Application of on-site EEW technology in South Korea.

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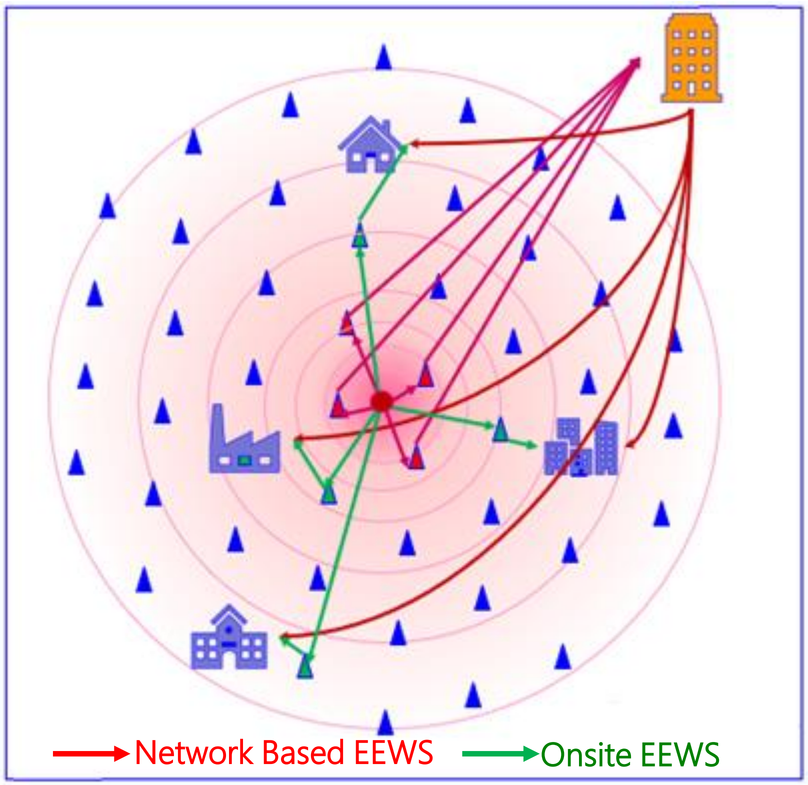
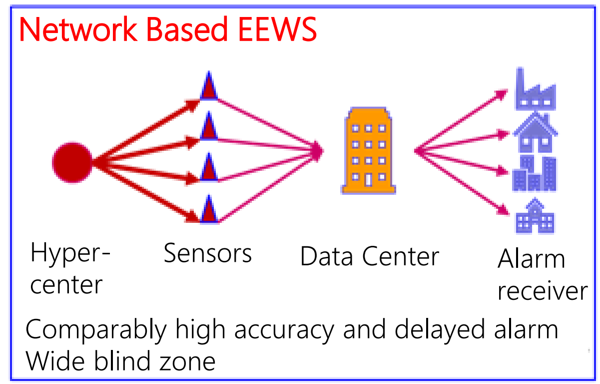
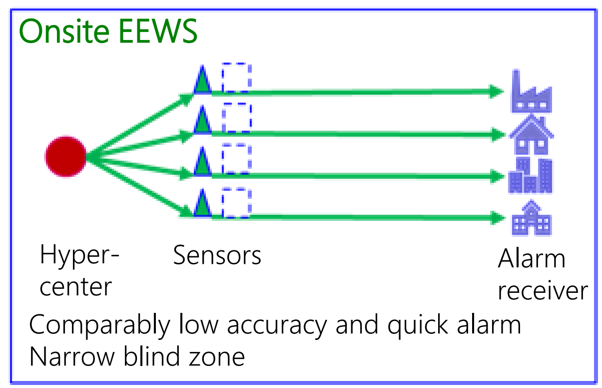
Onsite Earthquake Early Warning

Two types of EEWS for quick estimation and alarm of seismic motion.

- **Network Based EEWS** : Using multi stations, Estimation of earthquake magnitude and intensity, Network based alarm transfer, Wide Blind zone.
- **Onsite EEWS** : Using single or a few sensors, Estimation of on-site shaking and obtaining alarm





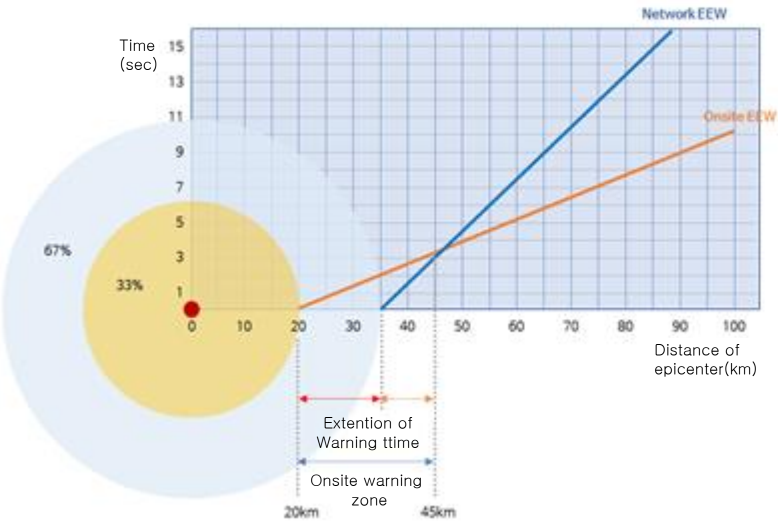


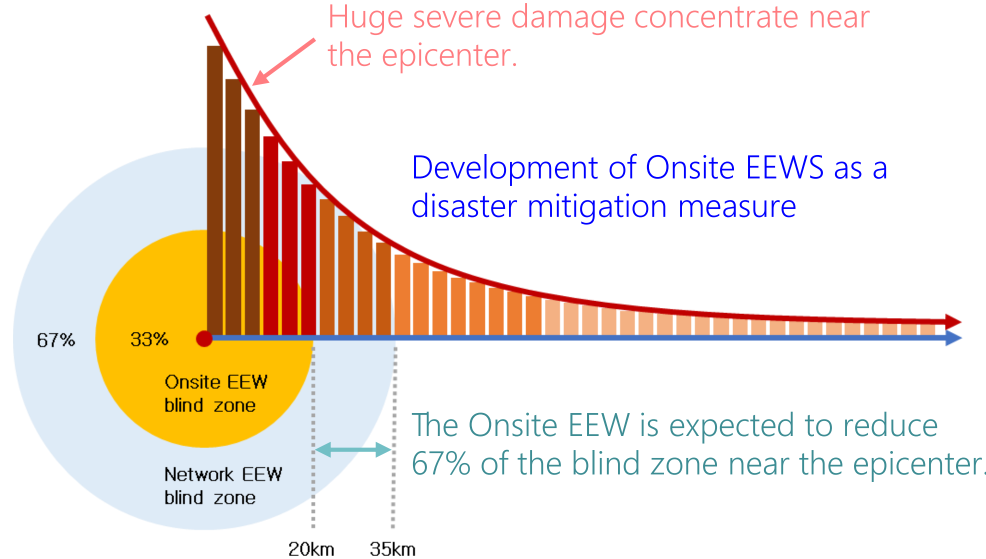
Importance of on-site EEW Tech. in South Korea.

Needs of the Onsite technique to compliment the network based EEWS in Korea.

- Korea does not have a lot of massive earthquakes, but it is the country that operates EEWS.
- KMA operates EEWS which could issue within 7 to 25 seconds after the first detection of seismic motion.
- Onsite EEWS is useful to reduce the blind zone of seismic warning and huge damages near the epicenter.
- Research on develop methods to estimate the on-site shaking from the P-wave features in Korea.
- Seismic records in Korea have been gathered and analyzed to get relation between P-waves and PGVs.

Onsite technique estimate PGVs using P-wave features sensed from single sensor installed on-site location.





Onsite EEWS Technology

- **The PGV is propotional to the amplitude of P-waves.**
  P-waves, PGVs relationships for the Onsite EEW have been derived in previous studies.

