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Ground Motion Estimation using Site Response Analysis for Deep Sedimentary Deposits

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Introduction

This study involves Ground Motion Estimation using Site Response Analysis for Deep Sedimentary Deposits of Dhaka City located in the central part of the Bengal basin which is one of the oldest urban seat of the Indian subcontinent.

In last three decades the city of Dhaka has become one of the 20 mega cities of the world having population of 20,000,000 by ranking this to be the 10th mega-city in the world.

Many geologists and seismologists consider Dhaka as one of the riskiest cities in the world due to many uncontrolled construction practices, poorly understood or inadequately studied seismo-tectonic boundary conditions over deep sedimentary deposits of the Bengal basin.

A Nonlinear Seismic Site Response Analysis is performed where the components of seismic hazard analysis are shown in the figure.

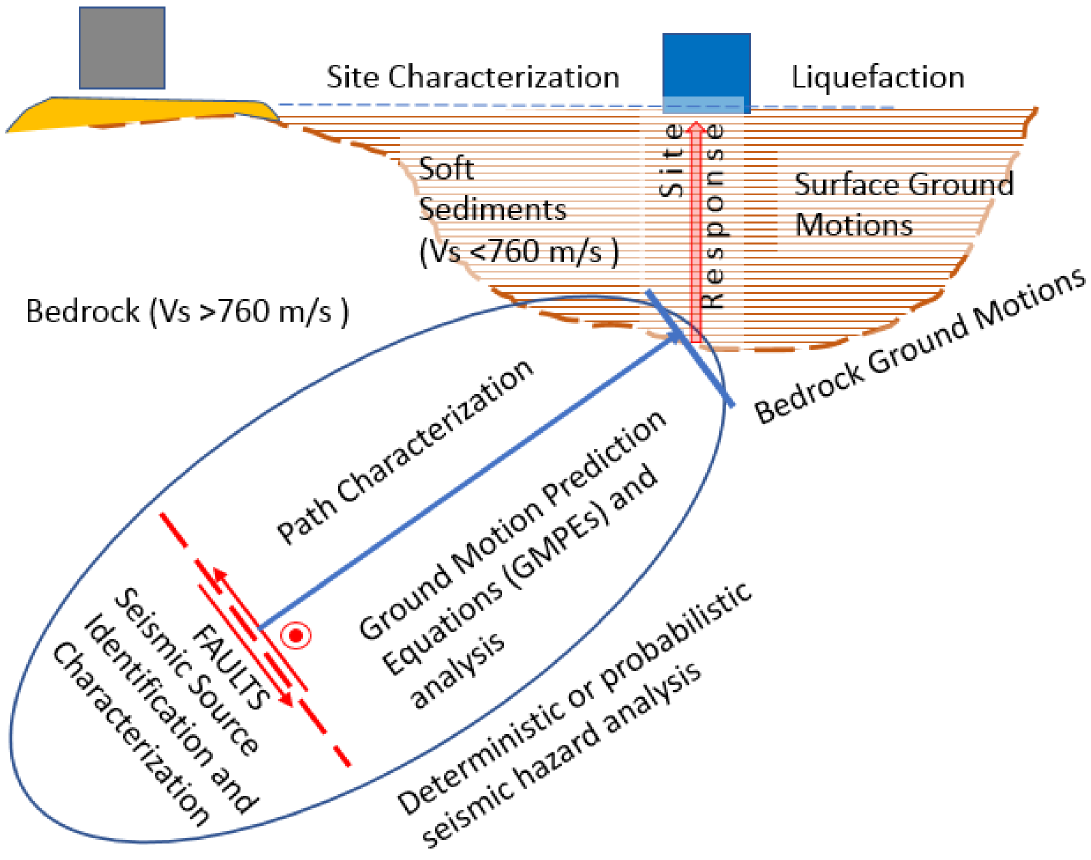


Fig. 1. Components of seismic hazard analysis

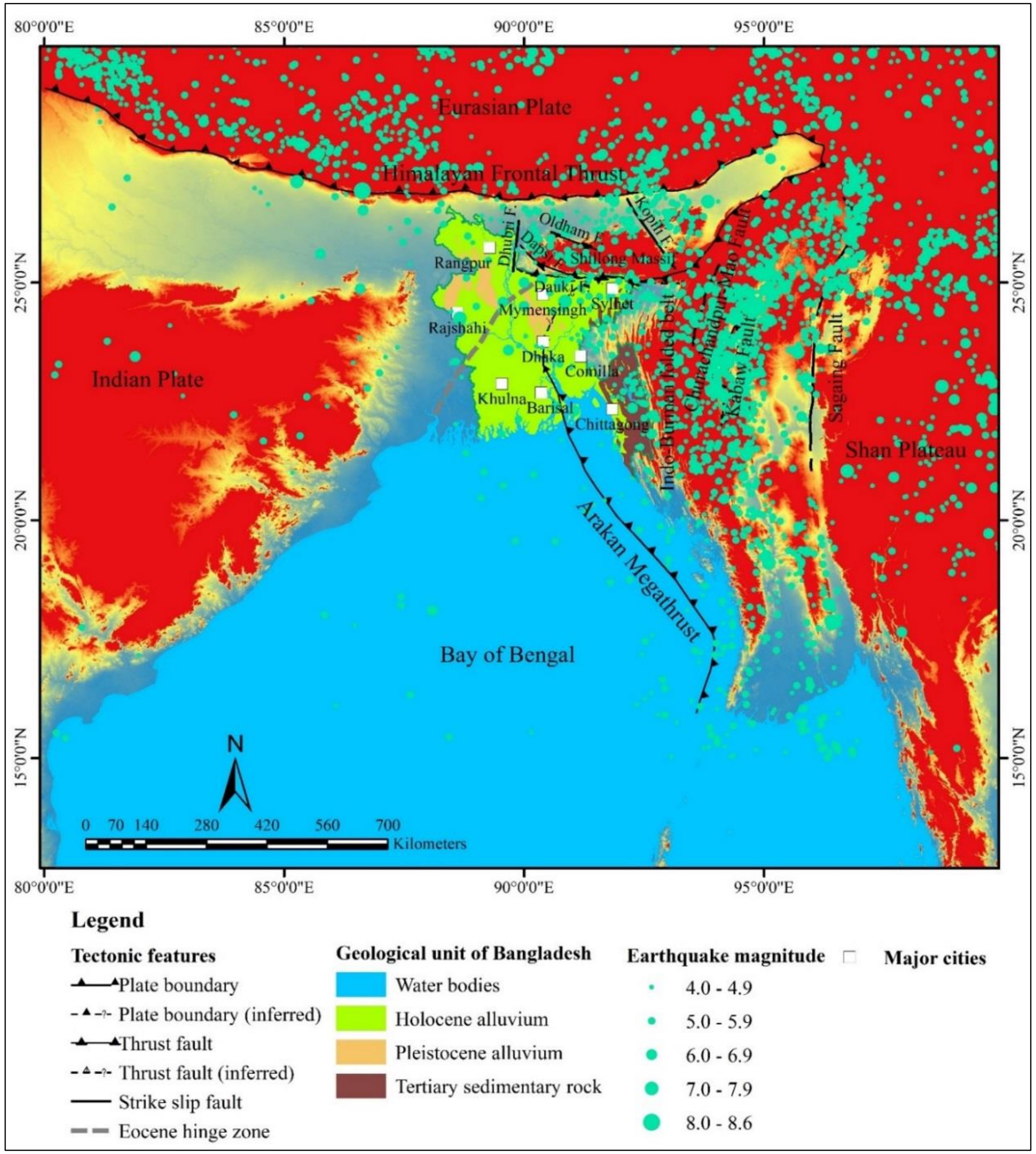


Fig. 1. Seismotectonic map of Bangladesh and surrounding regions (modified from Rahman et al. 2018).

