Supplemental document: Physically Adjusted Ground Motion Prediction Equations for Induced Seismicity at Preston New Road, UK

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Resume

The supplemental document is provided alongside a paper manuscript of Physically Adjusted Ground Motion Prediction Equations for Induced Seismicity at Preston New Road, UK. This supplementary material contains additional information, figures, tables, and equations related to the estimation of duration from PNR recordings, bias observation of 13 different periods (PGA, PGV, 0.03s, 0.05s, 0.075s, 0.1s, 0.2s, 0.3s, 0.5s, 0.75s, 1s, and 2s) from simulation before and after calibration, and also a table of the input list of set parameters used in the calibration process. We also provide the final table used to develop a hybrid ground motion model. In addition, the coefficient and ground motion variability tables for each previous existing model that are used in the study are listed in this document.

Duration

Figure S1 illustrate the comparison of significant duration from different duration matrices (5-75%, 5-95%, and 20-80%) of 2 different records from the same earthquake event. Based on the Arias intensity, we find the arrival time corresponding to each given proportion or percentage of the energy. The time interval between desirable lower and upper percentages is defined as the significant duration between two bounds. Compared to the other metrics, the D5-75 is more likely isolate the strongest part of the motion. Figure S2 show the correlations of different duration definitions computed for the PNR dataset. The middle subplot of Figure S2 indicate that 20-80% significant duration is in agreement with the 5-75% duration measure. As suggested by Boore and Thompson (2014), this metric is suitable for small earthquakes. Figure S3 show the comparison between theoretical duration (duration model used for Groningen GMPE, modified from Afshari and Stewart (2016) model) and observed significant duration from PNR recordings. Figures S4 and S5 show the median predictions from the adjusted Afshari and Stewart (2016) model with different magnitude and shear wave velocities with respect to epicentral distance.

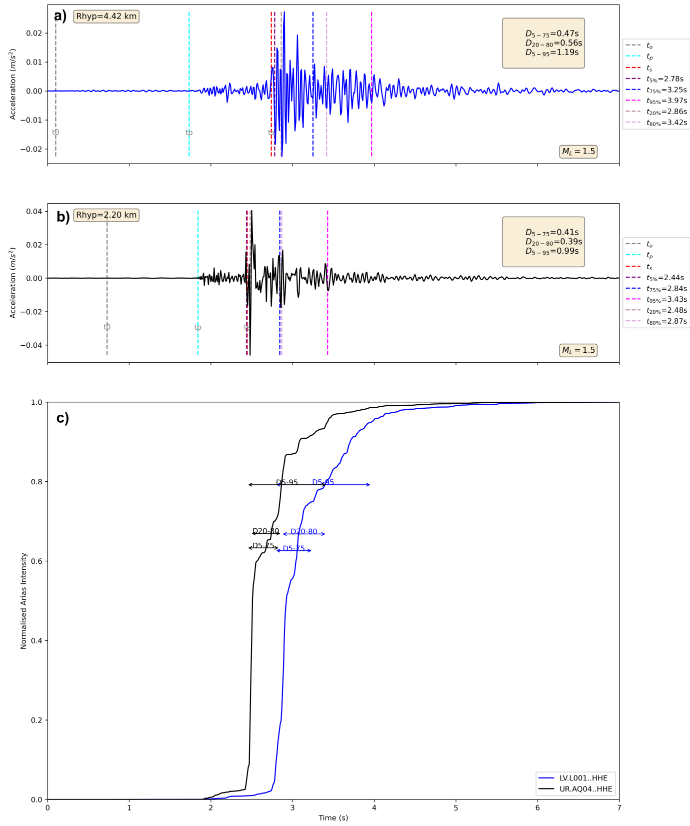

Fig. S1 Example of acceleration time-series and durations from the 1.5 ML PNR event (2018-12-11T11:21:15.1000) occurred at LV.L001 station (a) and UR.AQ04 (b). Corresponding arias intensity of both records (c) showing the duration intervals with different starting and finishing percentages of arias intensity. Dashed lines show the origin time (grey), arrival of P-wave (cyan), arrival of S-wave (red), time at the given percentage of accumulated energy: 5% (purple), 20% (light brown), 75% (blue), 80% (light pink), and 95% (pink).

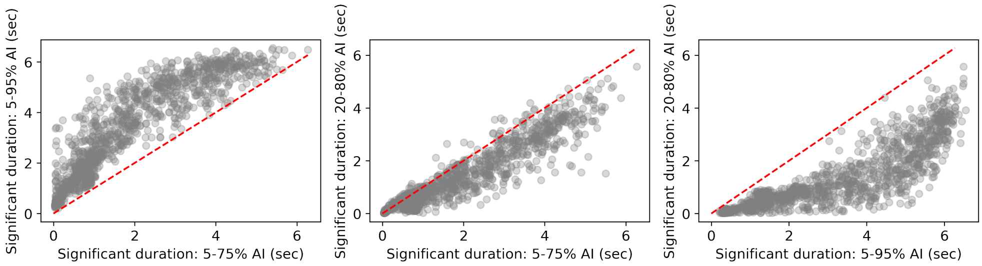

Fig. S2 Correlation between different duration matrices: (left) D5-75 and D5-95, (middle) D5-75 and D20-80, and (right) D5-95 and D20-80.