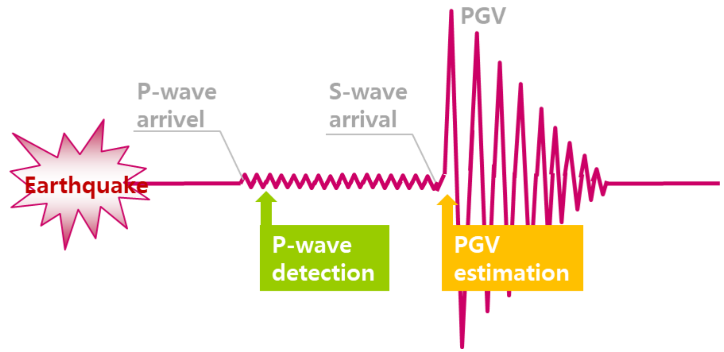
- Empirical equations that explain relationship between P-wave features and PGVs

$$\log PGV = -0.55(\pm 0.05) + 0.72(\pm 0.05) \log Pa \pm 0.61 \quad (1)$$

$$\log PGV = 0.72(\pm 0.06) + 0.93(\pm 0.05) \log Pv \pm 0.52 \quad (2)$$

$$\log PGV = 1.11(\pm 0.08) + 0.69(\pm 0.04) \log Pd \pm 0.61 \quad (3)$$

by S.Colombelli et.al.(2015)



$$\log PGV = 0.920 \log Pd + 1.642 \pm 0.326 \quad (4)$$

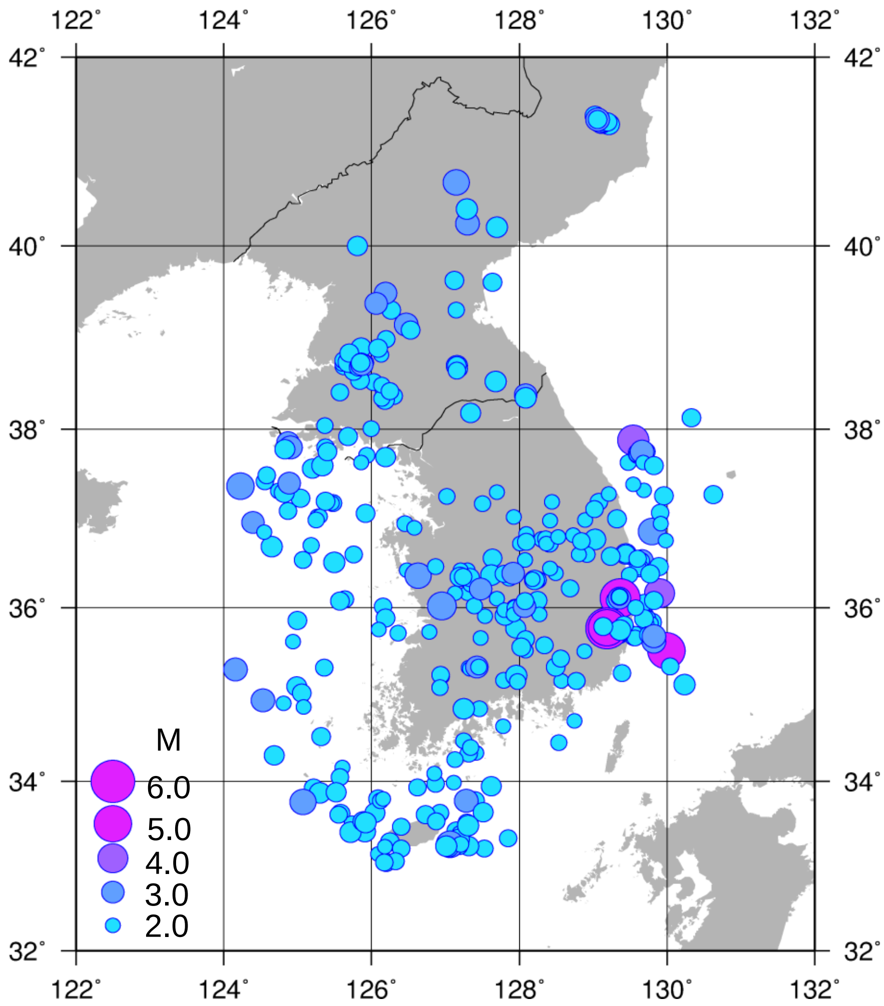
by Wu and Kanamori(2005)

(The variable Pa, Pv and Pd denote amplitudes of peak acceleration, velocity and displacement of initial P-waves in vertical direction.)

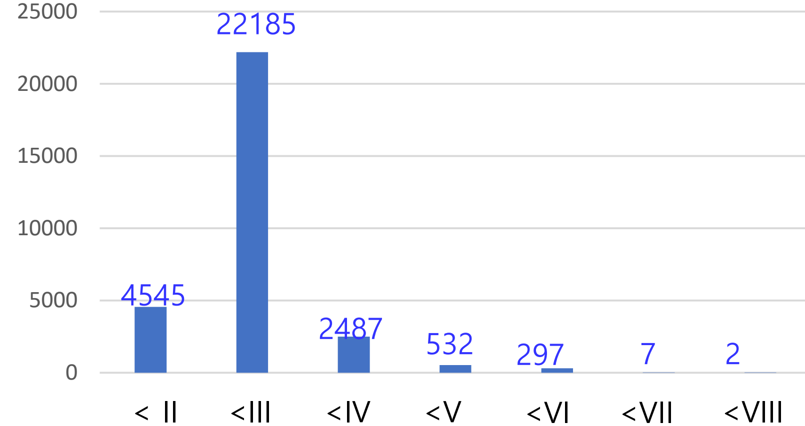
The relations between the PGVs and P-waves are to be driven using the seismic data observed in South Korea in this study.

Seismic Records in South Korea

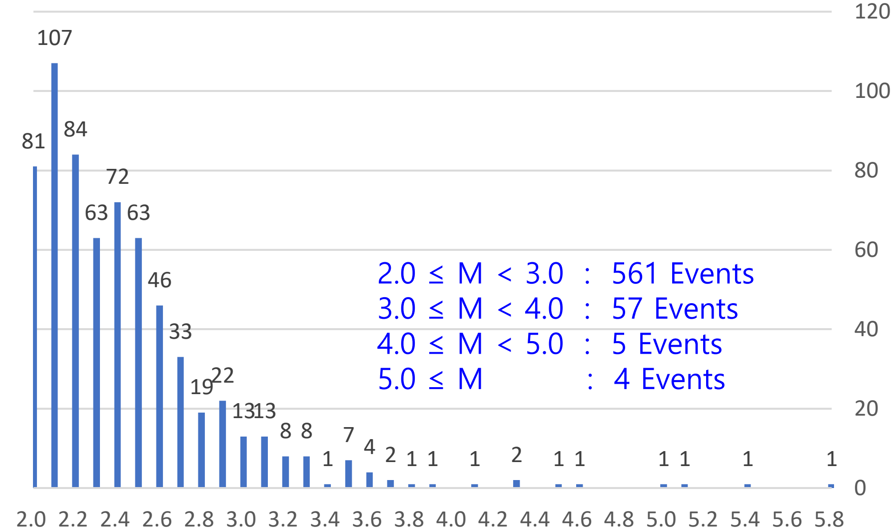
- **Seismic records used for analysis to derive field alert empirical expressions in Korea (May, 2015 ~ April, 2019, Total 657 Events, <37,000 Records)**