Tectonics and seismic source:

The records of historical earthquakes indicate that three large magnitude earthquakes occurred during the last 150 years within and in close proximity to Bangladesh.

Magnitudes of these earthquakes ranged from 6.9 to 8.7 occurring between 1885 and 1918.

It is believed that the 6.9 magnitude Bengal earthquake occurred at about 50 km from the city’

Many consider that the epicenter of this earthquake was 170 km away from Dhaka city and others inferred the epicenter to be somewhere along Madhupur fault, approximately 50 km away.

Bedrock ground motion parameters estimated using probabilistic seismic hazard analysis have been used for site response analysis.

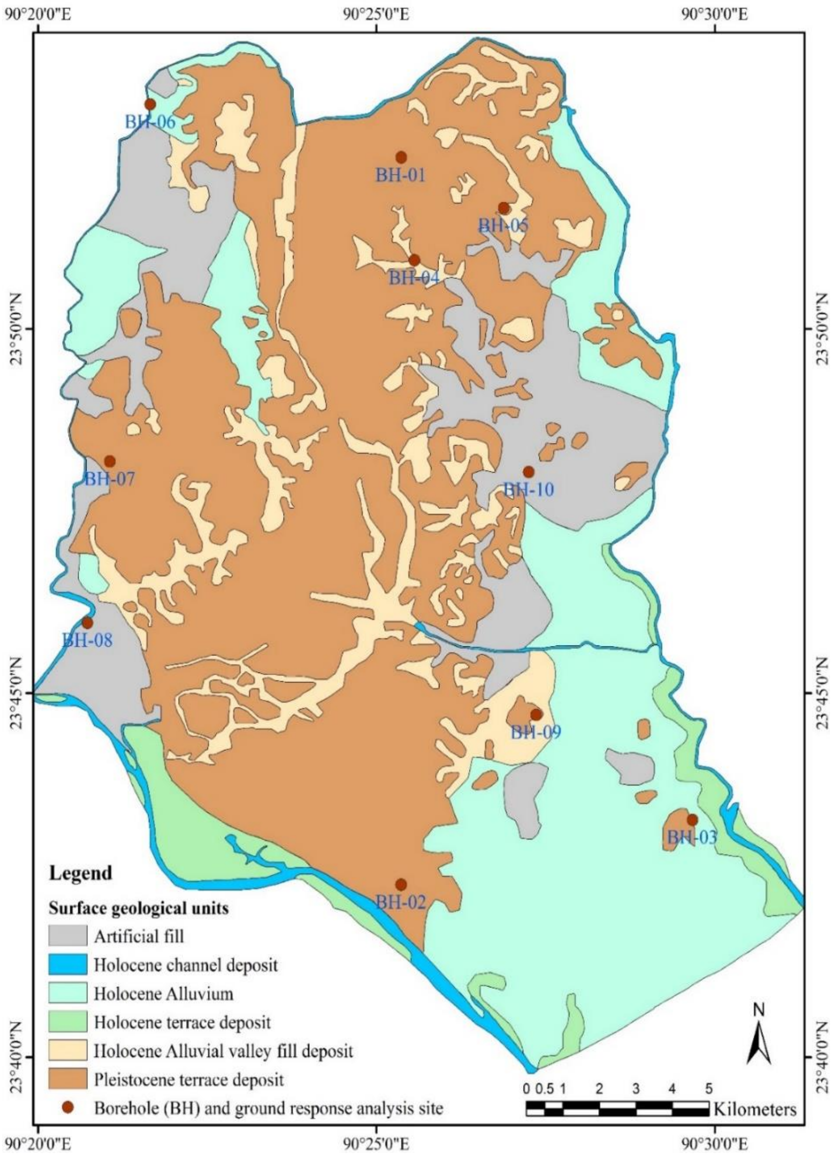


Fig. 2. Surface geological map of Dhaka City (modified from Rahman et al. 2015) showing geotechnical borehole locations and ground response analysis sites.

Generalized geology of Dhaka city :

The Mega City of Dhaka occupies an unique geological location and was built on a Plio-Pleistocene terrace in the central part of the Bengal basin. The subsurface geology is firm and almost homogenously consistent. There are three distinct geomorphological units which are raised considerably about 6m AMSL. The surrounding floodplains are at about 4m AMSL. The ground is composed of Madhupur Clay. The Clay is Over-consolidated. The shear strength properties are considerably high. The Thickness of Madhupur Clay is about 6 m and it overlies a firm sandstone bed, geologically known as Dupi Tila.

Generalized Geotechnical and seismic properties of Dhaka ground

(After Karim, M F and Rahman, M Z, 2002)

Formation	Average Thickness, meter	Consistency and Material	Average Moisture content, w_n %	Dry unit Weight, γ_d kN/m³	Average Undrained Shear Strength, s_u, kPa	N value Range (SPT count)	Shear Wave Velocity, m/sec
Madhupur Clay	6	Stiff Clay-SILT	25	16	150	10 - 30	>200 <300
Dupi Tila Sandstone	> 90	Soft Sedimentary rock (Sandstone with occasional Claystone)	< 20	> 16	ϕ > 30°	Often Refusal	> 350 <450

Seismic Site Response Analysis

Surface ground motion of soft sedimentary deposit is generally estimated by multiplying the bedrock motion with the site amplification factor that is estimated from the average shear wave velocity of the top 30 m (V_s^{30}) based on the site classes of National Earthquake Hazards Reduction Program (NEHRP) site , USA.

NEHRP (National Earthquake Hazards Reduction Program), USA

For example : Short period ground motion, S_s (0.2s) = 0.3 g

Long period ground motion, S_l (1.0s) = 0.13g at V_S^{30} = 760 m/s

NEHRP, USA		
Site class or Soil profile type	**Description**	**Average shear wave velocity of top 30 m (m/sec)**
A	Hard rock	> 1500
B	Rock	760 - 1500
C	Very dense soil/soft rock	360 - 760
D	Stiff soil	180 - 360
E	Soft soil	< 180
F	Special soils requiring site-specific evaluation (1. Soils vulnerable to potential failure or collapse under seismic loading, e.g., liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils; 2. Peats and/or highly organic clays (3 m or thicker layer); 3. Very highly plasticity clays (8 m or thicker layer with plasticity index > 75); 4. Very thick soft/medium stiff clays (36 m or thicker layer))	

Table 1, 2 and 3: Site Classes and Site Coefficients (BSSC, 2015)

Site Class	$S_S \le 0.25$	$S_S = 0.5$	$S_S = 0.75$	$S_S = 1.0$	$S_S = 1.25$	$S_S \ge 1.5$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.9	0.9	0.9	0.9	0.9	0.9
C	1.3	1.3	1.2	1.2	1.2	1.2
D	1.6	1.4	1.2	1.1	1.0	1.0
E	2.4	1.7	1.3	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7
F	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7

Note: Use straight-line interpolation for intermediate values of S_S.

Site Class	$S_1 \le 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 = 0.5$	$S_1 \ge 0.6$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.8	0.8	0.8	0.8	0.8	0.8
C	1.5	1.5	1.5	1.5	1.5	1.4
D	2.4	2.2[1]	2.0[1]	1.9[1]	1.8[1]	1.7[1]
E	4.2	3.3[1]	2.8[1]	2.4[1]	2.2[1]	2.0[1]
F	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7	See Section 11.4.7

Note: [1]Also, see requirements for site-specific ground motions in Section 11.4.7.
Note: Use straight-line interpolation for intermediate values of S_1.