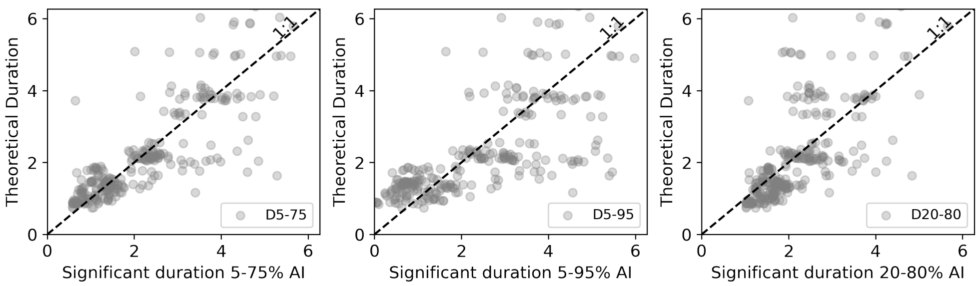

Fig. S3 Comparison between theoretical duration and significant duration with different matrices: (left) D5-75, (middle) D5-95, and (right) D20-80.

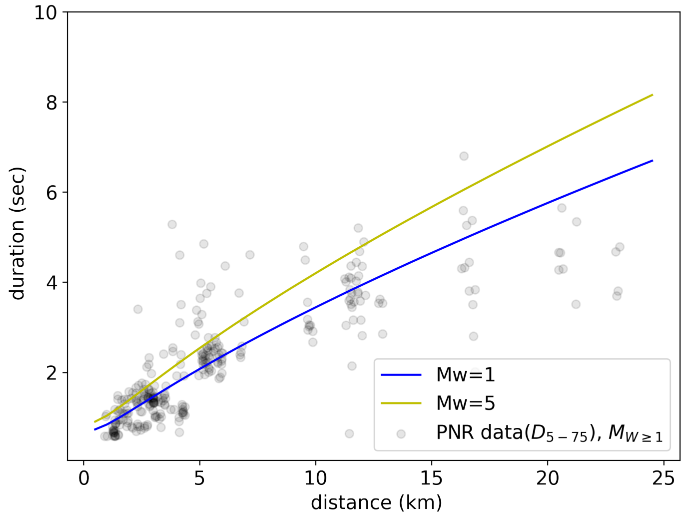

Fig. S4 Significant Duration of 5-75% AI from Event (MW≥ 1) occurred at Preston New Road (scattered point) and Theoretical Duration Model of Bommer et al. (2016) for magnitude 1 MW and 5 MW with respect to epicentral distances for different magnitude values. (Vs30 : 200m/s)

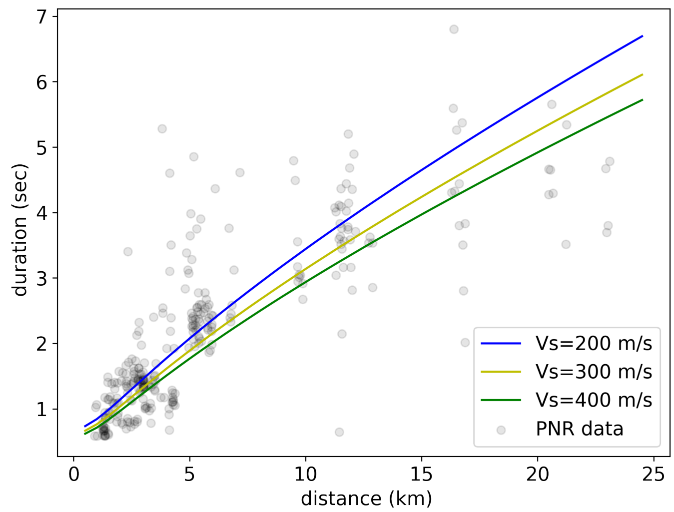

Fig. S5 Significant Duration of 5-75% AI from Event (MW≥ 1) occurred at Preston New Road (scattered point) and Theoretical Duration Model of Bommer et al. (2016) for magnitude 1 MW with respect to epicentral distances for different velocity values (200, 300, and 400 m/s).

Simulation using SMSIM tools

Details about the Stochastic-Method SIMulation are explained by Boore (2003) and accessible in www.daveboore.com. Below is an example of an SMSIM input parameter used in the study:

