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Preliminary Estimation of Ground Motion of September 24, 2013, Pakistan Earthquake Using Modified Semi-Empirical Approach

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ABSTRACT

Hazard plays a vital role in assessing the risk of any area. For earthquake hazard estimation, it is essential to obtain ground motion records from various seismic stations. However, it is not always easy to get ground motion data. The present study is an attempt to generate ground motions of the recent September 24, 2013, Pakistan earthquake using modified semi-empirical approach, which is based on ω^2 model. The first part of the method considers a time series having the basic spectral shape of acceleration. The deterministic model of rupture source has been used in the second part of the method to simulate the envelope of accelerogram. For the study, a MATLAB code is written to generate synthetic accelerograms at stations Awaran, Panjgur, Tagas, Korak, and Gajar. The results are compared with Ground Motion Prediction Equation (GMPE) proposed by Ramkrishnan et al., in 2019 [1]. The PGA values obtained from modified semi-empirical method gives satisfactorily good results in comparison with the PGA values from GMPE. However, slight variation is observed between synthetic accelerogram PGA values and GMPE values at Gajar, Korak, Tagas, Panjgur stations.

Keywords:
Synthetic accelerogram;
Envelope function;
Attenuation relationship;
Pakistan earthquake

1. Introduction

The shallow focus earthquake of Mw7.7 triggered at south-central Pakistan on September 24, 2013, at 11:29:47 UTC. The event was located at 26.951°N, 65.501°E which is about 63 km towards the north of Awaran, Pakistan [2]. This event occurred as the result of oblique strike-slip type motion at shallow crustal depths, above the Makran subduction zone. In recent past years, the Eurasian plate has not experienced great earthquakes, though the region is seismically active. A notable earthquake of Mw 6.1 happened within 200 km from the epicenter of 2013 Awaran, Pakistan earthquake in 1990 that killed six people [3]. An earthquake occurred in 1505 in the province of the north-west of Kabul, Afghanistan. The northern part of the Chaman fault was ruptured where the damage has been concentrated on the town of Paghman with an intensity of IX and X. Also, this event caused more destruction to structures [4]. Recently, another earthquake (Quetta earthquake) of Mw 7.6 occurred in the Sulaiman region, killing around 60,000 people. September 24, 2013, Pakistan earthquake (Mw 7.7) was caused by a strike-slip fault called Chaman fault and killed at least 850 people [5]. In the past 40 years, a significant earthquake of magnitude M 6.1 occurred within 200 km from the epicenter of the September 24, 2013 Pakistan earthquake (USGS).

Ten aftershocks of magnitude less than six

occurred within two days after the 2013 Pakistan main shock. The largest aftershock of Mw 6.8 occurred on September 26, 2013. Around 80% of mud-brick buildings were damaged in Awaran and Baluchistan. The buildings in these areas are predominantly unreinforced brick masonry, and rubble masonry and around 10% of the buildings are earthquake resistant. Over 300000 people have been affected across eight districts of Pakistan. Many of the cities around the globe felt this earthquake and reported intensity values are shown in Table (1) (USGS). Around ten cities had experienced a seismic intensity more than IV on the MMI scale in Pakistan. The city of Awaran has experienced a seismic intensity of VIII. Since this earthquake had occurred in a mountainous location, thus, it was not expected that this event would cause significant loss. Cities located more than 1000 km had also experienced a seismic intensity greater than II. It means that long-period surface waves have traveled at greater distances and caused shaking of high-rise buildings. In view of different ground shaking at several locations, the present paper has made an attempt to generate synthetic ground motions at different locations in Pakistan through the modified semi-empirical approach. The detailed description of the above method is provided in the methodology section.

Table 1. Few cities had experienced Pakistan earthquake occurred on 24 September 2013 (Source: USGS; accessed 15 November 2013).

City	Country	MMI Intensity	Distance from Epicenter (km)
Abu Dhabi	United Arab Emirates	II	1152
Al-Fujayrah	United Arab Emirates	IV	941
Ash-Shariqah	United Arab Emirates	III	1026
Chomun	India	II	1012
Dubai	United Arab Emirates	II	1036
Gharonda	India	III	1173
Gurgaon	India	III	1145
Karachi	Pakistan	IV	277
Khuzdar	Pakistan	IV	141
Kirman	Iran	II	904
Kot Abdul Malik	Pakistan	IV	385
Madeji	Pakistan	III	302
Mirpur Khas	Pakistan	II	383
Muscat	Oman	II	795
New Delhi	India	II	1167
Peshawar	Pakistan	I	971
Ras Al Khaimah	United Arab Emirates	III	965
Shymkent	Kazakhstan	II	1743

2. Seismo-Tectonics Setup and Fault System

The Himalayan region is the seismically active region in the Indian subcontinent, due to the continental collision of Indian and Eurasian plates. More stresses are cumulating at the junction of these seismotectonic plates due to the interaction between them. It is revealed that the convergence rate of the Central and Eastern Nepal Himalaya is estimated at 19±2.5 mm/yr, from geodetic measurements [6]. This convergence could likely cause great earthquakes along the Himalayan belt in future [7]. The Hindu Kush, Pamir and Karakoram mountains released significant amount of seismic energy due to the convergence of tectonic plates. The Hindu Kush and Pamir are among the most active regions in the world, which often generate quite large earthquakes at 300 km deep [8]. In the Hindu Kush region, the earthquake mechanism is usually thrust faulting and occasionally normal faulting [9]. The seismic activity coincides for the most part of the Himalayan Main Central Thrust (MCT) rather than the Himalayan Main Boundary Thrust (MBT) in the western Himalayas. The seismic gaps are the most active locations for the future great earthquakes, which are Kashmir gap, Central gap, and Assam gap. The interaction between Indian plate and Eurasian plate is classified into three parts, (1) continental convergent (4323.9 km), (2) continental transform (1586.7 km) and (3) continental ridge (126.5 km) [10].