NEHRP (National Earthquake Hazards Reduction Program), USA

- NEHRP amplification factor does not consider the response of the soft deposits that exist below 30 m depth.
- In the study area (Dhaka City, Bangladesh), the depth of the soft sedimentary deposits above the bedrock formation ($V_s^{30} \geq 760$ m/s) is more than 200 m.
- The soft sedimentary deposits are composed of sand, silt, and clay of the Holocene to Pliocene age.
- The state of seismic boundary between the soft sedimentary deposits and bedrock is not of a geological type but rather a gradational type.
- The impedance contrast is not very high along this boundary and the sediments above and below the boundary are not consolidated.
- Therefore, the ground motion estimation using empirically estimated amplification factor is not appropriate for the depth of soft deposits greater than 30 m.

One-dimensional Site Response Analysis

- One-dimensional site response analysis can be used for deep sedimentary deposits.
- The properties of the soft deposits are not linear.
- The ground motion estimation using one-dimensional linear and equivalent-linear response analyses become inaccurate at high strain (Kaklamanos et al., 2015).
- The nonlinear site response analysis has been performed to estimate the ground motion of deep and soft sedimentary deposits using DEEPSOIL (Hashash et al., 2017).

One-dimensional Site Response Analysis

Layer No.	Age	USCS soil class	BH-10 (Log)	Thickness (m)	Unit weight (kN/m^3)	Shear wave velocity (m/s)
1	Holocene (Gray soils)	Silty SAND (SM)		0.80	17.11	101.00
2				0.80		
3				0.80		
4				0.80		
5				0.80		
6		Inorganic SILT (ML)		0.67		
7				0.67		
8				0.67		
9		Organic SILT (OL)		0.75	16.95	
10				0.75		
11				0.75		
12				1.00		137.00
13				1.00		
14				1.00		
15				1.00		
16				1.00		
17				1.00		
18				1.00		
19				1.00		
20				1.00		
21				1.00		
22				1.00		
23	Plio-Pleistocene (Yellowish brown soils)	Inorganic CLAY (CL)		1.00	19.09	231.00
24				1.00		
25		Inorganic SILT (ML)		1.50		
26				1.50		
27		Inorganic CLAY (CL)		1.67		
28				1.67		
29				1.67		
30		SAND (SP)		2.74	19.96	350.00
31				2.74		
32				2.74		
33				2.74		
34				2.74		
35				2.74		
36				2.74		
37				2.74		
38				2.74		
39				2.74		
40				2.74		
41				2.74		
42				2.74		
43				2.74		
44				2.74		
45				2.74		
46				3.66		450.00
47				3.66		
48				3.66		
49				3.66		
50				3.66		
51				3.66		
52				3.66		
53				3.66		
54				3.66		
55				3.66		
56				3.66		
57				3.66		
58				3.66		
59				3.66		
60				3.66		
61				3.66		
62				4.88		600.00
63				4.88		
64				4.88		
65				4.88		
66				4.88		
67				4.88		
68				4.88		
69				4.88		
70				4.88		
71				4.88		
72		Inorganic CLAY (CH)		4.57	20.43	
73				4.57		
74				4.57		
75				4.57		
76				4.57		
77				4.57		
78				4.57		
79				4.57		
80				4.57		
81		SAND (SP)		4.88	19.96	
82				4.88		
83				4.88		
84				4.88		
85				4.88		
86				4.88		
87		Bedrock (SAND)		Base not seen	20.43	762.20

Fig. 3. soil profile (300 m depth)