Listing 1 SMSIM input parameters for PNR site in this study

```
!Revision of program involving a change in the parameter file on
    this date:
   12/16/09
!Title
Input Parameters for PNR
!rho, beta, prtitn (from dc_avg), radpat, fs:
    2.6 2.7 0.77 0.55 2.0
!spectral shape: source number, pf_a, pd_a, pf_b, pd_b
! where source number means:
!  1 = 1-corner (S = 1/(1+(f/fc)**pf_a)**pd_a)
!  2 = Joyner (BSSA 74, 1167--1188)
!  3 = Atkinson (BSSA 83, 1778--1798; see also Atkinson & Boore,
    BSSA 85,
!      17--30)
!  4 = Atkinson & Silva (BSSA 87, 97--113)
!  5 = Haddon 1996 (approximate spectra in Fig. 10 of
!          Haddon's paper in BSSA 86, 1300--1313;
!          see also Atkinson & Boore, BSSA 88, 917--934)
!  6 = AB98-California (Atkinson & Boore BSSA 88, 917--934)
!  7 = Boatwright & Choy (this is the functional form used by
!                          Boore & Atkinson, BSSA 79, 1736--1761, p.
     1761)
!  8 = Joyner (his ENA two-corner model, done for the SSHAC
    elicitation
!      workshop)
!  9 = Atkinson & Silva (BSSA 90, 255--274)
! 10 = Atkinson (2005 model),
! 11 = Generalized two corner model
!      (S = [1/(1+(f/fa)**pf_a)**pd_a]*[1/(1+(f/fb)**pf_b)**pd_b])
! pf_a, pd_a, pf_b, pd_a are used for source numbers 1 and 11,
    usually
! subject to the constraint pf_a*pd_a + pf_b*pd_b = 2 for an omega-
    squared
! spectrum. The usual single-corner frequency model uses
! pf_a=2.0,pd_a=1.0; the Butterworth filter shape is given by
! pf_a=4.0,pd_a=0.5.  pf_b and pd_b are only used by source 11, but
    dummy
! values must be included for all sources.
     1 2.0 1.0 0.0 0.0
!spectral scaling: stressc, dlsdm, fbdfa, amagc, c1_fa, c2_fa,
    amagc4fa
! (stress=stressc*10.0**(dlsdm*(amag-amagc))
```

```
! (fbdfa, amagc for Joyner model, usually 4.0, 7.0)
! c1_fa, c2_fa are the coefficients relating log fa to M in
! source 11, as given by the equation log fa = c1_fa + c2_fa*(M-
   amagc4fa).
! fb for source 11 is given such that the high-frequency spectral
   level
! equals that for a single corner frequency model with a stress
   parameter
! given by stress=stressc*10.0**(dlsdm*(amag-amagc).
! See Tables 2 and 3 in Boore (2003) for various source
   descriptions
! (Note: the parameters in the line below are not used for most of
   the
! sources, for which the spectrum is determined by fixed relations
   between
! corner frequency and seismic moment, but placeholders are still
   needed)
    00 0.0 0.0 0.0  0.0 0.0 0.0
!iflag_h_eff, c1_log10_h_eff, c2_log10_h_eff
!  If iflag = 1, compute an effective depth as
!  h_eff = 10.0**(c1_log10_h_eff + c2_log10_h_eff*amag) and modify
   the closest
!  distance by this depth: rmod = sqrt(r^2+h_eff^2)); use rmod in
!  the calculations
!  1 -0.05 0.15 ! Atkinson and Silva (2000) values
   0  -0.26418 0.183837
!gsprd: r_ref, nsegs, (rlow(i), a_s, b_s, m_s(i)) (Usually set
! r_ref = 1.0 km)
    1.0
    3
     1.0 #gamma0# 0.0 6.5
     7.0 #gamma1# 0.0 6.5
     12.0 #gamma2# 0.0 6.5
!q: fr1, Qr1, s1, ft1, ft2, fr2, qr2, s2, c_q
    1.0 #Q0# #alpha# 1.0 1.0 1.0 #Q0# #alpha# 2.7
!source duration: weights of 1/fa, 1/fb
    1.0 0.0
!path duration: nknots, (rdur(i), dur(i), slope of last segment
   Thompson & Boore 2014
    2
      0.0 #Path_Duration#
      999 #Path_Duration#
    0.00
!site amplification: namps, (famp(i), amp(i))
!site diminution parameters: fmax, kappa, dkappadmag, amagkref
! (NOTE: fmax=0.0 or kappa=0.0 => fmax or kappa are not used.  I
   included this
!  to prevent the inadvertent use of both fmax and kappa to control
    the diminution
```

```
!   of high-frequency motion (it would be very unusual to use both parameters
!   together.  Also note that if do not want to use kappa, dkappadmag must also
!   be set to 0.0).
     250.0 #kappa_0# 0.0 0.0
!low-cut filter parameters: fcut, norder
     0 10
!rv params: zup, eps_int (int acc), amp_cutoff (for fup), osc_crrctn(1=b&j;2=l&p)
     10.0 0.00001  0.001 2
!window params: idxwnd(0=box,1=exp), tapr(<1), eps_w, eta_w, f_tb2te, f_te_xtnd
     1 0.05 0.2 0.05 2.0 1.0
!timing stuff: dur_fctr, dt, tshift, seed, nsims, iran_type (0=normal;1=uniform)
     1.3   0.005 20.0 123.0 200 0
```

Site Corrections

The site-specific conditions can influence the behaviour of seismic waves in the site location. The site conditions in the PNR region are dominated by very low shear wave velocity and potentially strongly amplifying sediments. Therefore, for large-magnitude events, we expect significant non-linear effects. The period-dependent coefficients to calculate the non-linear effect are defined by Boore et al. (2014), and presented in the table below.