The significant major faults in Pakistan are Jhelum fault, the Main Karakoram Thrust (MKT), Sulaiman Range Fault, Chaman Transverse Fault, Pab Fault, Nai Rud Fault and Kirthar Fault, etc. [9]. A strike-slip Jhelum fault is trending north-south and extends along the Jhelum River [11]. A large number of earthquakes occurred in the MKT active thrust region (Seismic Risk Map of Northern Pakistan, 1988, PGS). The MKT represents the collision zone of the southern margin of the Eurasian plate in Asia and extends into the Baltistan area through Hashupa and Machie in the Shigar and Shyok

valleys, respectively. The Chaman fault is one of the major left-lateral transform faults of Pakistan that connects Makran convergence and Makran subduction zones. The length and width of the Chaman fault are 425 km and 25 km, respectively. The slip rate of the fault ranges 2-20 mm/yr. The Nai Rud fault is an active thrust fault, located adjacent to the Makran convergence zone and trending east-west. It has a NE-SW trending, almost parallel to the Nai Rud valley and bears the characteristics of thrust with left-lateral strike-slip component [9].

3. Past Earthquakes

Pakistan is located at the northwestern side of the Indian subcontinent that experienced a great earthquake of M 8.1 (1945 Balochistan earthquake) and eight major earthquakes of magnitude greater than M 7.0 (2013 Pakistan-M 7.8; 1935 Balochistan-M 7.7; 2005 Kashmir-M 7.6; 1931 Balochistan-M 7.4; 2011 Pakistan-M 7.2; 1909, 1929 and 1931 Balochistan-M 7.0) since 1900 [2]. The seismicity of Pakistan from 1900 to 2013 is shown in Figure (1). The location of past major earthquakes and major cities in Pakistan are shown in Figure (2).

Pakistan is divided into four seismic zones based on expected peak ground acceleration. The major portion of southern parts is under zone II and parts of coastal Pakistan till Karachi lies in zone III. The major cities of Pakistan like Peshwar, Rawalpindi, and Islamabad are under zone II. However, these cities frequently experience major earthquakes (Pakistan Meteorological Department). The 2005 Kashmir earthquake was recorded at three seismic stations, namely, Abbottabad, Murree, and Nilore. The peak ground acceleration of 0.237 g was recorded at the Abbottabad station, which was situated about 50 km from the epicenter of the 2005 Kashmir earthquake [12]. From the above literature, it is evident that few earthquakes had ground motion records in the near-field region (<100 km). The near-field ground motion records are essential to assess the damage of a structure. This paper makes

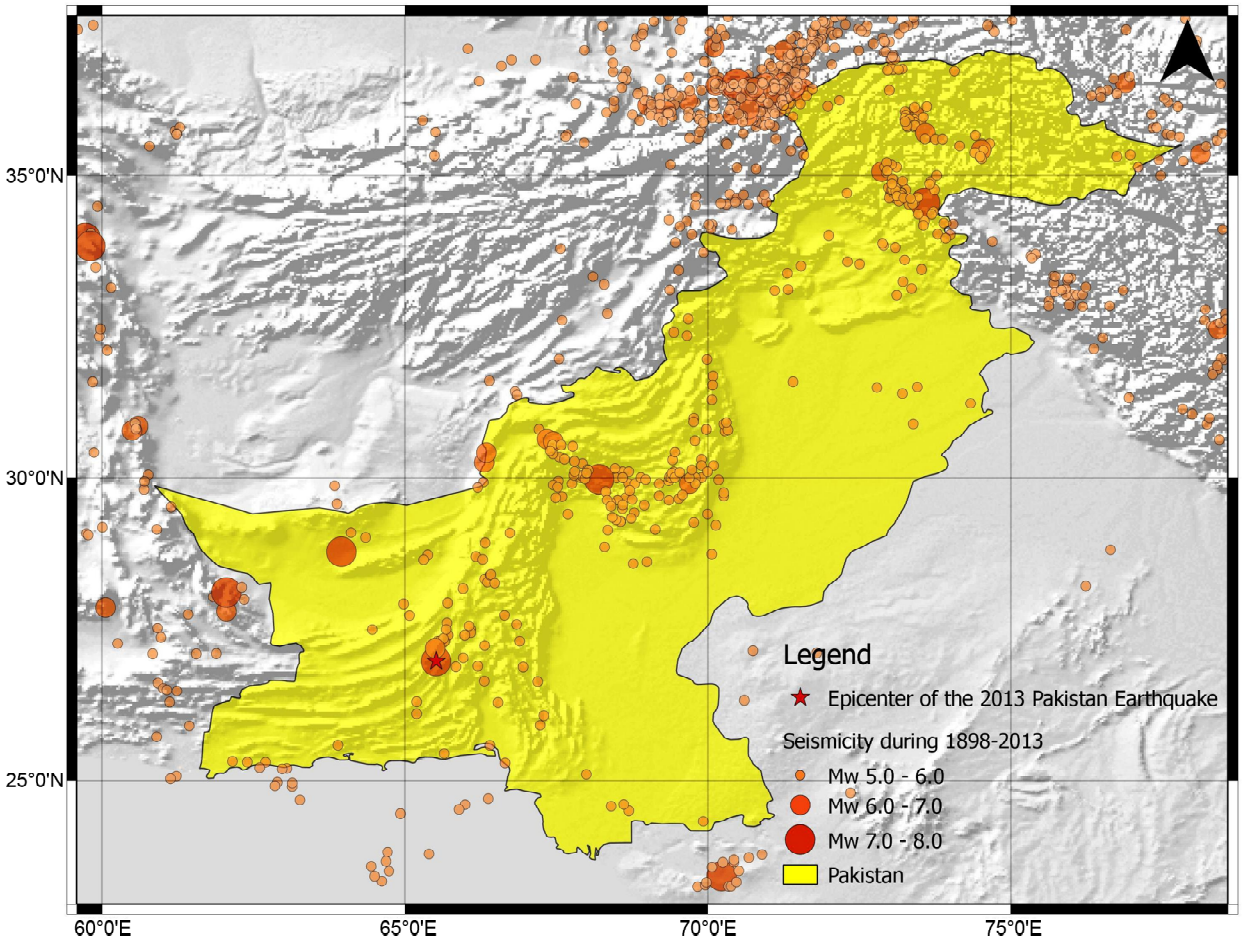

Figure 1. Seismicity of Pakistan from 1900 to 2013 with magnitude Mw 5.0-Mw 8.0 (Earthquake Data: Northern California Earthquake Data Center, NCEDC [26]).