Epicenter and Magnitude of Earthquake Events



Number of Records as MMIs

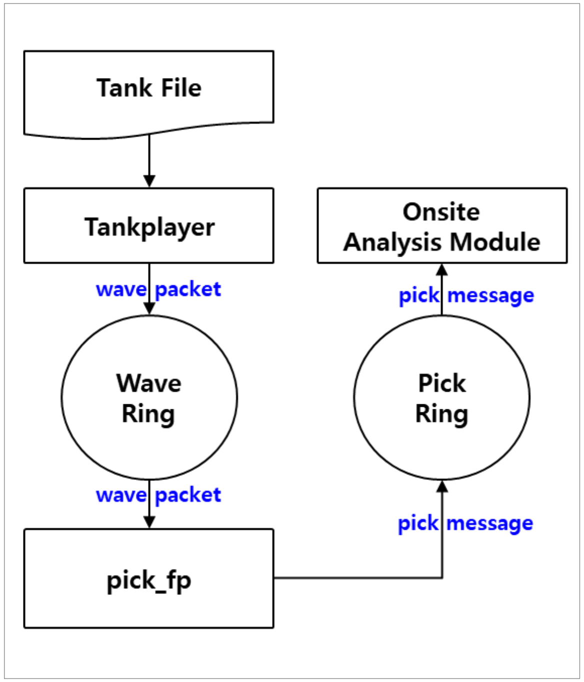


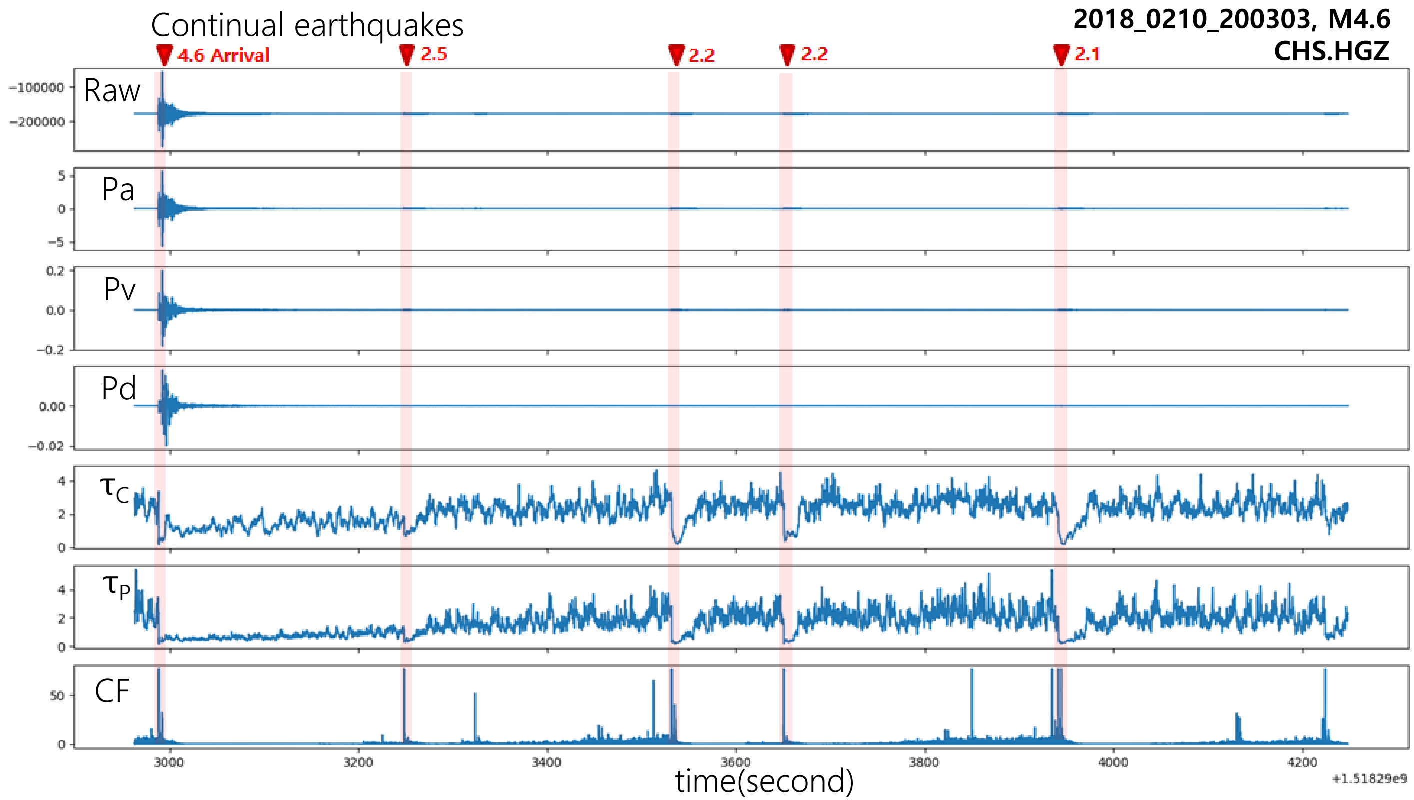
Number of Earthquakes as Magnitudes

Detecting and Extracting P-wave Features

- **Detecting and identifying number of P-wave features using Filter Picker(Lomax et al., 2012)**

- Modified Pick_fp module extract P-wave CF(Characteristic Function), Peak Acceleration, Peak Velocity, Peak Displacement, τ_C and τ_P etc. consistently and reliably.
※ CF(Lomax et al.,2012), τ_P(Allen and Kanamori,2003), τ_C(Wu and Kanamori, 2005)



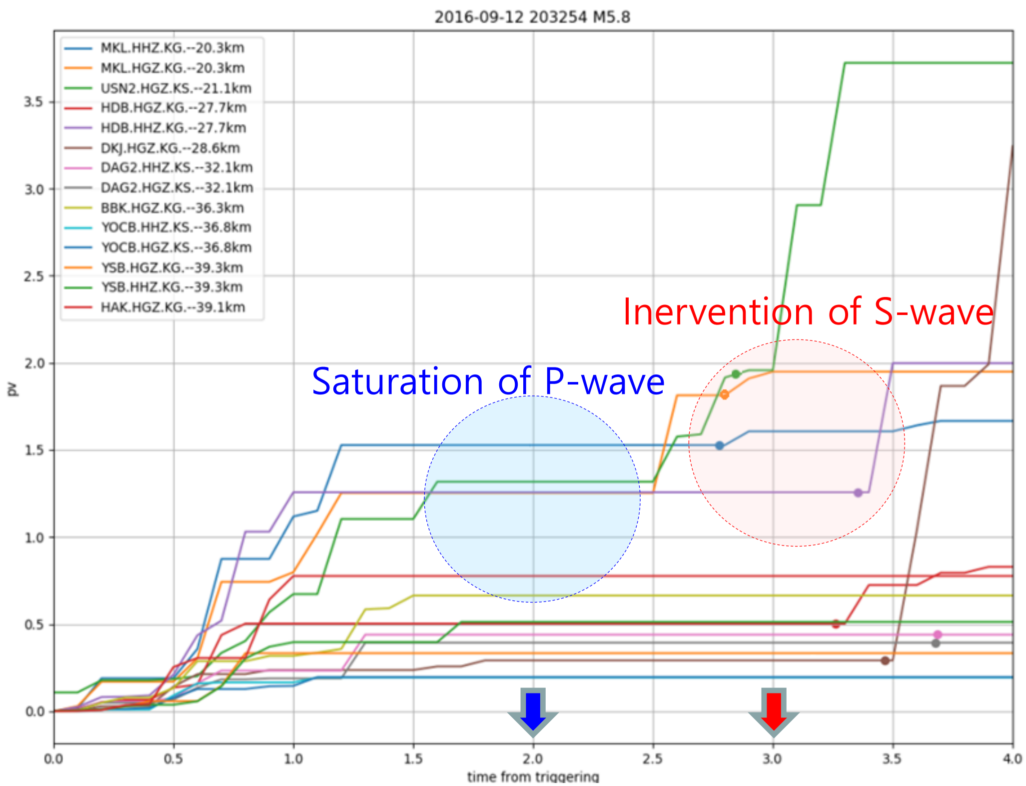


Modified Filter Picker and extracted P-wave feature

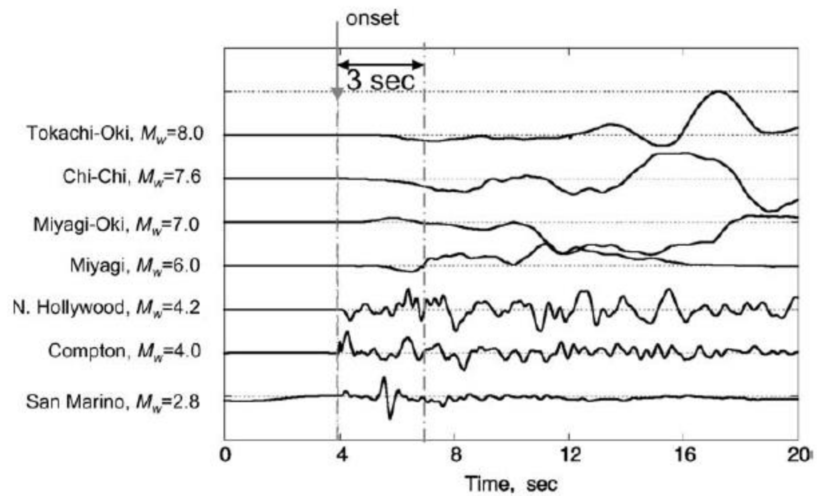
P-wave Time Window

What is the optimum PTW for P Extraction?