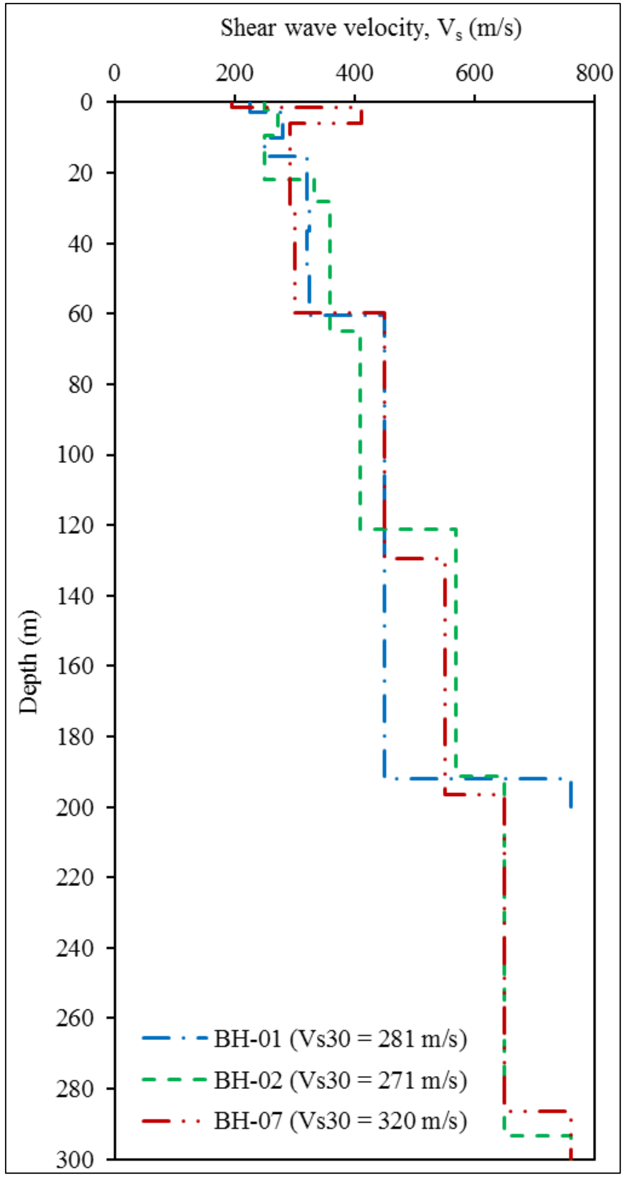


Fig. 4. shear wave velocity profile

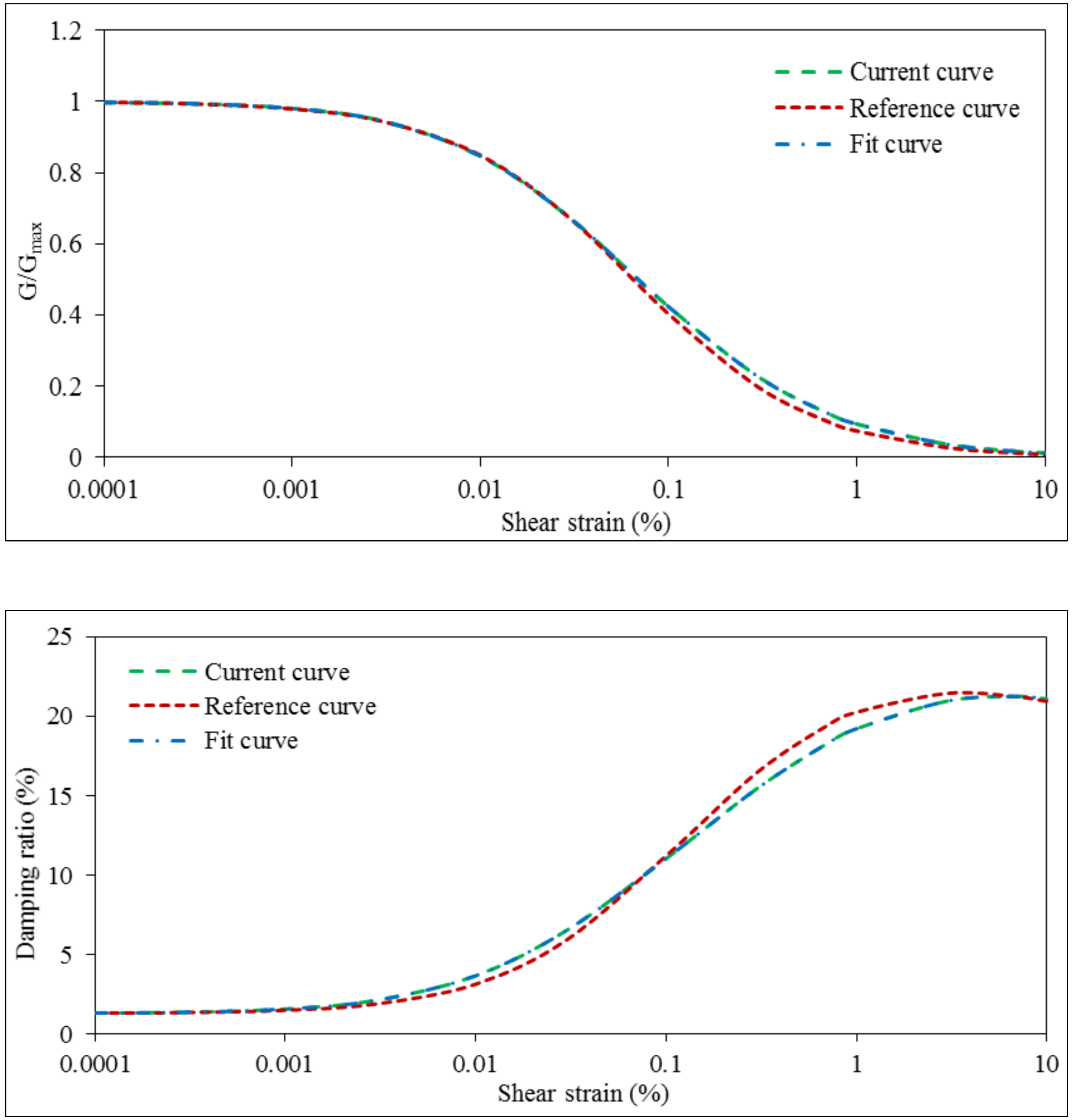


Fig. 5. Modulus reduction and damping curves

Nonlinear Site Response Analysis

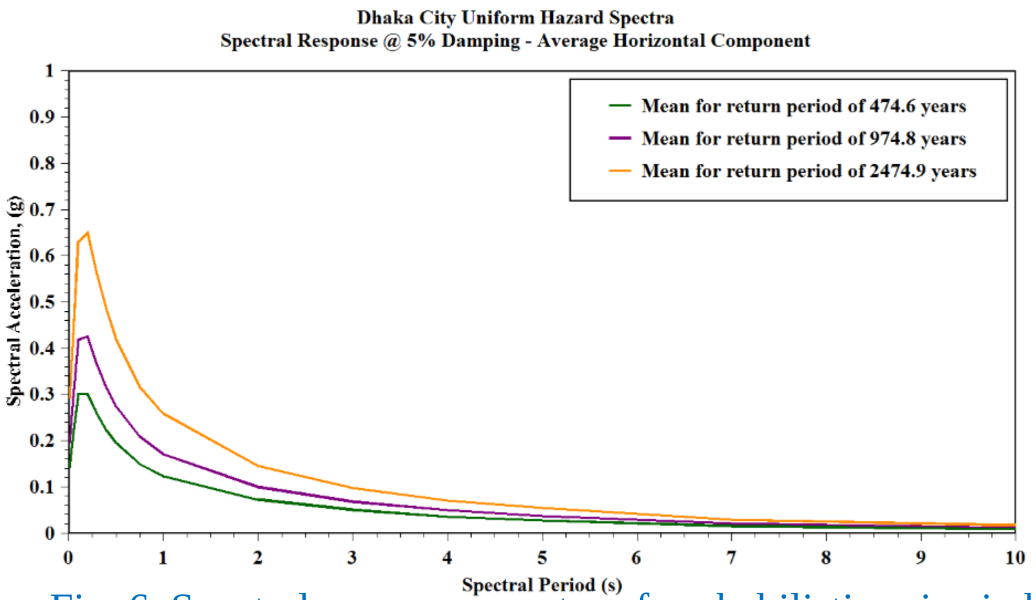


Fig. 6. Spectral response spectra of probabilistic seismic hazard analysis using EZ-FRISK (Fugro Consultants Inc., 2014)

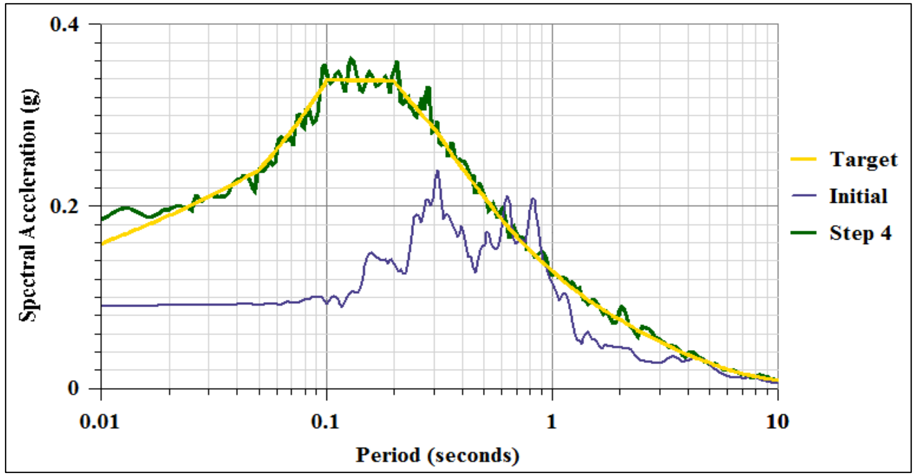


Fig. 7. Spectral matching using EZ-FRISK (Fugro Consultants Inc., 2014)

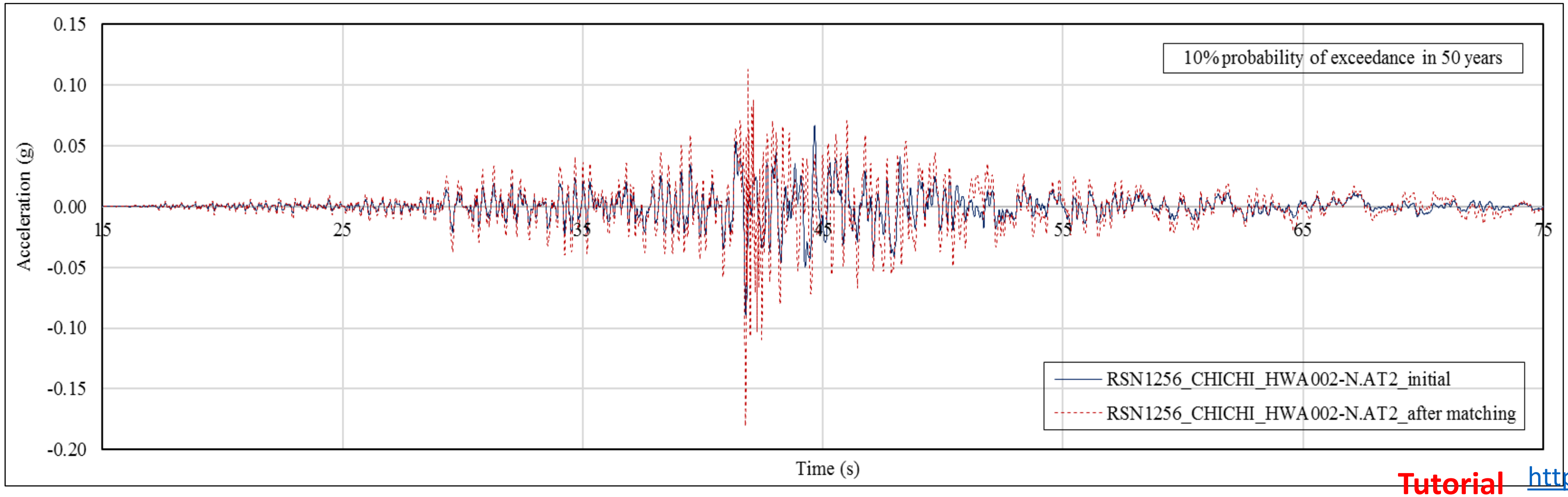


Fig. 8. Initial time history (solid blue) form the PEER NGA WEST2 database and match time history (dashed brown line) (Ancheta et al., 2013)