Table 1 Period dependent coefficients of Boore et al. (2014) that used to account non-linear site term

T	$clin$	V_c	V_{ref}	f_1	f_3	f_4	f_5
PGV	-0.84000	1300.00	760.0	0.0	0.1	-0.100000	-0.00844
PGA	-0.60000	1500.00	760.0	0.0	0.1	-0.150000	-0.00701
0.03	-0.53414	1502.95	760.0	0.0	0.1	-0.154850	-0.00735
0.05	-0.45795	1501.42	760.0	0.0	0.1	-0.192000	-0.00647
0.1	-0.48724	1479.12	760.0	0.0	0.1	-0.249160	-0.00560
0.2	-0.68762	1392.61	760.0	0.0	0.1	-0.246580	-0.00614
0.3	-0.84165	1308.47	760.0	0.0	0.1	-0.219120	-0.00670
0.5	-0.96930	1203.91	760.0	0.0	0.1	-0.175000	-0.00744
1.0	-1.05000	1109.95	760.0	0.0	0.1	-0.105210	-0.00844
2.0	-1.03920	1009.49	760.0	0.0	0.1	-0.036136	-0.00479

Residual Analysis

Figure S6 & S7 shows the bias between observed and predicted ground motions of Atkinson (2015) and Edwards et al. (2021) models. In addition to bias between observed and simulated ground motions (before calibration) with respect to magnitude and distance. The bias between observed and models examined for PGV, PGA, and PSA at different periods. Figure S8 & S9 presents the comparison between the simulated before and after the calibration process. A list of the initial set of parameter combinations (N= 500) and the 50 new lists of parameter combinations utilised in the second stage of the calibration process can be accessed in link for supplemental folder.

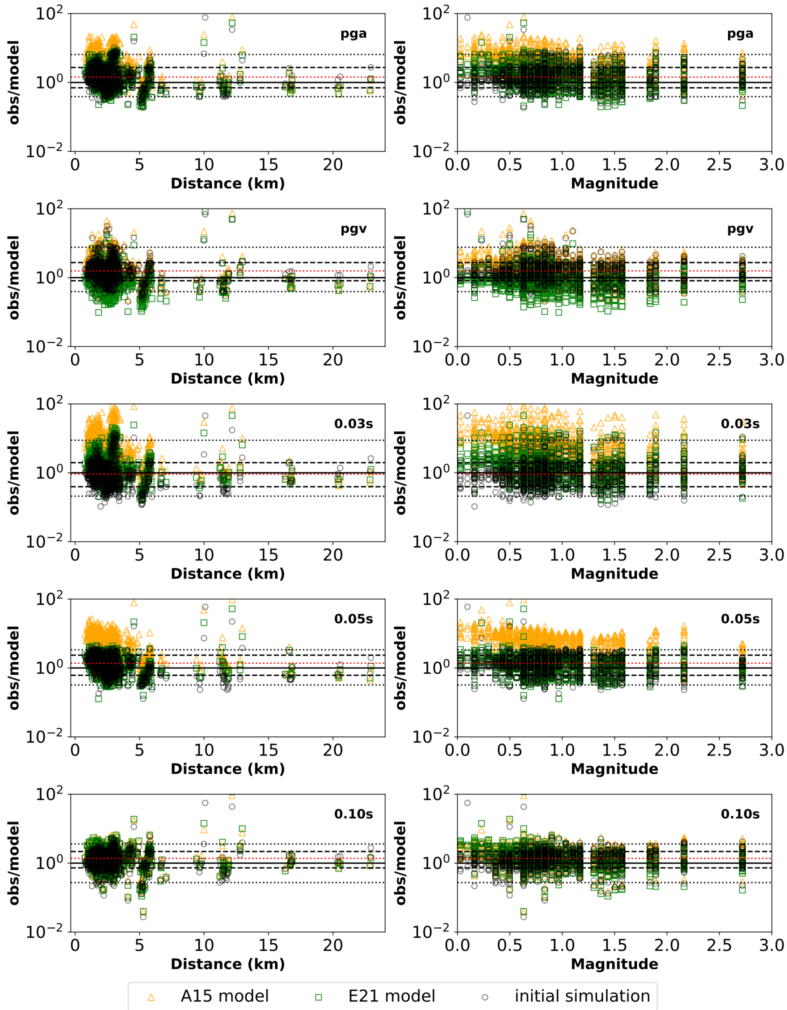

Fig. S6 Bias [Observed/Model] of PGA, PGV, and PSA (at 0.03s, 0.05s, and 0.1s). Modelled ground motions refer to the ground motion computed using a) GMPE- Atkinson (2015), b) GMPE- Edwards, et al. (2021), and c) Stochastic Simulation.