- In general 3 seconds of PTW is selected as a period of full saturation of P-wave without S-wave intervantion
- In earthquakes with a M6.0 or lower, S-wave interference is included when PTW is selected for 3 seconds.
- At 2 seconds, the P-wave is fully saturated without 2 wave interference.



Form of growth over time after arrival of P-wave at the seismic stations in case of M5.8 Kyungju earthquake in 2016.



Waveform after P-wave Arrival as Earthquake Magnitude(Kanamoro,2005)

Application of Onsite Tech. In South Korea

- **Case studies to derive P-PGV emphirical relationship using seismic records in South Korea.**

Case	Seismic Records[*1]		HPF Freq.	Data Binning (EA/MMI)	Regression Equation[*2]
	Analyzed from	Estimation			
1	Observed Records for 4yrs(M≥2.0)	Seismic Records for 4yrs(M≥2.0)	0.3Hz	-	SR
2	Observed Records for 4yrs(M≥3.0)	Seismic Records for 4yrs(M≥3.0)	1.0Hz	-	SR Ave. MR
3	Observed Records for 4yrs(M≥3.0)	Seismic Records for 4yrs(M≥3.0)	1.0Hz	200	
4	Pseudo Records of M5.8(2016)	Seismic Records for 4yrs(M≥3.0)	1.0Hz	≒ 7,000	
5	Pseudo Records of M5.8(2016)	M5.4 Obs. Records of M5.4(2017)	1.0Hz	≒ 7,000	

[*1] Seismic Records
Observed Records : Observed Seismic records from May, 2015 to May, 2019 in Korea
Pseudo Records: Spatially interpolated seismic records from a single event records

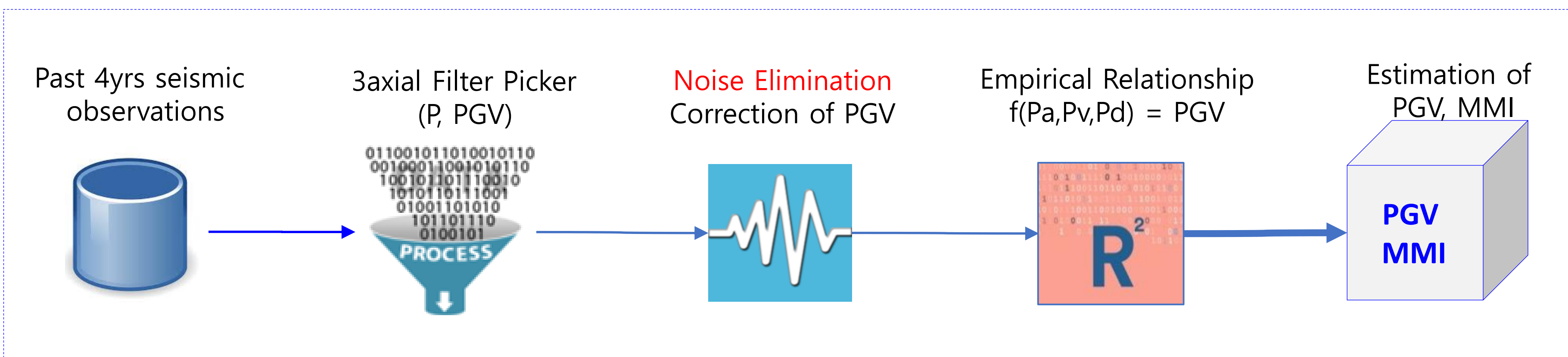
- 1 Hz High Pass Filter is applied to remove the long-period noise inherent in P waves.
- Measured PGV is converted to the values on the bed rock (Ministry of Public Safety and Security, 2017)

[*2] Regression Equation
SLR : Simple Linear Regression ; f(Pa) = g(Pv) = h(Pd) = PGV
SLR Ave. : Averaged SL ; f(Pa) + g(Pv) + h(Pd) = 3 x PGV
MR : Multiple Regression ; F(Pa,Pv,Pd) = PGV

Case 1 ; Simple Linear Regression of Records

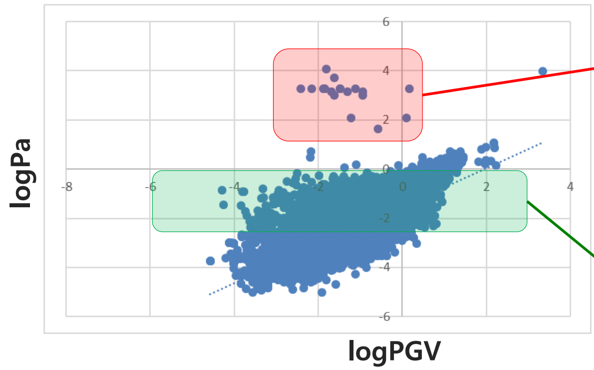
- Case 1 : **Onsite Warning through single linear regression seismic records over the past four years**

- Extracting maximim P-wave vertical amplitude (Pa, Pv, Pd) within 2 seconds of PTW from seismic records.
- Eliminate noise in P-waves(background ambient noise, low-intensity data not needed for alarms, etc.).
- Simple linear regression analysis to derive relationship between PGV and Pa, Pv and Pd.
- Derives MMI from predicted PGV and determines and estimate the error.



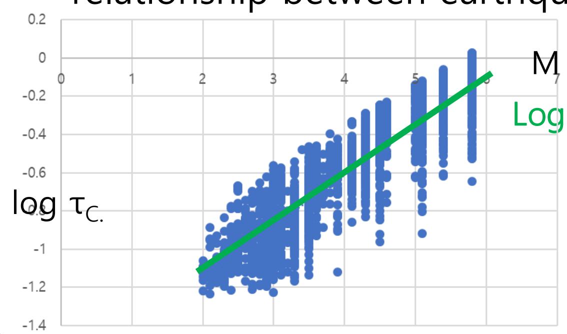
Seismic Records Refining

- **Elimination of Noises in P-waves(Background Noise, Far-field Records, Low Intensity Records, etc) and Site Correction on the Bed Rock.**

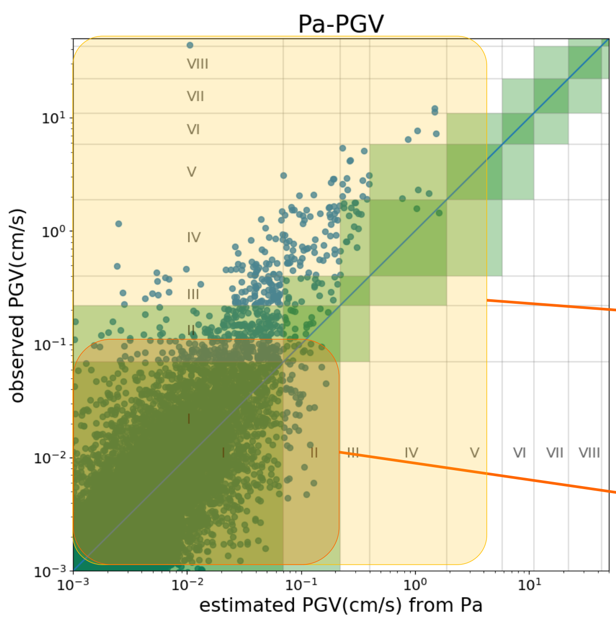


- Low quality seismic records.
→ Remove data from the seismic station more than 150 km from the epicenter.

- Long periodic ground noise
→ Eliminate excessive period of data from the relationship between earthquake magnitude and τ_C.



Log τ_C= 0.2438M - 1.3739 ± 0.0723
Accept only within a 10% margin of error in relation to the estimated τ_C and M.