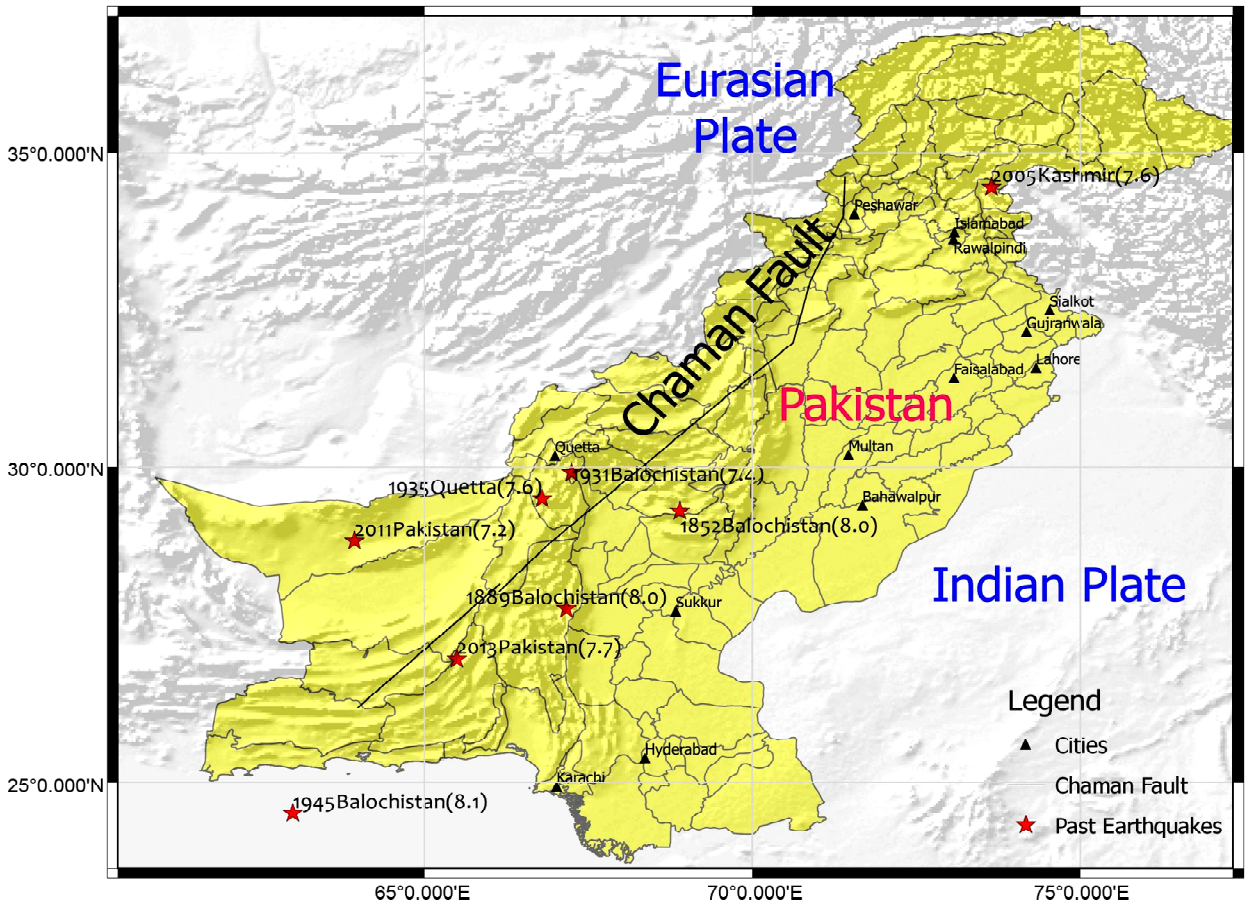

Figure 2. Location of past earthquakes (stars) and location of major cities in Pakistan during 1900 - 2013.

an attempt to generate near field ground motions of the 2013 Pakistan earthquake at five seismic stations with epicentral distance ranging from 15 km to 150 km using modified semi-empirical approach. The following section describes the methodology to generate synthetic accelerograms.

4. Methodology

This section describes a step-by-step procedure of the semi-empirical simulation approach to generate synthetic accelerograms [13-14]. The method is based on ω^2 model [15]. The initial part of the analysis considers the spectral shape of acceleration. Other part of the analysis simulates the envelope of accelerogram. The detailed description of the above approach is given below.