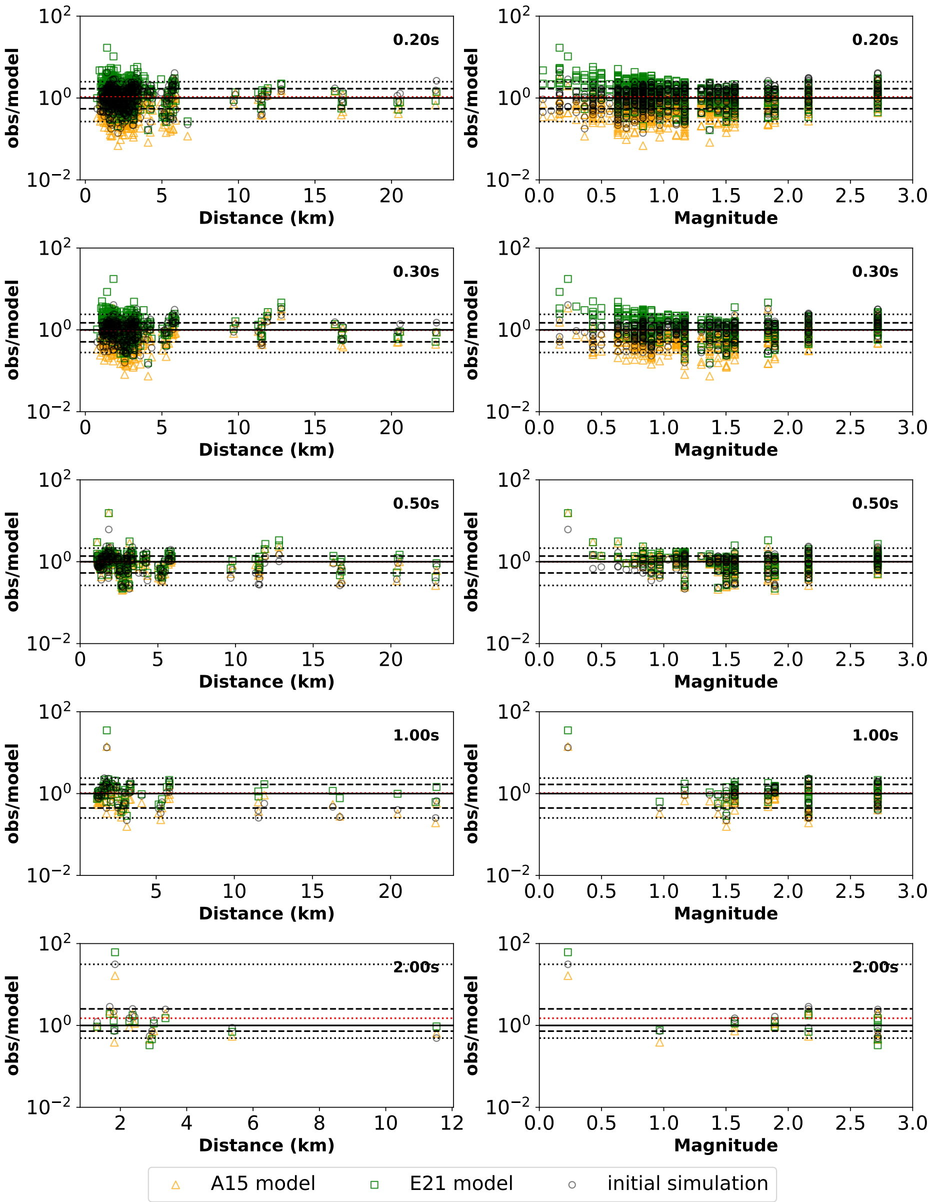

Fig. S7 Bias [Observed/Model] of PSA at 0.2s, 0.3s, 0.5s, 1s, and 2s. Modelled ground motions refer to the ground motion computed using a) GMPE- Atkinson (2015), b) GMPE- Edwards, et al. (2021), and c) Stochastic Simulation.