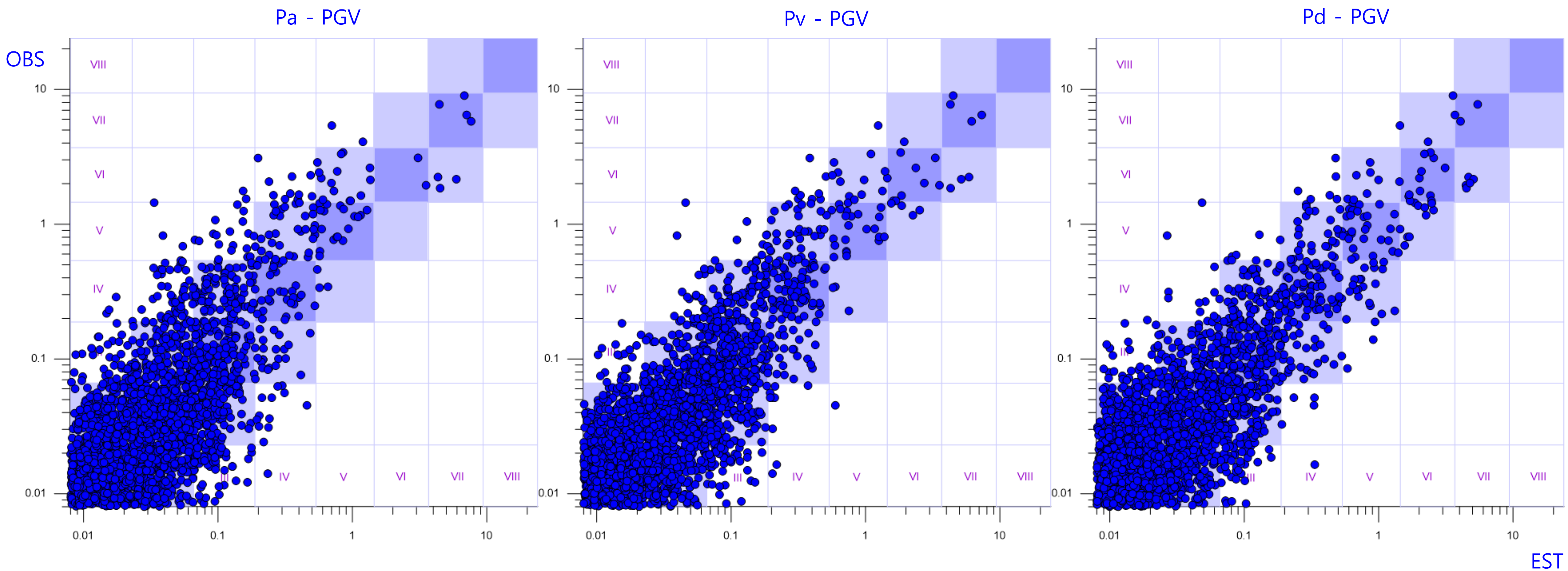


- Site correction for seismic station on the ground
→ Site response were removed using the VS30 values if the seismic station locates on the ground. (MPSS Korea ,2017).

- Data from low intensity
→ Eliminate data under the PGV of 0.02(MMI<1.5).

Derive the empirical equations for Onsite EEW(1)

- **Estimation of PGV from P-wave properties using empirical equations for raw seismic records in Korea.**



- Comparison of PGV Observations and estimations through simple linear regression for M≥2.0 seismic records and evaluation of success rate

Performance of Onsite EEW in Case 1

Derived empirical equation for Onsite EEW in Korea (M<6.0)

$$\log PGV = 0.9563(\pm 0.0257)\log Pa - 1.2503(\pm 0.0219), \quad stdv = 0.4548, \; R^2 = 0.6599$$

$$\log PGV = 0.9343(\pm 0.0225)\log Pv + 0.5404(\pm 0.0576), \quad stdv = 0.4218, \; R^2 = 0.7075$$

$$\log PGV = 0.7944(\pm 0.0196)\log Pd + 1.5297(\pm 0.0828), \quad stdv = 0.4294, \; R^2 = 0.6968$$

Evaluation of Onsite EEW Performance

MMI	False	Success	Total	Suc. Ratio
1	65	2748	2813	97.69
2	12	742	754	98.41
3	44	295	339	87.02
4	53	124	177	70.06
5	22	51	73	69.86
6	12	19	31	61.29
7	2	4	6	66.67
8	0	1	1	100.00

PGV from Pa

MMI	False	Success	Total	Suc. Ratio
1	49	2764	2813	98.26
2	8	746	754	98.94
3	25	314	339	92.63
4	20	157	177	88.70
5	11	62	73	84.93
6	8	23	31	74.19
7	1	5	6	83.33
8	0	1	1	100.00

PGV from Pv

MMI	False	Success	Total	Suc. Ratio
1	43	2770	2813	98.47
2	4	750	754	99.47
3	39	300	339	88.50
4	12	165	177	93.22
5	8	65	73	89.04
6	6	25	31	80.65
7	1	5	6	83.33
8	1	0	1	0.00

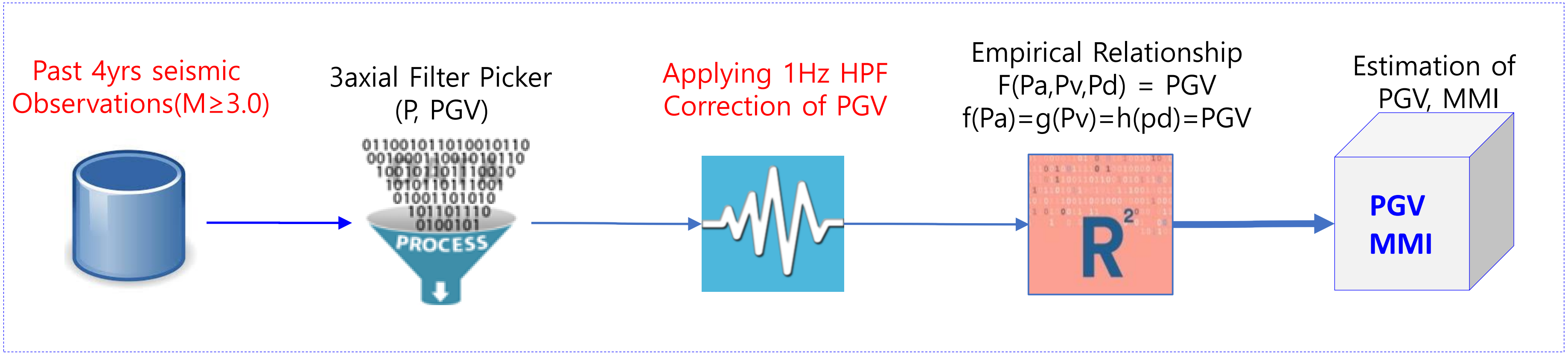
PGV from Pd

- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Case 2 ; Simple Linear & Multiple Regression of M≥3.0 Records