4.1. Stochastic Simulation Technique

In the stochastic simulation technique, the normalized white Gaussian noise of zero expected mean and variance has been chosen of desired length. The normalized time series is converted into amplitude spectrum using Fourier transform and maximum amplitude is maintained as unity. The amplitude spectrum is passed through theoretical filter, which is given in Equation (1) [15]. Again the amplitude spectrum is converted into time series and ensures that the time series must be normalized, so that the prediction of peak ground acceleration will be reasonable. The shape of acceleration spectra $A(f)$ at a site located at a hypo-central distance R is as follows:

$$A(f) = C.S(f).P(f).\left[e^{(-\pi fR/\beta Q)} / R\right] \quad (1)$$

where C is a constant scaling factor, including seismic moment (M_o) given by Boore [15]. $S(f)$ is source filter [16], $P(f)$ is high frequencies attenuation filter [15], the exponential term filter represents an elastic attenuation, R is hypo-central distance in km, β is the shear wave velocity in km/sec, and Q is a frequency-dependent quality factor.

$$S(f) = \frac{(2\pi f)^2}{\left[1+\left(f / f_c\right)^2\right]} \quad (2)$$

$$P(f) = \frac{1}{\left[1+\left(f / f_m\right)^8\right]^{0.5}} \quad (3)$$

where f_c represents corner frequency and f_m represents maximum frequency. These are calculated as follows:

$$f_c = 4.9\times10^6 \beta(\Delta\sigma / M_o)^{1/3} \quad (4)$$

$$f_m = 7.31\times10^3 M_o^{-0.12} \quad (5)$$

where $\Delta\sigma$ represents the stress drop in bars, M_o represents the seismic moment of an earthquake in dyne.cm. As empirical relationship between cut-off frequency and seismic moment for the Pakistan region is unavailable, authors have taken the relationship provided by Boore [15]. The time series in this technique overestimates the high frequencies and underestimates the low frequencies in the simulated ground motion. This is due to the difference between the slip duration of the target and the small earthquake considered as sub-faults. A correction $F(t)$ is introduced to minimize above difference and it is as follows [17, 18]:

$$F(t) = \delta(t) + [(N-1)/T_R(1-e^{-1})].e^{(-t/T_R)} \quad (6)$$

where $\delta(t)$ represents the delta function, N is the total number of sub-faults, and T_R is the rise time of the target earthquake. The acceleration record $A_{ij}(t)$ is as follows:

$$A_{ij}(t) = F(t).a_{ij}(t) \quad (7)$$

where *i* and *j* represent the location of sub-fault on a fault plane, aij is the corresponding ground motion prediction equation for calculating peak ground acceleration.

4.2. Semi-Empirical Technique

A scaling relationship between the magnitude of the main event (*M*) and the magnitude of the small event (*m*) is used to calculate the number of sub faults [19]. The acceleration envelope function for each sub-fault is as follows:

$$e_{ij}(t) = \left[a_{ij}\frac{t}{T_d}e^{\left(1-\frac{t}{T_d}\right)}\right]; E(t) = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N} e_{ij}^2(t-t_{ij})} \quad (8)$$

where T_d is the duration parameter [20], t_{ij} is the arrival time from nucleation point to sub-faults.

Ground Motion Prediction Equation (GMPE) plays a vital role in the generation of ground motion. For the purpose of the study, Shah's GMPE has been selected for the Pakistan region [9]. A catalog of 25 earthquakes with 128 ground motions has been considered for generating GMPE [9]. This GMPE is valid for a range of local magnitude 4.0-7.6 and is valid for an epicentral distance less than 265 km [9]. The above GMPE is used to generate envelope function. The total time of ground motion record is considered as 90 s and the time interval as 0.02 s due to unavailability of recorded ground motion data.

The GMPE used in the study and duration parameters are as follows:

$$\log_e(a) = -6.0985 + 1.4004M_L - 1.5357\log_e R \quad (9)$$

$$T_d = 0.0015\left(10^{0.5M_L}\right) + 1.08R^{0.41} \quad (10)$$

The obtained acceleration record $ac_{ij}(t)$ is the product of acceleration record from stochastic simulation technique and envelope function from semi-empirical simulation technique as:

$$ac_{ij}(t) = e_{ij}(t).A_{ij}(t) \quad (11)$$

The schematic diagram of both methods is shown in Figure (3).

The above method is quite successful in generating strong ground motions for a wide range of earthquakes like 1991 Uttarkashi earthquake [21], 1999 Chi-Chi earthquake [22], 2011 Tohoku earthquake [23], 2011 Sikkim earthquake [20], 2013 Doda earthquake [24] and 2013 Iran-Pakistan border earthquake [25]. Also, the ground motion records are compared with the Stochastic Finite Fault Simulation method and the Stochastic Point Source method to validate modified semi-empirical approach [24]. Based on the above studies, it is concluded that the above method yields acceptable results. The seismological parameters for the 2013 Pakistan earthquake are shown in Table (2).

5. Results and Discussion

In this study, modified semi-empirical method used to generate synthetic accelerograms of the 2013 Pakistan earthquake at stations Awaran, Panjgur, Tagas, Korak, and Gajar. The location of selected