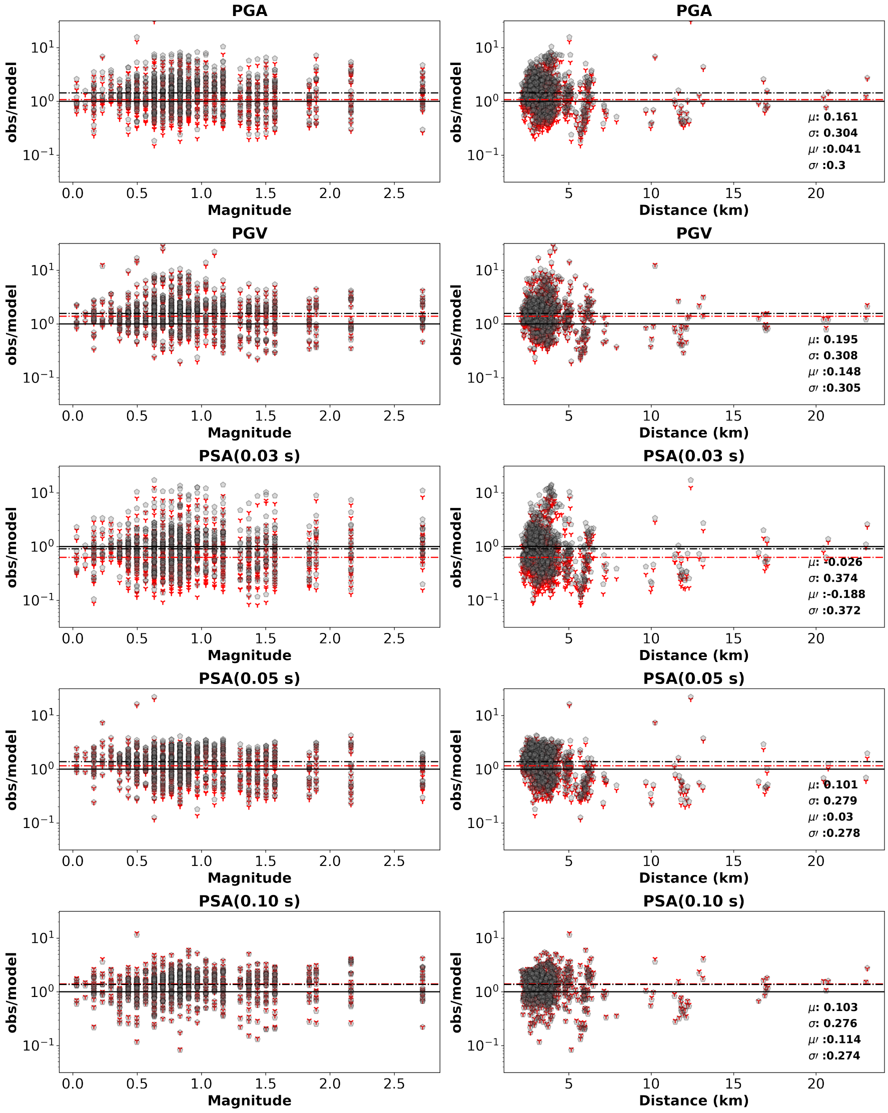

Fig. S8 Bias between simulated PGA, PGV, and PSA (at 0.03s, 0.05s, and 0.1s) using the initial and calibrated model. The black line represents the zero levels of residual, while the dashed line shows the median percentile of residual from the initial simulation (black) and calibrated model (red).

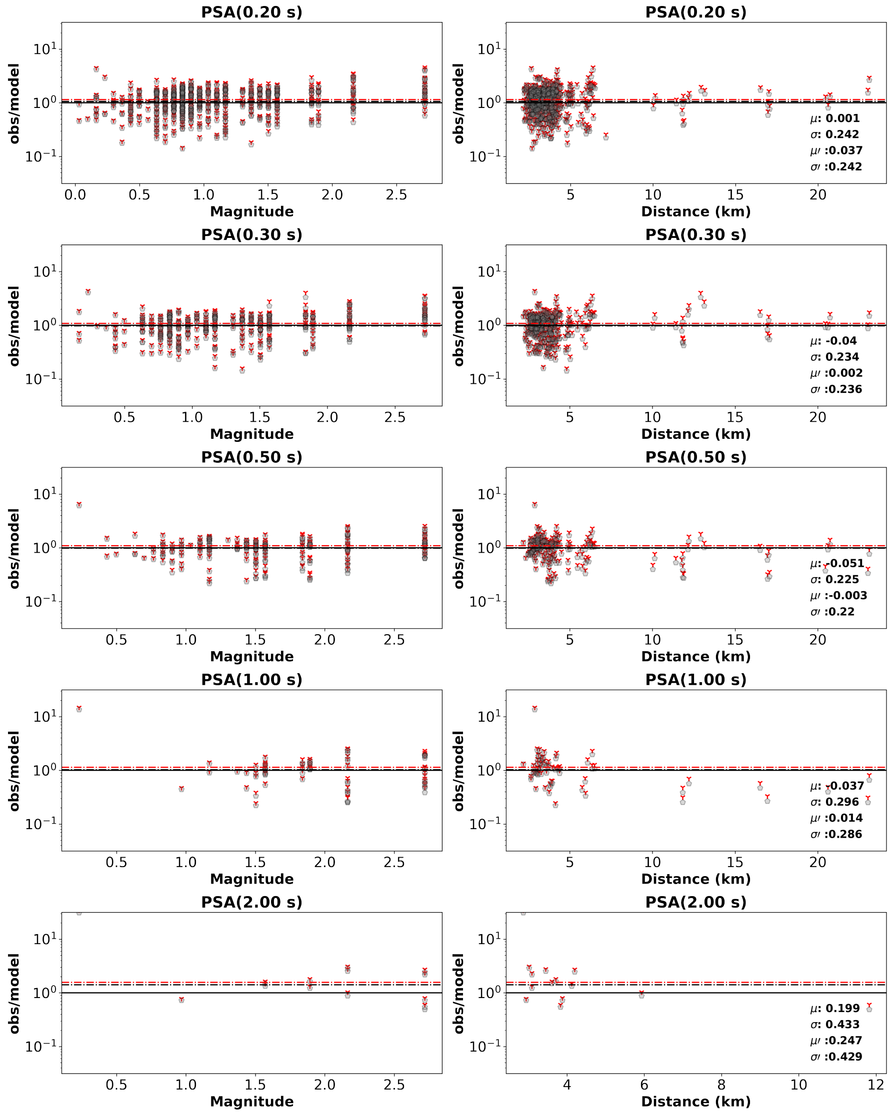

Fig. S9 Bias between simulated PSA at period of 0.2s, 0.3s, 0.5s, 1s, and 2s using the initial and calibrated model. The black line represents the zero levels of residual, while the dashed line shows the median percentile of residual from the initial simulation (black) and calibrated model (red).