Tutorial https://www.youtube.com/watch?v=-Wwe4KQvnMk

Nonlinear Site Response Analysis

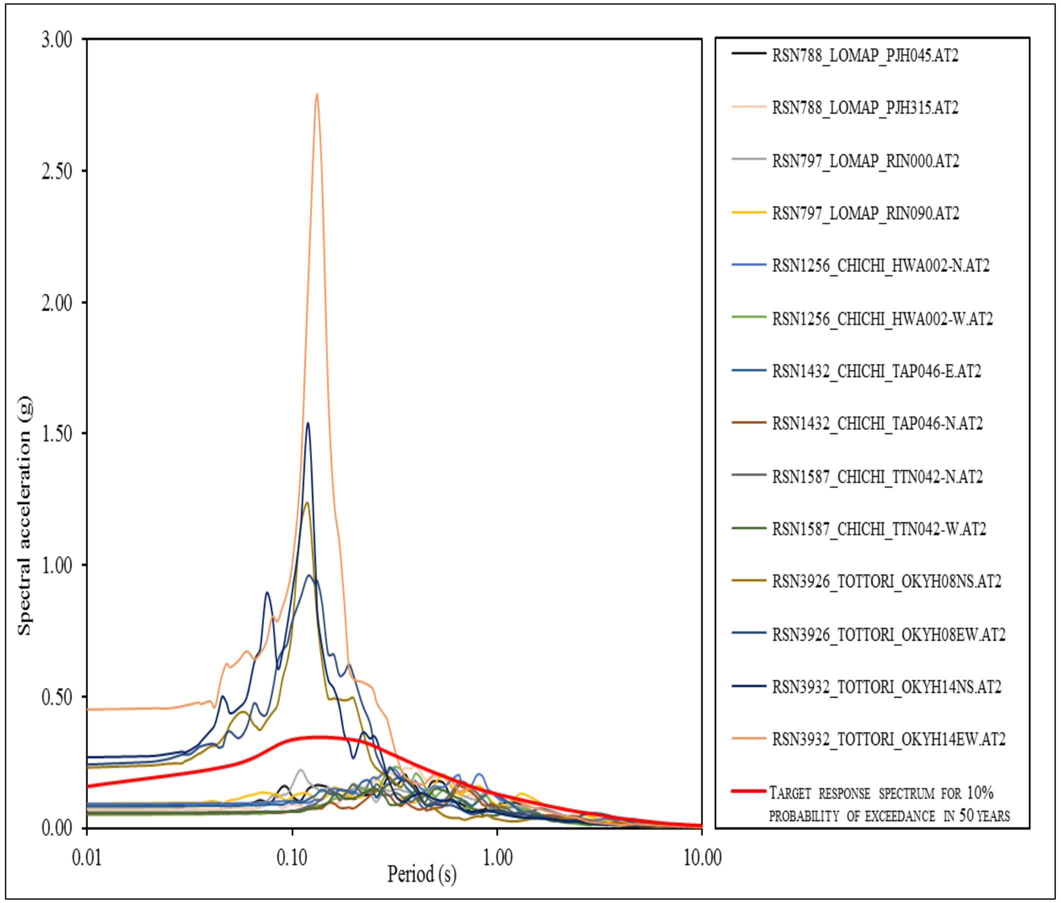


Fig. 9. Response spectra of 14 time histories from 3 earthquakes with target response spectrum for 10 % probability of exceedance in 50 years at BH-03 site

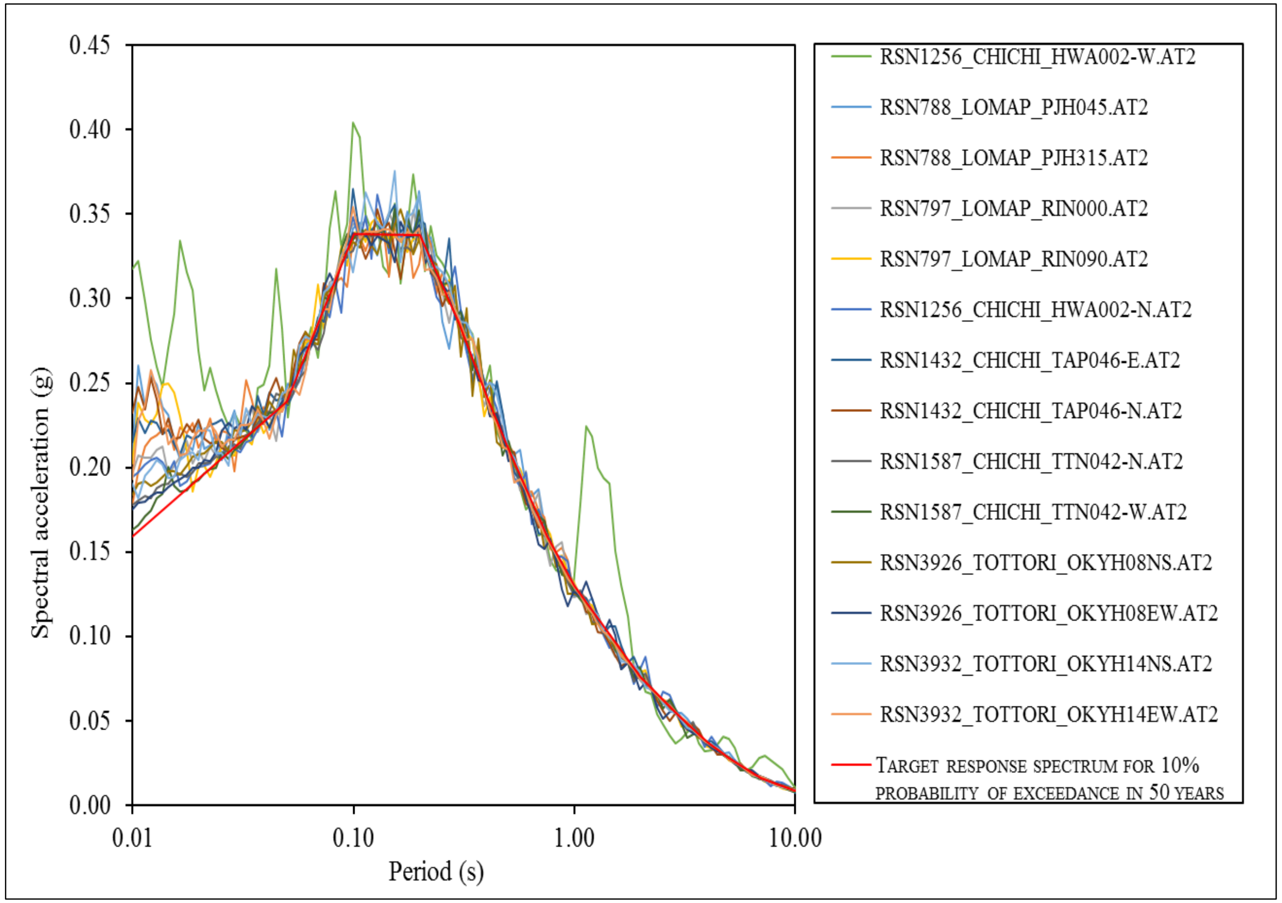


Fig. 10. Matched response spectra of 14 time histories from 3 earthquakes with target response spectrum for 10 % probability of exceedance in 50 years at BH-03 site