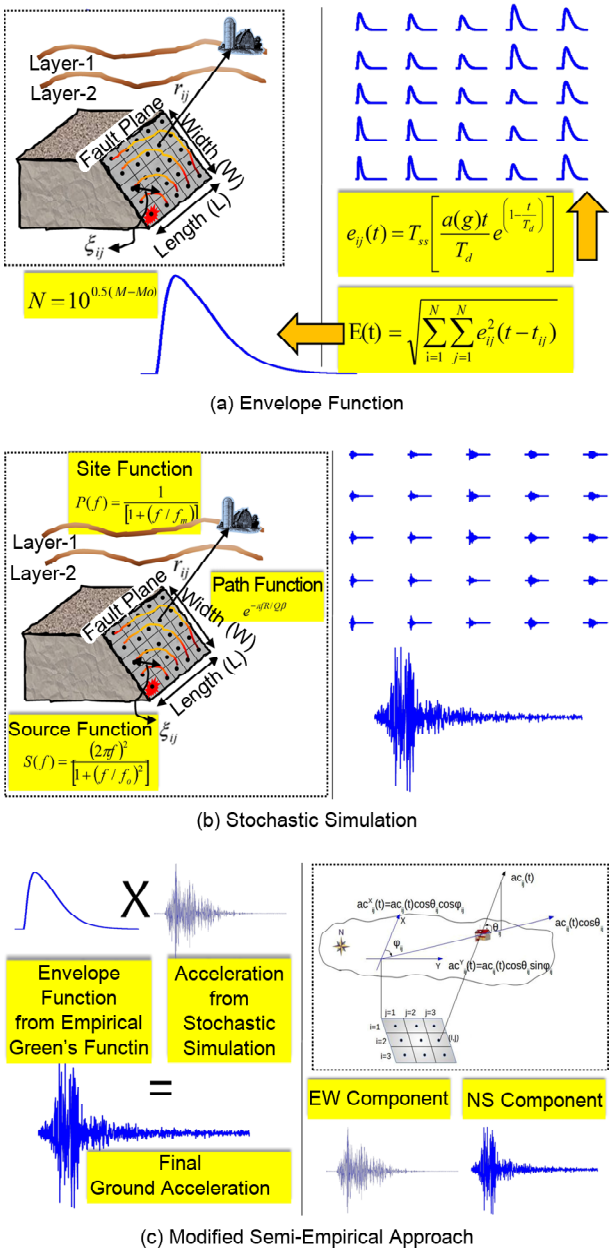

Figure 3. Schematic diagram of modified semi-empirical approach [20].

stations for this study is shown in Figure (4). A MATLAB code is written to generate synthetic accelerograms at five seismic stations and the maximum PGA values are compared with GMPE proposed by Ramkrishnan [1]. The GMPE equation is as follows:

$$\log_{10}(Y) = -2.135 + 0.437M - 1.099\log(X + e^{(-0.08M)}) \pm 0.549 \quad (12)$$

where 'Y is PGA in terms of 'g', 'M refers to the moment magnitude, and 'X is the epicentral distance. The results of synthetic accelerograms are summarized below:

Table 2. Geophysical parameters of 24 September 2013, Pakistan earthquake.

Parameters	Values
Magnitude	7.7
Type of Fault	Strike-Slip Fault
Name of Fault	Chaman Fault
Strike Angle (φ)	216.5°
Dip Angle (θ)	44.3 °
(Source: http://earthquake.usgs.gov/earthquakes/eventpage/usb000jyiv#scientific_finite-fault)	
Shear Wave Velocity, β (km/s)	3.3
Rupture Velocity, V_r (km/s)	0.9β
Seismic Moment, M_o (dyne.cm)	6.19×10^{27}
Frequency Dependent Quality factor	$Q(f) = 164f^{0.4}$ [27]
Stress Drop, Δσ (bar)	50
Maximum Frequency (f_{max})	3.38
Time Interval (s)	0.02
Attenuation: ln(a) = -6.0985+1.4004M_L-1.5357lnR [9]	
Corner Frequency (f_o)	0.043
Rupture Length (km)	120 km
Downward Extension (km)	15 km

Gajar: The station Gajar is located 15 km from the epicenter of the 2013 Pakistan earthquake and 45 km normal to the Chaman fault. The estimated PGA values along NS and EW components are 0.39 g and 0.19 g, respectively. Also, Fourier amplitude spectra are plotted for both components. The PGA obtained through GMPE is 0.308 g. Though results obtained from the analysis are slightly larger than the PGA obtained from GMPE, a fairly good match of results is observed in PGA values through synthetic accelerograms and PGA values from GMPE. The results are satisfactorily good at Gajar station.

Korak: The station Korak is located 30 km from the epicenter of the 2013 Pakistan earthquake and 80 km normal to Chaman fault. The estimated PGA values along NS and EW components are 0.14 g and 0.06 g, respectively. Also, Fourier amplitude spectra are plotted for both components. The PGA obtained through GMPE is 0.134 g. A fairly good match of results is observed in PGA values between synthetic accelerograms along with NS component and PGA values from GMPE. The results are satisfactorily good at Korak station.

Awaran: The station Awaran is located 90 km from the epicenter of the 2013 Pakistan earthquake and 127 km normal to Chaman fault. The estimated PGA values along NS and EW components are