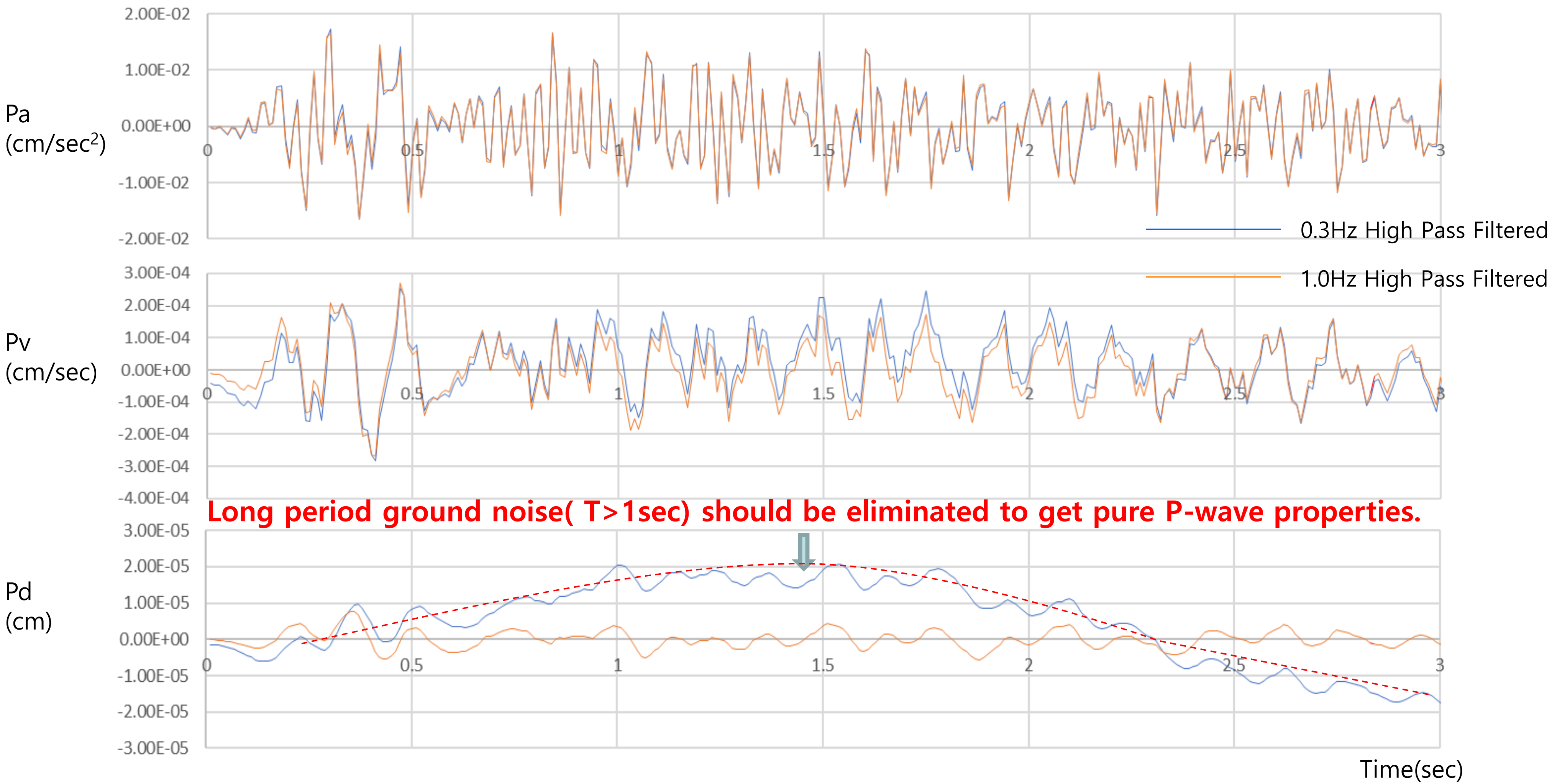
- Case 2 : **Onsite EEW through simple linear and multiple regression of M≥3.0 over the past 4yrs**

- Extracting maximim P-wave vertical amplitude (Pa, Pv, Pd) of M≥3.0 earthquake within 2 seconds of PTW.
- Simple linear and multiple regression analysis of PGV and Pa, Pv and Pd.
- Derives MMI from predicted PGV and determines and estimate the error.



Control of Ground Long-Period Noise with HPF

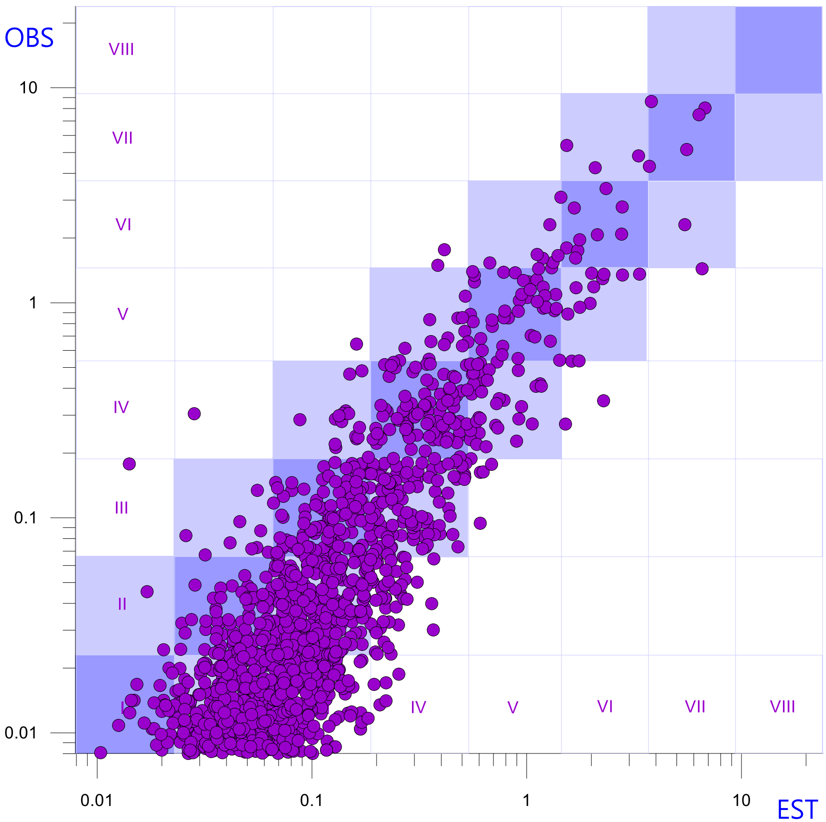
- **Comparison of P-wave vertical amplitude variation with long-period component filtering on the ground**



M3.1 , Station : CIGB.HHZ.KS, Inst. MMI : 1.0

Performance of Onsite EEW in Case 2

- **Comparison of Observed and Estimated PGV (M≥3.0, 1Hz HPF) and evaluation of EEW performance**
  - Averaged PGV estimated through simple linear regression ; **f(Pa) + g(Pv) + h(Pd) = 3 x PGV**



logPGV = 0.998(±0.011)logPa - 1.263(±0.009) stdv = 0.371 R^2 = 0.764

logPGV = 0.992(±0.009)logPv +0.536(±0.023) stdv = 0.329 R^2 = 0.814

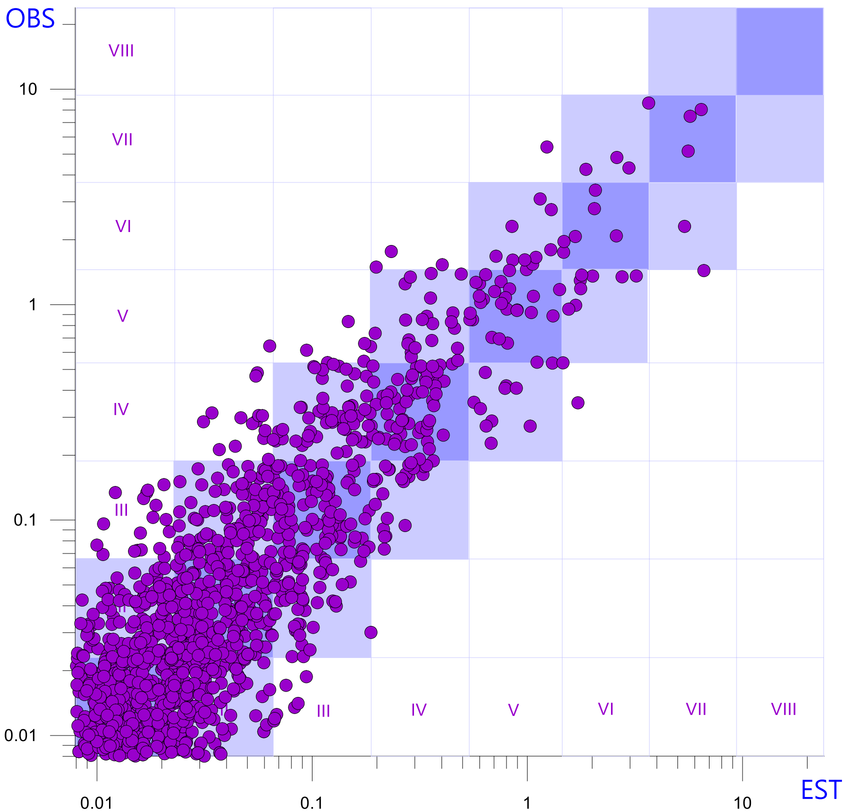
logPGV = 0.883(±0.010)logPd +1.588(±0.040) stdv = 0.386 R^2 = 0.744