Nonlinear Site Response Analysis

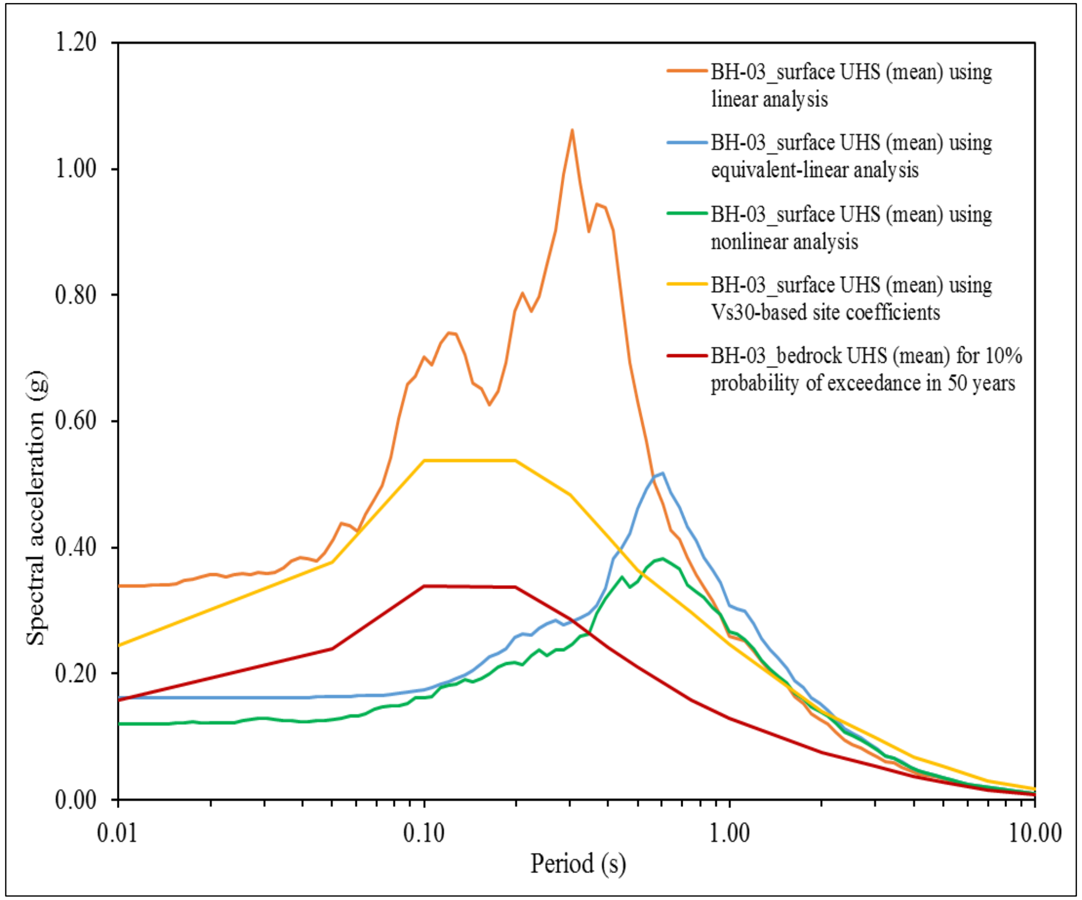


Fig. 11. Uniform hazard spectra (UHS) at ground surface using V_s^{30}-based site coefficients and UHS at ground surface using linear, equivalent-linear, and nonlinear ground response analysis at BH-03 site using the soil profile down to a depth of 303m at which the V_s = 760 m/s.

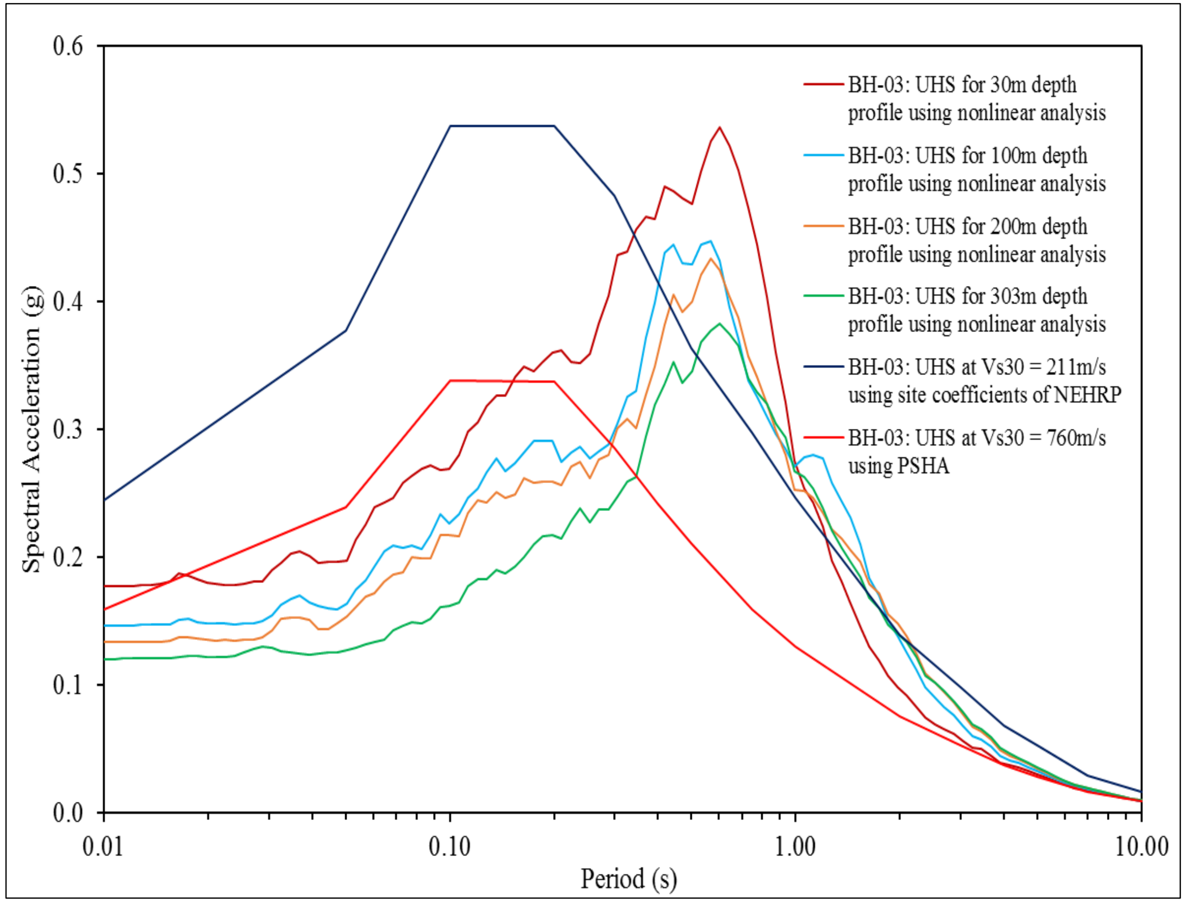


Fig. 12. Uniform hazard spectra (UHS) at bedrock condition (V_s^{30} = 760 m/s) using probabilistic seismic hazard analysis, UHS at ground surface using V_s^{30}-based site coefficients, nonlinear ground response analysis using different depths of soil profiles at BH-03 site for 10 % probability of exceedance in 50 years.