Comparison with other GMPEs

In the development of a new hybrid GMPE for the PNR case study, we utilise GMPE from Atkinson (2015) as a base model. The coefficient and variability of ground motion modelled by Atkinson (2015) is available in Tabel 2. Apart from that, comparisons were also made between the newly developed physically-adjusted GMPE (this study) and several existing models, such as Edwards et al. (2021), Rietbrock et al. (2013), Douglas et al. (2013), Cremen et al. (2020), Boore et al. (2014), as well as simulation results following the Rietbrock and Edwards (2019) model. Some of the GMPE coefficients used are provided below.

Table 2 Coefficient and ground motion variability of Atkinson (2015) model

T (s)	c0	c1	c2	c3	σ_{intra}	σ_{inter}	σ_{total}
5	-4.321	1.08	0.009376	-1.378	0.25	0.18	0.31
3	-3.827	1.06	0.009086	-1.398	0.24	0.22	0.32
2	-4.462	1.485	-0.03815	-1.361	0.24	0.23	0.33
1	-4.081	1.742	-0.07381	-1.481	0.26	0.22	0.34
0.5	-3.873	2.06	-0.1212	-1.544	0.29	0.2	0.35
0.3	-2.794	1.852	-0.1078	-1.608	0.3	0.19	0.36
0.2	-2.266	1.785	-0.1061	-1.657	0.3	0.21	0.37
0.1	-1.954	1.83	-0.1185	-1.774	0.29	0.25	0.39
0.05	-2.018	1.826	-0.1192	-1.831	0.28	0.3	0.41
0.03	-2.283	1.842	-0.1189	-1.785	0.28	0.27	0.39
PGA	-2.376	1.818	-0.1153	-1.752	0.28	0.24	0.37
PGV	-4.151	1.762	-0.09509	-1.669	0.27	0.19	0.33

Table 3 Coefficient and ground motion variability of Edwards et al. (2021) model in which τ is the Between Event, ϕ the Within Event,ϕ_{S2S} the Within Event Site-to-Site Variability and σ the Total Standard Deviations

var	$\Delta c0$	$\Delta c1$	$\Delta c2$	$\Delta c3$	τ	ϕ	ϕ_{S2S}	σ
PGV	0.5491	-0.08294	0.02353	-0.496128	0.058481	0.301525	0.217752	0.307143
PGA	0.760372	-0.057531	0.008329	-0.511863	0.064	0.319186	0.256915	0.325539
0.03	1.153064	-0.08642	0.014357	-0.808598	0.082792	0.378933	0.286087	0.387872
0.05	1.144637	-0.138839	0.021397	-0.732073	0.062399	0.261928	0.207916	0.269258
0.1	0.045688	0.272474	-0.044161	-0.284998	0.035851	0.268433	0.223404	0.270816
0.2	-0.828996	0.473393	-0.064206	0.00449	0.055877	0.236646	0.205798	0.243154
0.3	-0.868126	0.403655	-0.055583	0.140767	0.080273	0.231795	0.220696	0.245301
0.5	0.133834	-0.057892	0.021385	-0.231994	0.08537	0.203371	0.204862	0.220562
1	-0.187912	0.148589	0.00849	-0.499591	0.036686	0.204644	0.204731	0.207906
2	-0.342342	0.42676	-0.034681	-0.675497	0.075986	0.213305	0.231626	0.226435

Table 4 Coefficients Derived from the Simulations Using the Magnitude-Dependent Stress Parameter Model by Rietbrock et al. (2013)

