani MR (2003): An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history. *Sedimentary Geology*, **155**, 179–208.

[3] Lee T-Y, Lawver L (1995): Cenozoic plate reconstruction of Southeast Asia. *Tectonophysics*, **251**, 85-138.

[4] Acharyya SK (1998): Break-up of the greater Indo-Australian continent and accretion of blocks framing south and east Asia. *Journal of Geodynamics*, **26**, 149–170.

[5] Islam MS, Shinjo R, Kayal JR (2011): Pop-up tectonics of the Shillong Plateau in northeastern India: Insight from numerical simulations. *Gondwana Research*, **20** (2-3), 395-404.

[6] Morino M, Kamal ASMM, Ali RME, Talukder A, Khan MMH (2013): Report of active fault mapping in Bangladesh: Paleo-seismological study of the Dauki fault and the Indian-Burman plate boundary fault. *Comprehensive Disaster Management Programme (CDMP II),* Ministry of Disaster Management and Relief.

[7] Khan FH (1991): *Geology of Bangladesh*. The University Press.

[8] Mukherjee A, Fryar AE, Thomas WA (2009): Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India and Bangladesh. *Journal of Asian Earth Sciences*, **34** (3), 227–244.

[9] Paul BK, Bhuiyan RH (2010): Urban Earthquake Hazard: Perceived Seismic Risk and Preparedness in Dhaka City, Bangladesh. *Disasters*, **34(3)**, 337–359.

[10] Rahman MZ, Siddiqua S, Kamal ASMM (2015): Liquefaction hazard mapping by liquefaction potential index for Dhaka City, Bangladesh. *Engineering Geology*, **188**, 137–147.

[11] Bilham R (2004): Earthquakes in India and the Himalaya: tectonics, geodesy and history. *Annals of Geophysics*, **47** (2/3), 839-858.

[12] Al-Hussaini TM, Chowdhury IN, Noman NA (2015): Seismic hazard assessment for Bangladesh – Old and new perspectives. *Proceedings of the First International Conference on Advances in Civil Infrastructure and Construction Materials*, Dhaka, Bangladesh.

[13] Bilham R, England P (2001): Plateau ‘‘pop-up’’ in the great 1897 Assam earthquake. *Nature*, **410**, 806–809.

[14] David Wilson, U.S. Geological Survey, Albuquerque Seismological Laboratory, personal communication, April 2016.

[15] Douglas J, Aochi H (2008): A survey of techniques for predicting ground motions for earthquake engineering. *Surveys in Geophysics*, **29**, 187–220.

[16] Taborda R, Roten D (2015): Physics-based ground motion simulation. *Encyclopedia of Earthquake Engineering*, Beer M, Patelli E, Kougioumtzoglou I, Au S (Eds.), Springer Berlin Heidelberg, 33 pp.

[17] Curray JR, Emmel FJ, Moore DG, Raitt RW (1982): Structure, tectonics and geological history of the northeastern Indian Ocean. *The Ocean Basins and Margins. The Indian Ocean*, Nairn AEM, Stehli FG (Eds.), Plenum, New York, **6**, 399– 450.

[18] Hutchison C.S. (1989): *Geological evolution of South-East Asia*. Clarendon Press, London.

[19] Curray JR (1991): Geological history of the Bengal geosyncline. *Journal of the Association of Exploration Geophys*ics, **XII**, 209–219.

[20] Curray JR, Munasinghe T (1989): Timing of intraplate deformation, northeastern Indian Ocean. *Earth Planetary Science Letters*, **94**, 71–77.

[21] Morgan JP, McIntire WG (1959): Quaternary geology of the Bengal basin, east Pakistan and India. *Geological Society of America Bulletin*, **70**, 319–342.

[22] West WD (1949): Geological map of India. *Geological Survey of India Records* **81** (1), 222.

[23] Cummins PR (2007): The potential for giant tsunami-genic earthquakes in the northern Bay of Bengal. *Nature*, **449**, 75–78.

[24] Ambraseys NN, Douglas J (2004): Magnitude calibration of north Indian earthquakes. *Geophysical Journal International*, **159** (1), 165–206.