Nonlinear Site Response Analysis

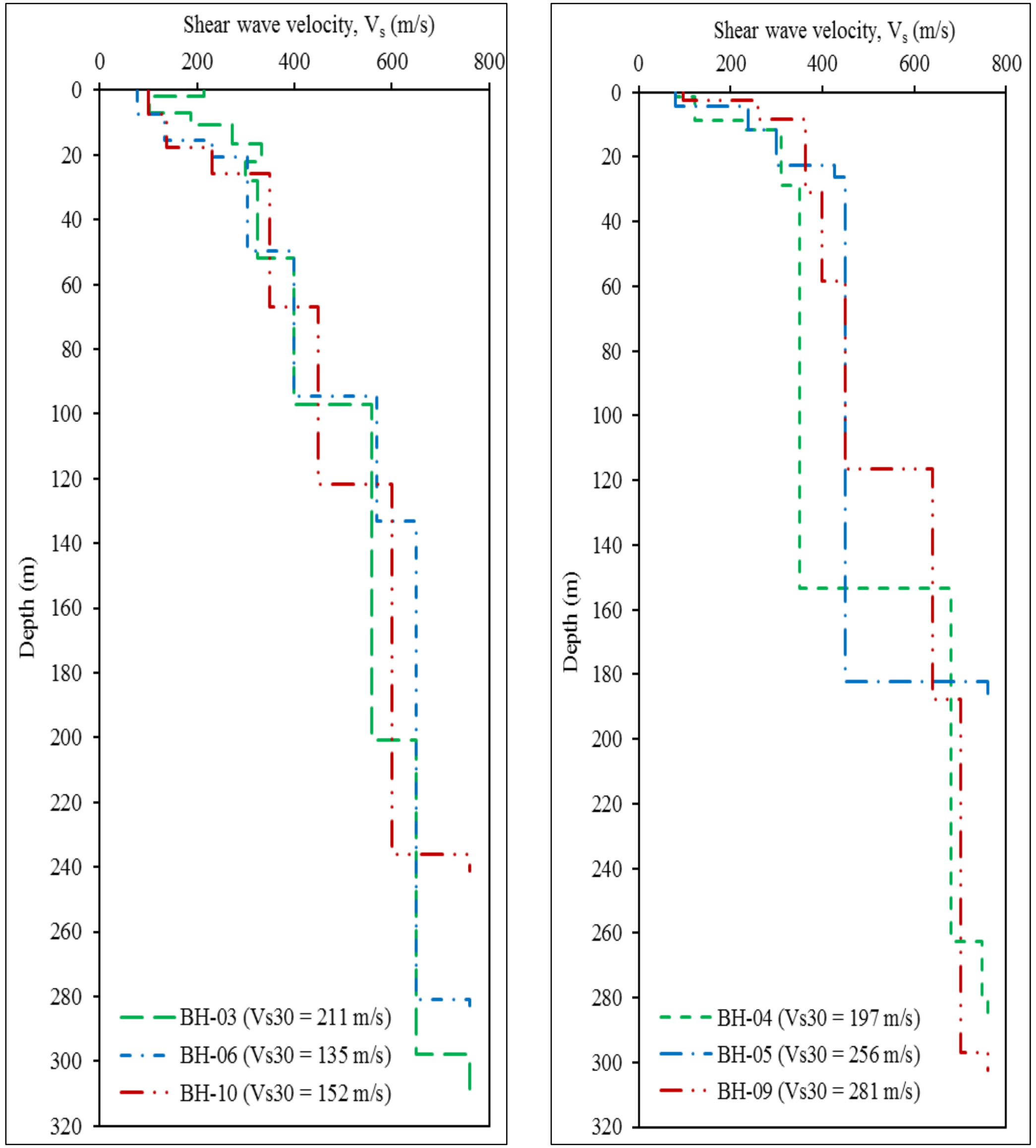


Fig. 13. shear wave velocity profile

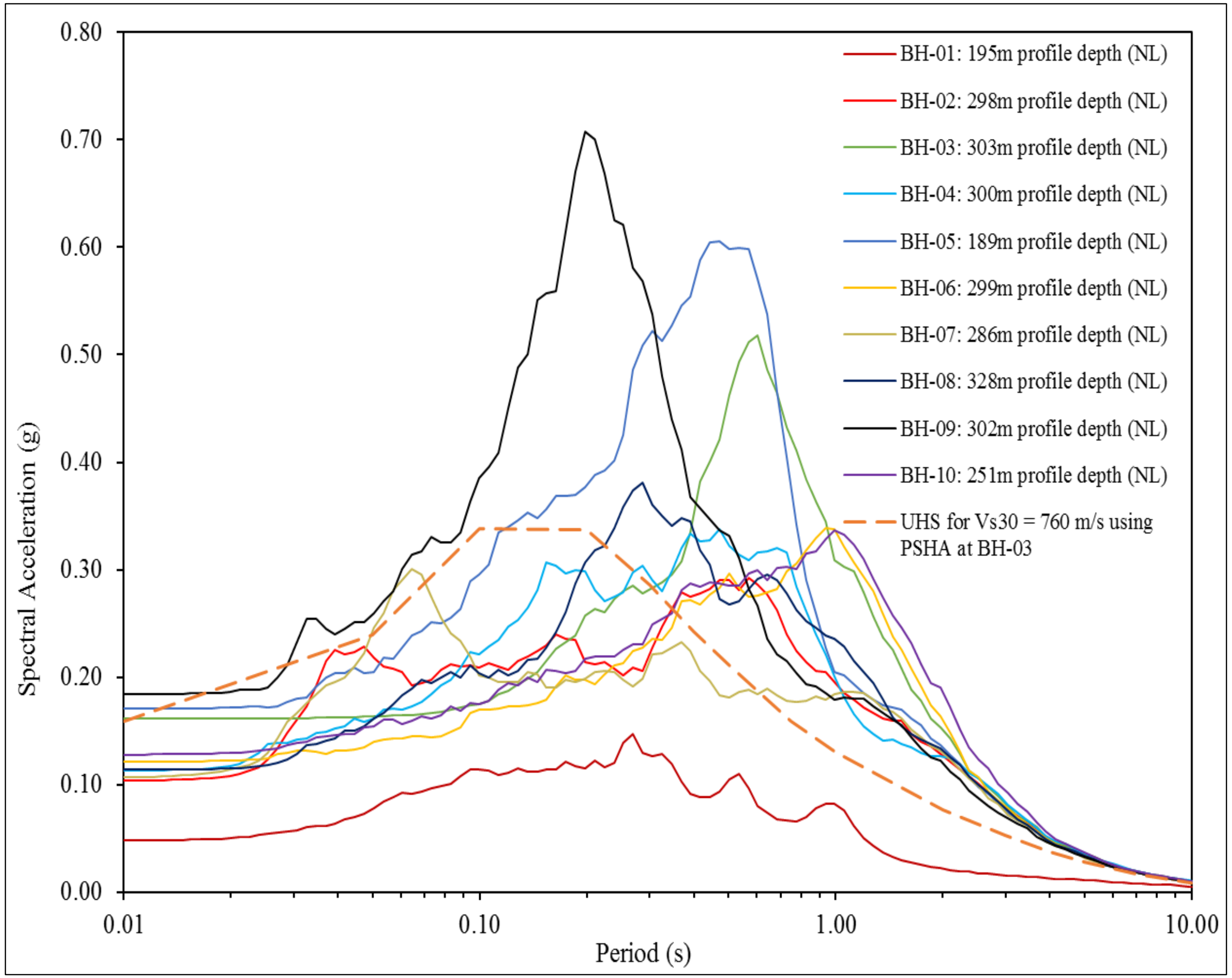
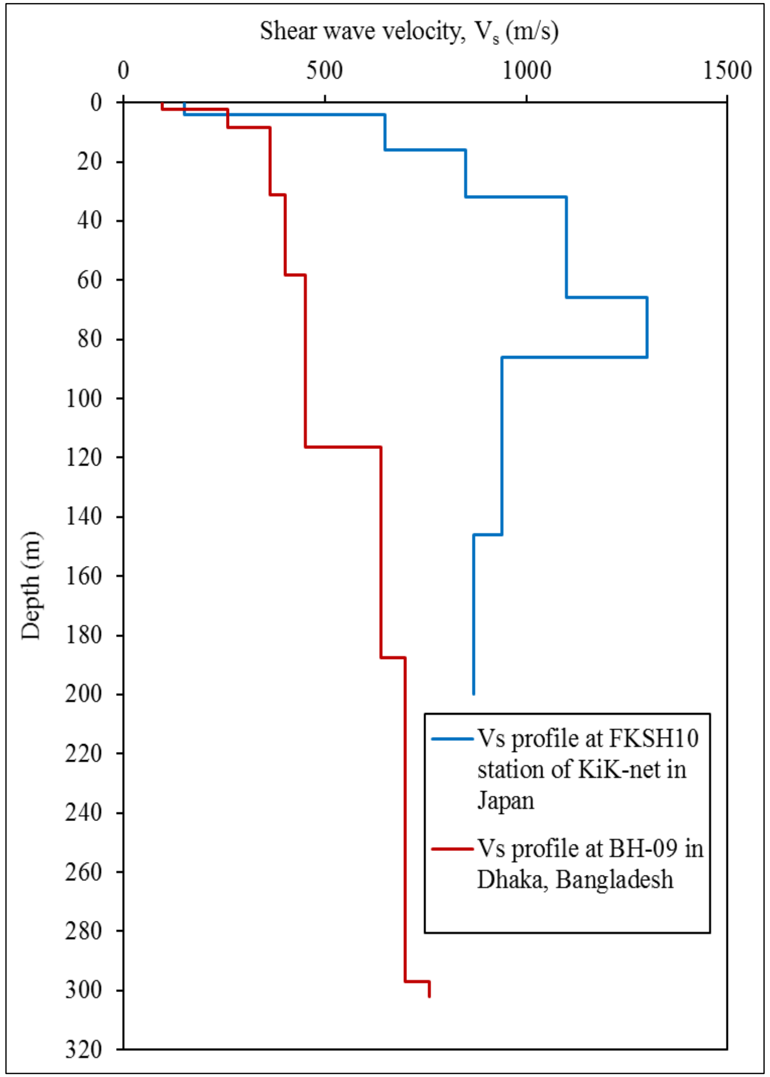