MMI	False	Success	Total	Suc. Ratio
1	4	1631	1635	99.76
2	0	406	406	100.00
3	20	219	239	91.63
4	15	132	147	89.80
5	8	55	63	87.30
6	3	17	20	85.00
7	1	7	8	87.50
8	0	0	0	
9	0	0	0	
10	0	0	0	

- Comparison of PGV observations and prediction through simple linear regression for 1Hz HPF applied M≥3.0 seismic records.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Performance of Onsite EEW in Case 2

- **Comparison of Observed and Estimated PGV (M≥3.0, 1Hz HPF) and evaluation of EEW performance**
  - PGV estimated through multiple regression ; **F(Pa, Pv, Pd) = PGV**



logPGV = 0.482 + 0.195 logPa + 0.626 logPv + 0.183 logPd

stdv = 0.327 R^2 = 0.816

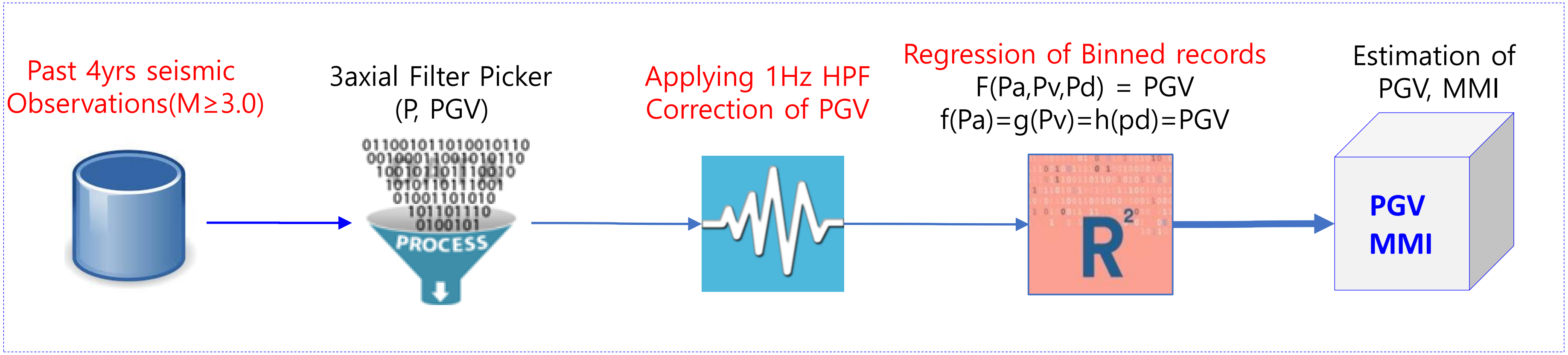
MMI	False	Success	Total	Suc. Ratio
1	7	1628	1635	99.57
2	0	406	406	100.00
3	21	218	239	91.21
4	18	129	147	87.76
5	8	55	63	87.30
6	3	17	20	85.00
7	1	7	8	87.50
8	0	0	0	
9	0	0	0	
10	0	0	0	

- Comparison of PGV observations and prediction through multiple regression for 1Hz HPF applied M≥3.0 seismic records.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Case 3 ; Simple Linear & Multiple Regression of Binned Records

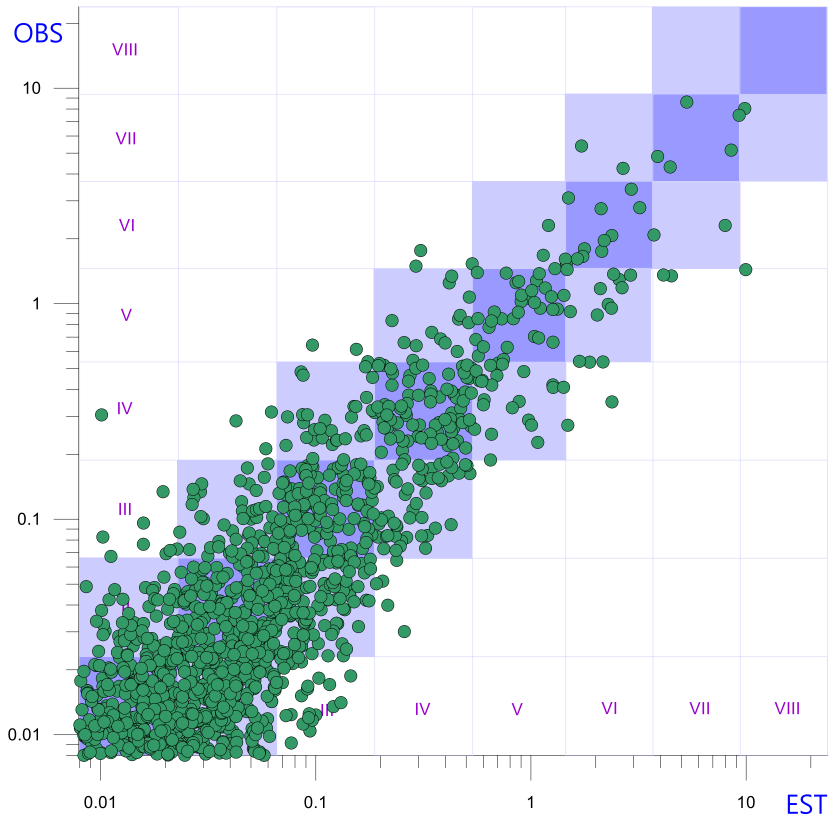
Case 3 : **Simple linear and multiple regression using seismic records binned by MMI grade.**

- Extracting maximim P-wave vertical amplitude (Pa, Pv, Pd) of M≥3.0 earthquake within 2 seconds of PTW.
- Simple linear and multiple regression analysis between PGV and Pa, Pv and Pd using binned seismic records – 200 records were binned per MMI each, and the same MMI grade of records was inputed in duplicate if the records was insufficient at each MMI grade.
- Derives MMI from predicted PGV of and determines and estimate the error.



Performance of Onsite EEW in Case 3

- **Comparison of Observed and Estimated PGV (M≥3.0 binned, 1Hz HPF) and evaluation of EEW performance**
  - Averaged PGV estimated through simple linear regression ; **f(Pa) + g(Pv) + h(Pd) = 3 x PGV**



logPGV = 1.011(±0.010)logPa - 1.038(±0.010) stdv = 0.354 R^2 = 0.872

logPGV = 1.032(±0.009)logPv +0.765(±0.014) stdv = 0.314 R^2 = 0.899

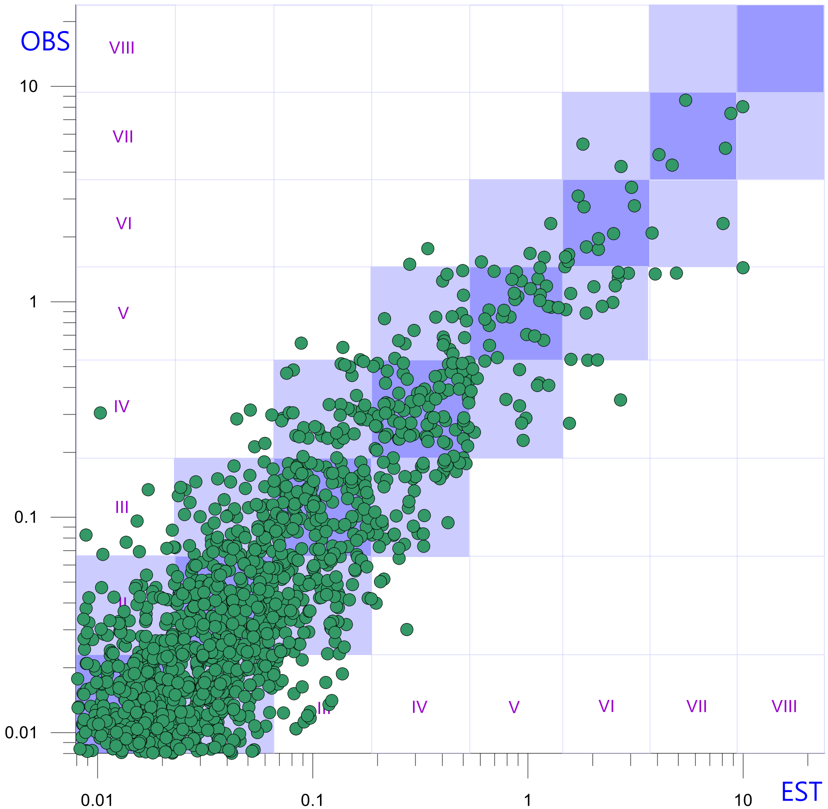
logPGV = 0.905(±0.010)logPd +1.855(±0.028) stdv = 0.365 R^2 = 0.864