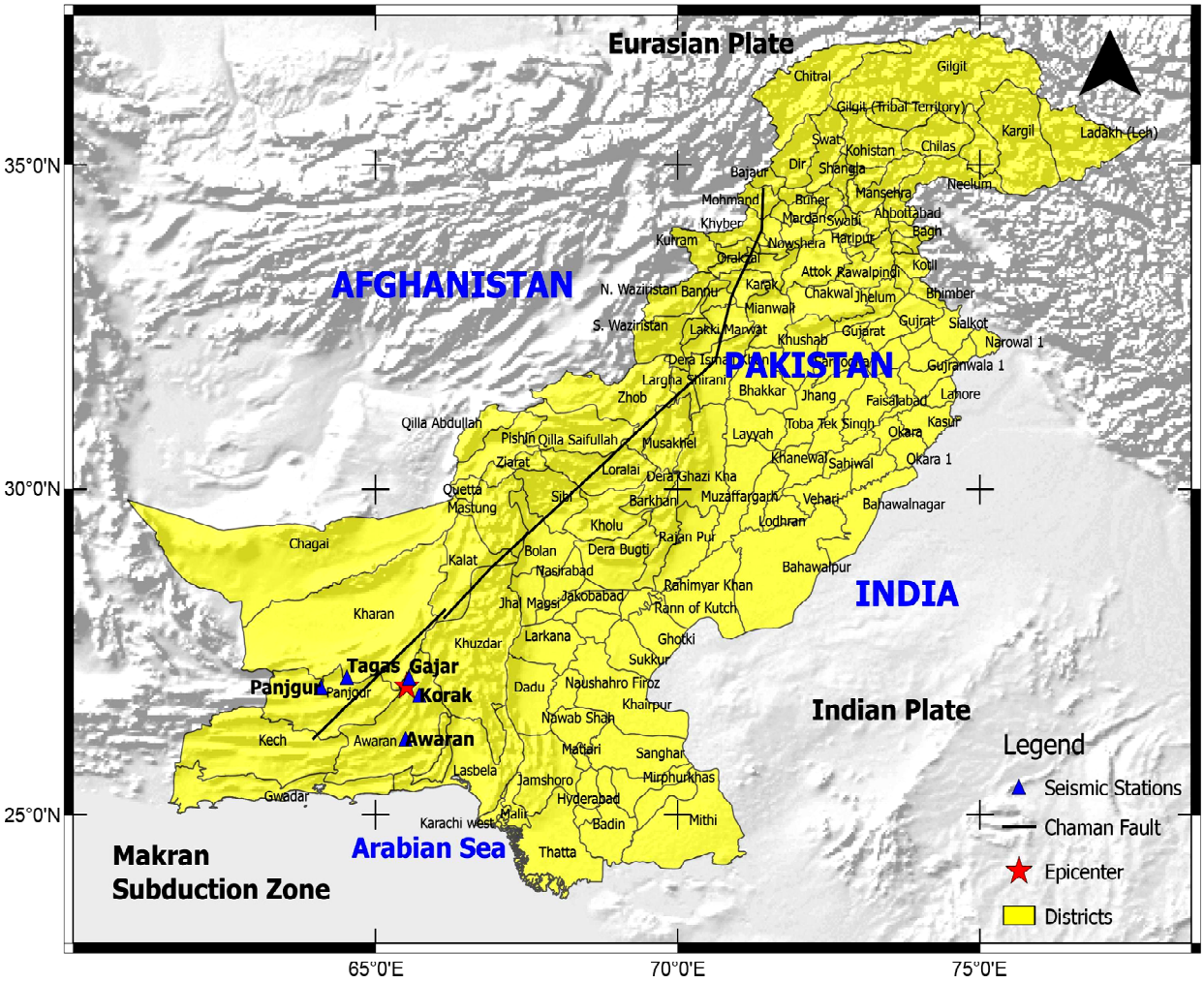

Figure 4. The location of seismic stations, epicenter of the 2013 Pakistan earthquake.

0.27 g and 0.13 g, respectively. The PGA obtained through GMPE is 0.038 g. Also, Fourier amplitude spectra are plotted for both components. The synthetic accelerogram results are larger than PGA values of GMPE.

Tagas: The station Tagas is located 110 km from the epicenter of the 2013 Pakistan earthquake and 33 km normal to Chaman fault. The estimated PGA values along NS and EW components are 0.08 g and 0.03 g, respectively. The PGA obtained through GMPE is 0.03 g. Also, Fourier amplitude spectra are plotted for both components. Though there is a variation between synthetic accelerogram results and PGA values of GMPE, the synthetic accelerogram results are slightly higher than PGA values obtained from GMPE.

Panjgur: The station Panjgur is located 157 km from the epicenter of the 2013 Pakistan earthquake and 55 km normal to Chaman fault. The estimated PGA values along NS and EW components are 0.01 g and 0.008 g, respectively. The PGA obtained through GMPE is 0.020 g. Also, Fourier amplitude spectra are plotted for both components. The large variation is observed among synthetic accelerogram PGA values, and GMPE PGA values. The synthetic accelerograms for all stations along NS and EW components are shown in Figure (5). The Fourier amplitude spectra have drawn from synthetic accelerograms for all stations as shown in Figure (6). The summary of the results is shown in Table (3). Figure (7) represents a comparison between simulated PGA values and GMPE.

From the above results, it is concluded that the modified semi-empirical approach yields satisfactory results at seismic stations Gajar, Korak, Tagas, and Panjgur. However, large variation is observed between synthetic accelerogram and GMPE values at seismic station Awaran.