[25] Abe (1981): Magnitudes of large shallow earthquakes from 1904 to 1980. *Physics of the Earth and Planetary Interiors*, **27** (1), 72–92.

[26] Alam E, Dominey-Howes D (2014): An analysis of the AD1762 earthquake and tsunami in SE Bangladesh. *Natural Hazards*, **70**, 903–933.

[27] Shamsuddin AHM, Abdullah SKM (1997): Geological evolution of the Bengal basin and its implication in hydrocarbon exploration in Bangladesh. *Indian Journal of Geology,* **69**, 93–121.

[28] USGS-Bangladesh Gas Assessment Team (2001): U.S. Geological Survey–PetroBangla cooperative assessment of undiscovered natural gas resources of Bangladesh. *U.S. Geological Survey Bulletin 2208-A*, Petroleum Systems and Related Geologic Studies in Region 8, South Asia, Wandrey CJ (Ed.), U.S. Geological Survey, U.S. Department of Interior.

[29] Bangladesh National Building Code (1993). Ministry of Works.

[30] Bangladesh National Building Code (2005). Ministry of Works.

[31] Bangladesh National Building code (2014). Ministry of Works.

[32] Parvez IA, Vaccari F, Panza GF (2003): A deterministic seismic hazard map of India and adjacent areas. *Geophysical Journal International,* **155**, 489–508.

[33] Mitra S, Bhattacharya SN (2008): Crustal structure of the western Bengal basin from joint analysis of teleseismic receiver functions and Rayleigh-wave dispersion. *Bulletin of the Seismological Society of America*, **98** (6), 2715–2723.

[34] Rajshekhar RP, Mishra DC (2008): Crustal structure of Bengal basin and Shillong plateau: Extension of eastern Ghat and Satpura mobile belts to Himalayan fronts and seismotectonics. *Gondwana Research*, **14**, 523-534.

[35] Graves RW (1996): Simulating seismic wave propagation in 3D elastic media using staggered-grid finite differences. *Bulletin of the Seismological Society of America*, **86** (4), 1091–1106.

[36] Komatitsch D, Vilotte J-P (1998): The spectral element method: An efficient tool to simulate the seismic response of 2D and 3D geological structures. *Bulletin of the Seismological Society of America*, **88** (2), 368–392.

[37] Bao H, Bielak J, Ghattas O, Kallivokas LF, O'Hallaron DR, Shewchuk JR, Xu J (1998): Large-scale simulation of elastic wave propagation in heterogeneous media on parallel computers. Computational Methods in Applied Mechanics and Engineering, **152** (1-2), 85–102.

[38] Tu T, Yu H, Ramírez-Guzmán L, Bielak J, Ghattas O, Ma K-L, O'Hallaron DR (2006): From mesh generation to scientific visualization: An end-to-end approach to parallel supercomputing. *SC'06: ACM/IEEE International Conference for High Performance Computing, Networking, Storage and Analysis*, IEEE Computer Society, 15 pp.

[39] Taborda R, López J, Karaoglu H, Urbanic J, Bielak J. (2010): Speeding up finite element wave propagation for large-scale earthquake simulations. *Technical Report CMU-PDL-10-109*, Parallel Data Lab, Carnegie Mellon University, Pittsburgh, USA.

[40] Bielak J, Karaoglu H, Taborda R (2011): Memory-efficient displacement-based internal friction for wave propagation simulation. *Geophysics*, **76** (6): T131–T145.

[41] Bielak J, Graves RW, Olsen KB, Taborda R, Ramírez-Guzmán L, Day SM, Ely GP, Roten D, Jordan TH, Maechling PJ, Urbanic J, Cui Y, Juve G (2010): The ShakeOut earthquake scenario: Verification of three simulation sets. *Geophysical Journal International*, **180** (1): 375–404.

[42] Taborda R, Bielak J (2013): Ground-motion simulation and validation of the 2008 Chino Hills, California, earthquake. *Bulletin of the Seismological Society of America*, 103 (1): 131–156.

[43] Taborda R, Azizzadeh-Roodpish S, Khoshnevis N, Cheng K (2016): Evaluation of the southern California seismic velocity models through simulation of recorded events. *Geophysical Journal International*, **205** (3): 1342–1364.