Parameter	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	σ_T	σ_B	σ_W
PGV	-4.9398	1.7051	-0.1081	-1.6063	0.2084	-1.6040	0.1527	-2.2932	0.0659	-0.001643	3.1138	0.276	0.229	0.155
PGA	-2.6934	1.7682	-0.1366	-1.8544	0.2123	-1.8467	0.1590	-1.8809	0.0681	-0.002888	2.1589	0.335	0.298	0.154
0.03	-1.9654	1.7265	-0.1346	-2.1011	0.2101	-2.0063	0.1555	-1.3684	0.0946	-0.004626	1.3437	0.348	0.304	0.169
0.04	-2.3216	1.7592	-0.1328	-1.7198	0.1635	-1.6582	0.1192	-1.3348	0.0730	-0.004488	1.3363	0.343	0.305	0.157
0.05	-2.4879	1.7771	-0.1328	-1.5910	0.1502	-1.5447	0.1087	-1.4304	0.0599	-0.004056	1.3942	0.339	0.304	0.150
0.06	-2.6647	1.8009	-0.1336	-1.4916	0.1409	-1.4576	0.1013	-1.5603	0.0494	-0.003549	1.4587	0.335	0.302	0.144
0.08	-2.8579	1.8325	-0.1353	-1.4169	0.1349	-1.3909	0.0959	-1.6918	0.0423	-0.003077	1.5466	0.330	0.299	0.140
0.1	-3.0920	1.8771	-0.1381	-1.3587	0.1312	-1.3363	0.0919	-1.8091	0.0363	-0.002651	1.6583	0.325	0.295	0.138
0.12	-3.3595	1.9336	-0.1419	-1.3133	0.1289	-1.2908	0.0884	-1.9038	0.0322	-0.002311	1.7807	0.320	0.289	0.137
0.16	-3.6974	2.0096	-0.1472	-1.2717	0.1262	-1.2472	0.0847	-1.9844	0.0286	-0.002015	1.8540	0.314	0.282	0.138
0.2	-4.1004	2.1032	-0.1537	-1.2341	0.1234	-1.2055	0.0809	-2.0474	0.0254	-0.001772	1.9055	0.307	0.273	0.141
0.25	-4.5462	2.2068	-0.1607	-1.1985	0.1198	-1.1658	0.0770	-2.0935	0.0227	-0.001579	1.9052	0.301	0.263	0.145
0.31	-5.0372	2.3180	-0.1679	-1.1625	0.1155	-1.1258	0.0728	-2.1276	0.0201	-0.001419	1.8732	0.294	0.253	0.150
0.4	-5.5650	2.4307	-0.1745	-1.1242	0.1104	-1.0847	0.0682	-2.1519	0.0176	-0.001282	1.8142	0.288	0.242	0.155
0.5	-6.0933	2.5325	-0.1795	-1.0837	0.1043	-1.0436	0.0635	-2.1680	0.0152	-0.001166	1.7238	0.282	0.231	0.161
0.63	-6.5914	2.6123	-0.1820	-1.0432	0.0985	-1.0044	0.0591	-2.1775	0.0129	-0.001066	1.6524	0.276	0.220	0.167
0.79	-7.0402	2.6616	-0.1813	-1.0023	0.0927	-0.9683	0.0552	-2.1820	0.0109	-0.000977	1.5900	0.272	0.210	0.172
1	-7.4028	2.6715	-0.1767	-0.9634	0.0877	-0.9394	0.0526	-2.1827	0.0092	-0.000898	1.5549	0.268	0.201	0.177
1.25	-7.6577	2.6402	-0.1686	-0.9299	0.0842	-0.9226	0.0519	-2.1811	0.0079	-0.000827	1.5712	0.265	0.193	0.181
1.59	-7.8128	2.5609	-0.1559	-0.9021	0.0829	-0.9242	0.0544	-2.1782	0.0069	-0.000756	1.6701	0.262	0.185	0.186
2	-7.8368	2.4440	-0.1409	-0.8896	0.0857	-0.9546	0.0613	-2.1751	0.0064	-0.000691	1.9205	0.260	0.177	0.191
2.5	-7.7341	2.2967	-0.1244	-0.9012	0.0975	-1.0270	0.0747	-2.1717	0.0066	-0.000634	2.6233	0.258	0.169	0.195
3.13	-7.4991	2.1232	-0.1072	-0.9638	0.1202	-1.1604	0.0965	-2.1763	0.0077	-0.000571	3.5221	0.256	0.161	0.199
4	-7.1376	1.9232	-0.0893	-1.1238	0.1549	-1.3647	0.1284	-2.1901	0.0114	-0.000515	4.0984	0.253	0.152	0.203
5	-6.7757	1.7502	-0.0753	-1.3603	0.1960	-1.5804	0.1613	-2.2070	0.0191	-0.000518	4.3313	0.251	0.144	0.205

Table 5 Coefficient and ground motion variability of Cremen et al. (2020) model in which τ is the Between Event, ϕ the Within Event, and σ the Total Standard Deviations

	a	b	c	h	d	ϕ	τ	σ
PGA	-5.096	2.14	-2.611	Constrained to zero	-0.023	0.563	0.437	0.712
PGV	-10.213	2.913	-2.719	Constrained to zero	-0.046	0.553	0.158	0.575
0.05	-5.027	2.7171	-2.89	Constrained to zero	-0.008	0.696	0.378	0.792
0.1	-4.988	2.814	-2.723	Constrained to zero	-0.039	0.632	0.227	0.672
0.2	-7.704	3.639	-2.276	Constrained to zero	-0.057	0.549	0.43	0.698

Table 6 Coefficients for Douglas et al. (2013)- Model 2 for Selected Periods in which τ is the Between Event, ϕ the Within Event, and σ the Total Standard Deviations

	a	b	c	d	ϕ	τ	σ
PGA	−7.198	1.991	−1.105	−0.048	0.731	1.08	1.304
0.1	−8.079	2.375	−0.778	−0.058	0.589	0.787	0.983
0.2	−10.118	2.783	−0.799	−0.044	0.554	0.658	0.86
0.5	−12.829	3.055	−0.624	−0.053	0.573	0.696	0.902
PGV	−10.846	1.961	−0.962	−0.056	1.031	1.536	1.85

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