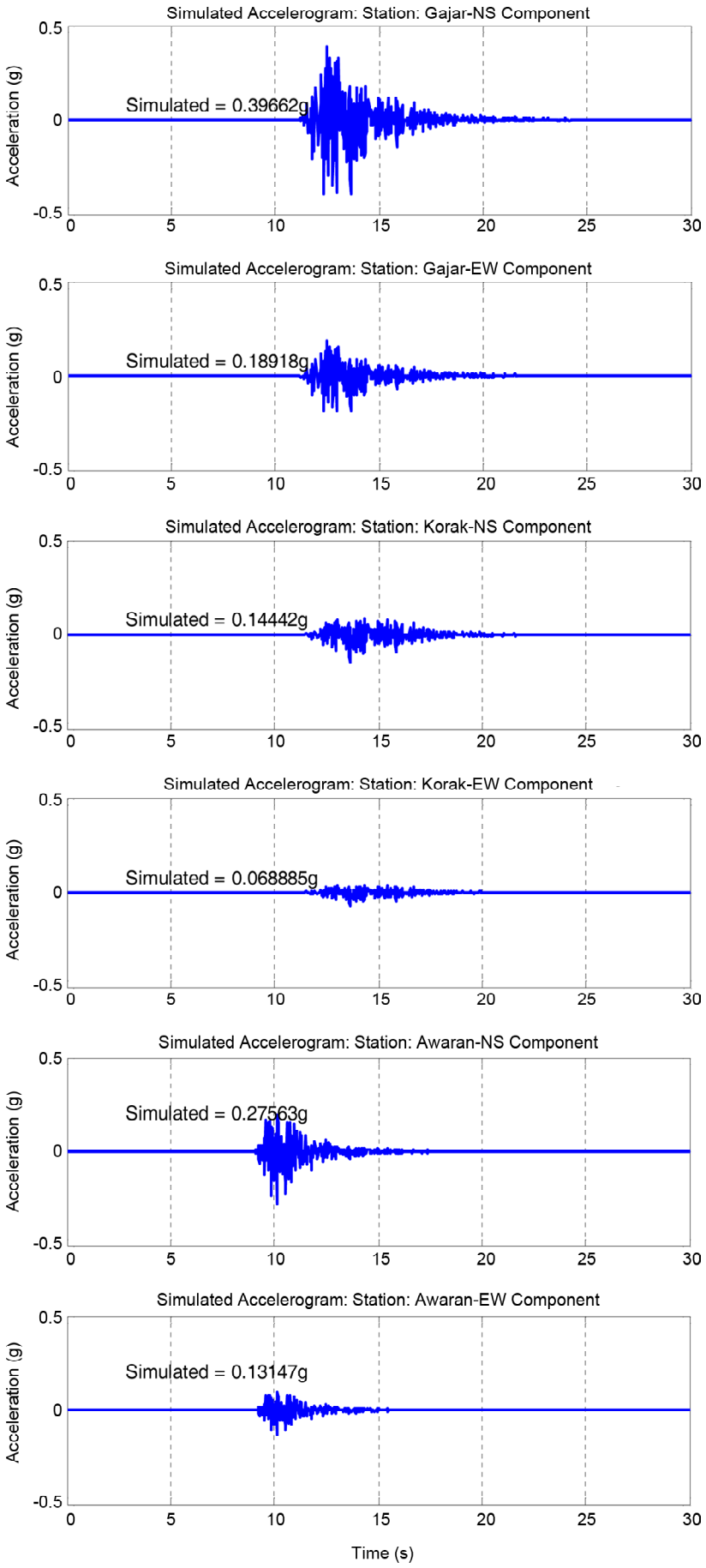

Figure 5. Synthetic accelerograms at five seismic stations using modified semi-empirical approach.

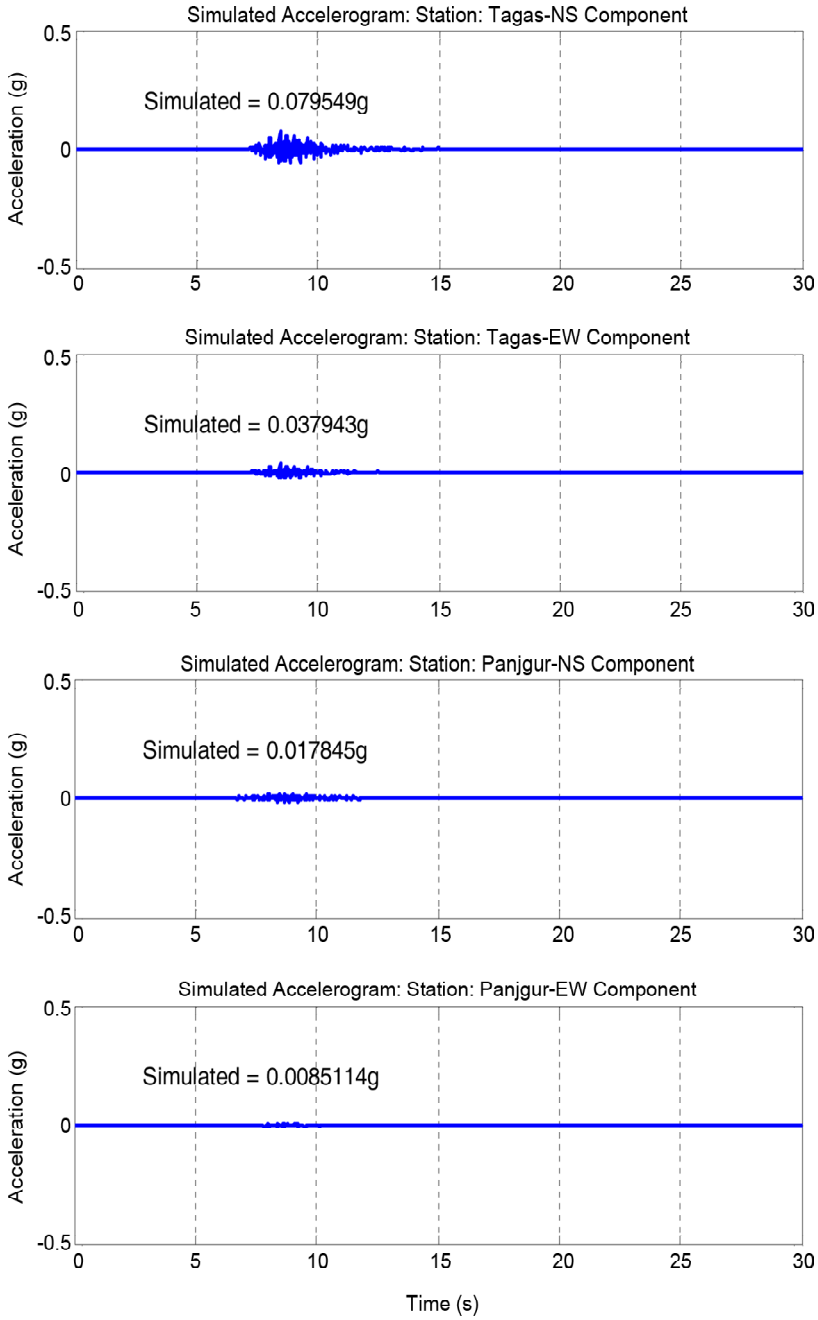

Figure 5. Continue.

Table 3. Comparison of PGAs with GMPE at five stations.