Fig. 14. Nonlinear site response at 10 sites

Nonlinear Site Response Analysis



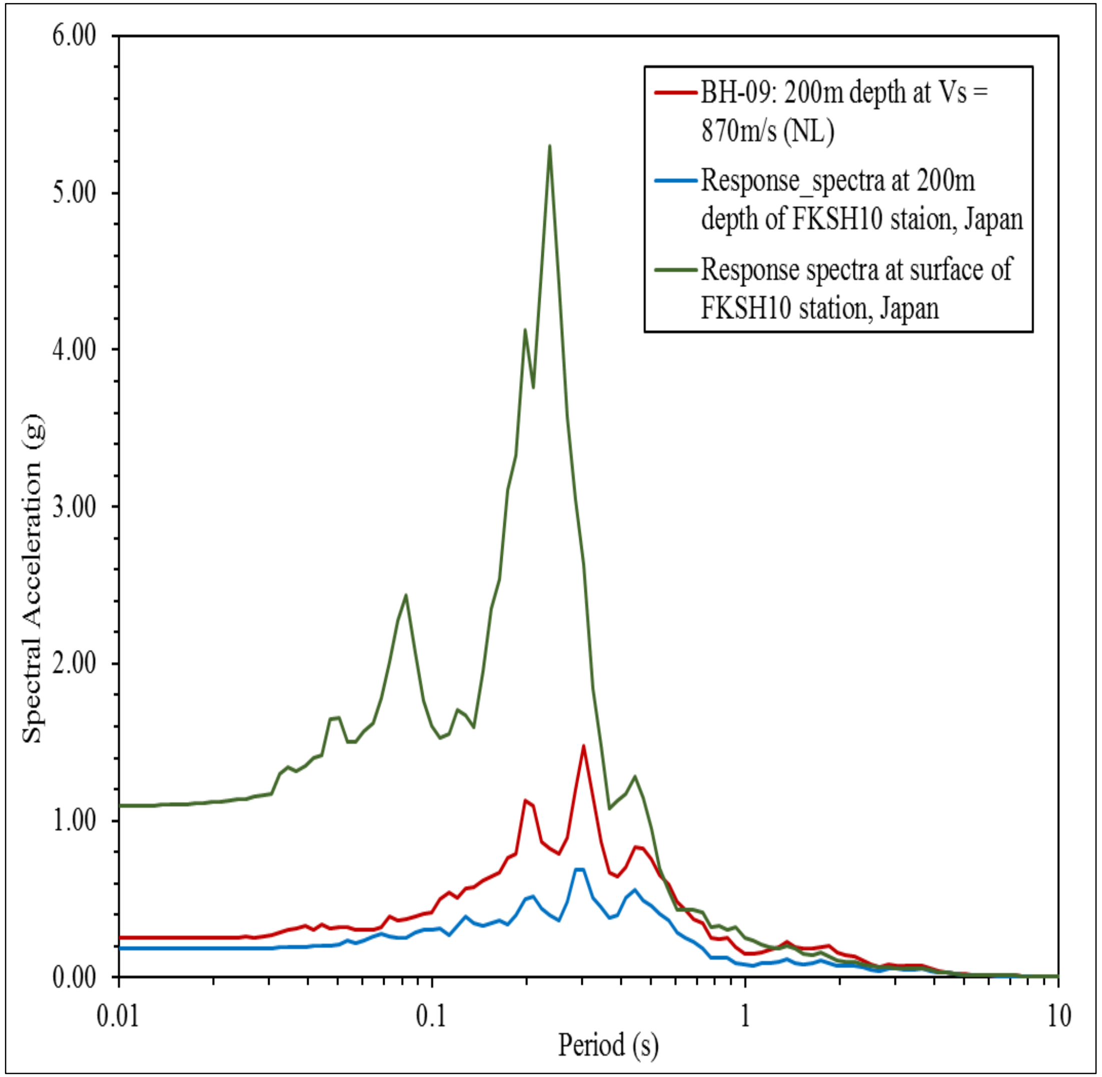


Fig. 15. Shear wave velocity profiles at BH-09 in Dhaka and at FKSH10 station of KiK-net in Japan, (b) uniform hazard spectrum (UHS) at BH-09 in Dhaka and the response spectra of the surface and borehole seismographs at FKSH10 of KiK-net station in Japan. ***(Link*** http://www.kyoshin.bosai.go.jp/**)**

Conclusions

- The bedrock motion is deamplifying at short spectral periods and amplifying at long spectral periods with the increasing depth of soft sedimentary deposits.
- The bedrock motion is always amplified in case of the V_s^{30}-based site response analysis.
- It has been identified that large magnitude seismic sources ($M_w > 8.0$) are located more than 100 km away from the study area, therefore, the peak ground acceleration and spectral acceleration of short period seismic waves will be attenuated and spectral acceleration of long period seismic waves will be amplified in the study areas due to deep and soft deposits.

Continued…

Conclusions

- The long period seismic waves of the far-field earthquakes will match with the natural periods of the high-rise buildings, and resonance will occur.
- The damage to high-rise buildings will be increased.
- The high-rise buildings on the deep and soft sedimentary deposits of the study area are potentially vulnerable to far-field large earthquakes.
- For deep and soft sedimentary deposits, non-linear site response analysis should be performed.

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Thank you all for your kind attention