S. No	Station	Co.ordiantes		R (km)	R' (km)	PGA (g)		GMPE (g)
		Lat.	Long.			NS	EW	
1.	Gajar	27.10	65.56	15	45	0.400	0.190	0.308
2.	Korak	26.84	65.73	30	80	0.144	0.060	0.134
3.	Awaran	26.16	65.50	90	127	0.270	0.130	0.038
4.	Tagas	27.11	64.53	110	33	0.080	0.030	0.030
5.	Panjgur	26.96	64.10	157	55	0.010	0.008	0.020

(* Source: Building code of Pakistan, 2007; https:/iisee.kenken.go.jp/net/)

R - Epicentral Distance

R' - Perpendicular Distance From Chaman Fault to Station

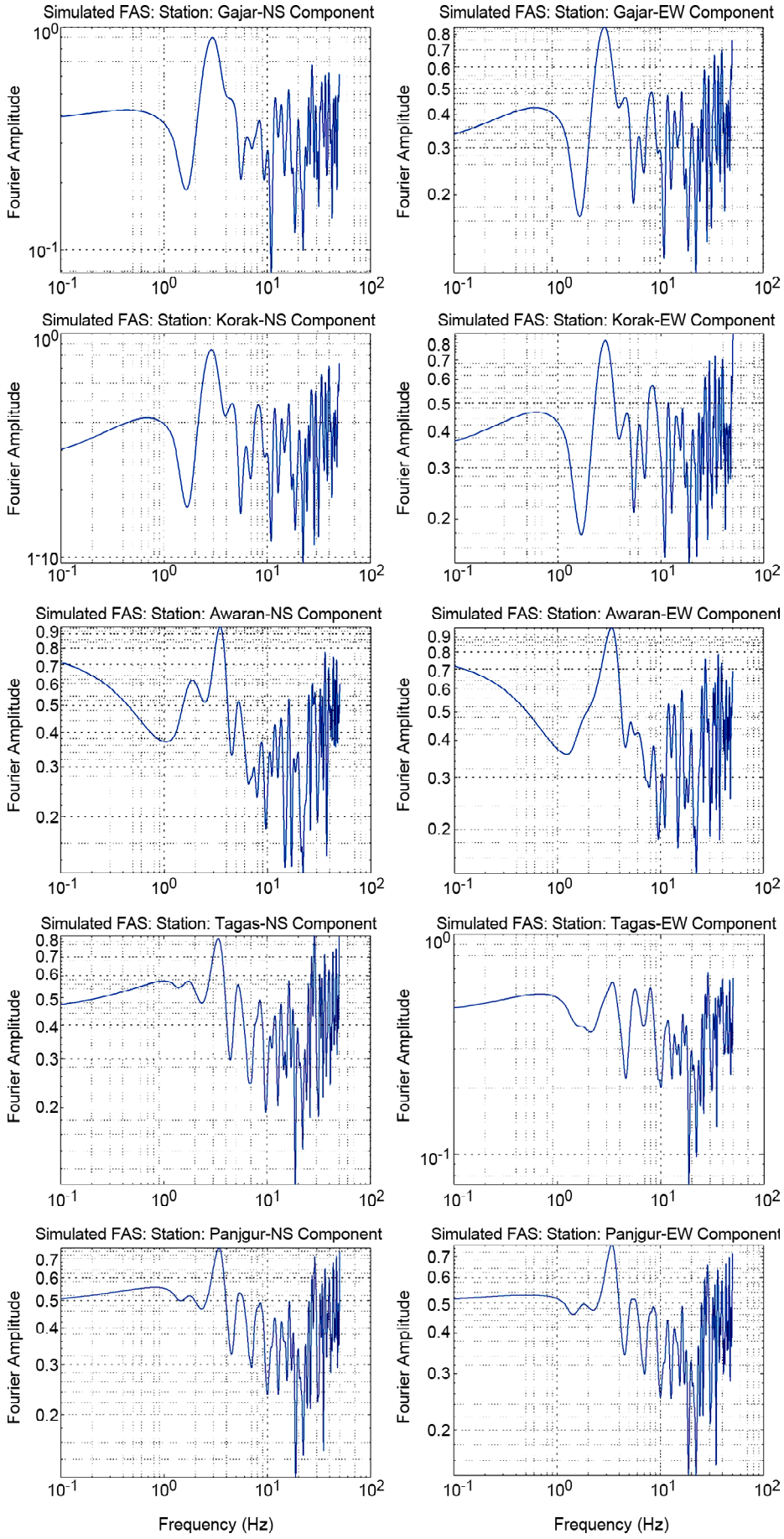

Figure 6. Fourier amplitude spectrum from synthetic accelerograms at five seismic stations.

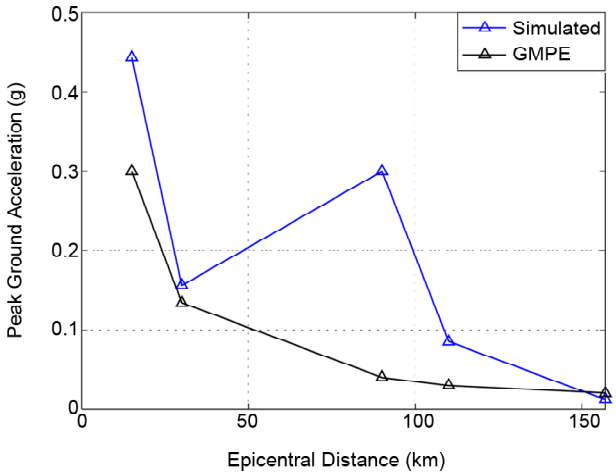

Figure 7. Comparison of PGAs between simulated ground motions and GMPE.

6. Conclusions

The present study made an attempt to generate ground motions of the recent 24 September, 2013, Pakistan earthquake through the modified semi-empirical approach. For the purpose of the study, a MATLAB code is written to generate synthetic accelerograms at stations Awaran, Panjgur, Tagas, Korak, and Gajar. Since, the ground motion records are unavailable for the earthquake, synthetic ground motions are generated and the results are compared with a selected GMPE for Pakistan. It is observed that the method gives acceptable results with the PGA of the selected GMPE. However, large variation is observed between synthetic accelerogram PGA values and GMPE PGA values at station Awaran.

Conflict of Interest: The authors declare that they have no conflict of interest.

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