MMI	False	Success	Total	Suc. Ratio	Binning EA
1	25	1466	1491	98.32	1637(200)
2	4	309	313	98.72	404(200)
3	9	182	191	95.29	239(200)
4	8	127	135	94.07	142(200)
5	6	55	61	90.16	61(200)
6	2	17	19	89.47	20(200)
7	0	8	8	100.00	8(200)
8	0	0	0		total(used)
9	0	0	0		
10	0	0	0		

- Comparison of PGV observations and prediction through simple linear regression for 1Hz HPF applied M≥3.0 seismic records binned by MMI grade.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Performance of Onsite EEW in Case 3

- **Comparison of Observed and Estimated PGV (M≥3.0 binned, 1Hz HPF) and evaluation of EEW performance**
  - PGV estimated through multiple regression ; **F(Pa, Pv, Pd) = PGV**



logPGV = 0.568 + 0.208 logPa + 0.685 logPv + 0.130 logPd

stdv = 0.130 R^2 = 0.900

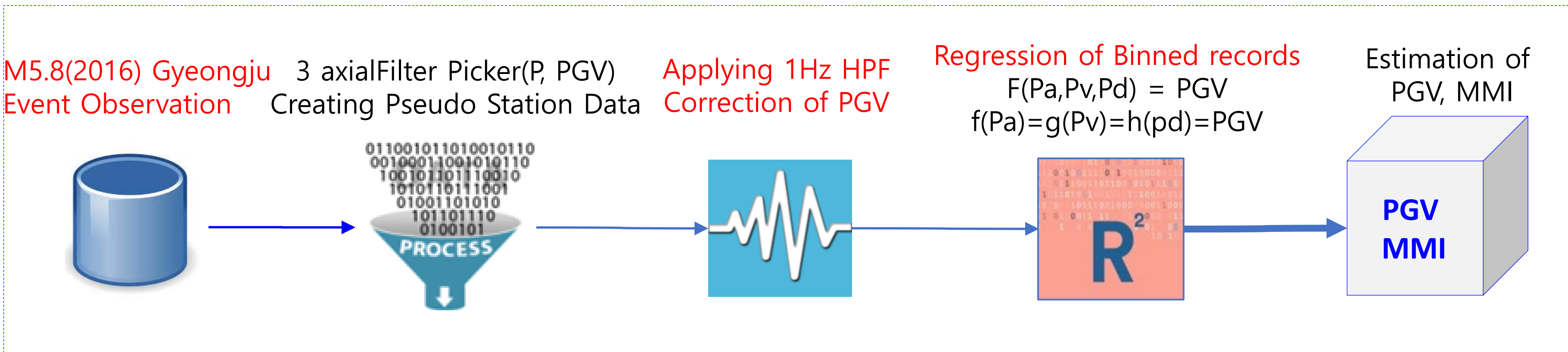
MMI	False	Success	Total	Suc. Ratio	Binning EA
1	18	1617	1635	98.90	1637(200)
2	5	401	406	98.77	404(200)
3	11	228	239	95.40	239(200)
4	10	137	147	93.20	142(200)
5	6	57	63	90.48	61(200)
6	2	18	20	90.00	20(200)
7	0	8	8	100.00	8(200)
8	0	0	0		total(used)
9	0	0	0		
10	0	0	0		

- Comparison of PGV observations and prediction through multiple regression for 1Hz HPF applied M≥3.0 seismic records binned by MMI grade.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Case 4 ; Regression using Virtual Station Records

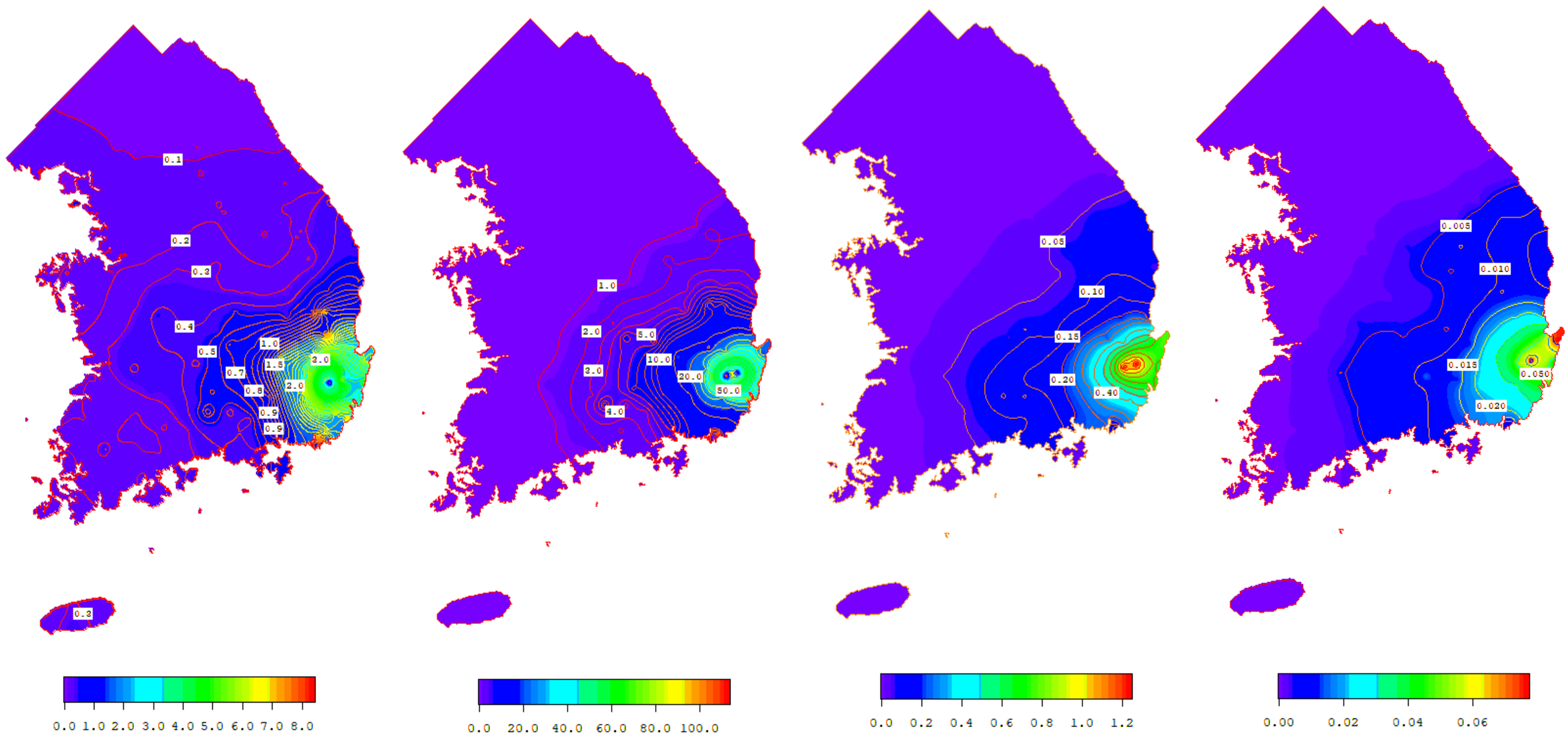
- Case 3 : **Regression using virtual station records created by interpolation of existing station records**

- M5.8 Gyeongju event(2016) produces virtual records of Pa, Pv, Pd, and PGV from a virtual station created by interpolation of observations into the Korean Peninsula. (Total 114,304 sets)
- Simple linear and multiple regression analysis between PGV and Pa, Pv and Pd using binned seismic records – 7,000 records were randomly selected and binned per MMI each except for MMI I and II.
- Derives MMI from predicted PGV of M5.4 Pohang event and determines and estimate the error.



Creating Pseudo Station Records of M5.8

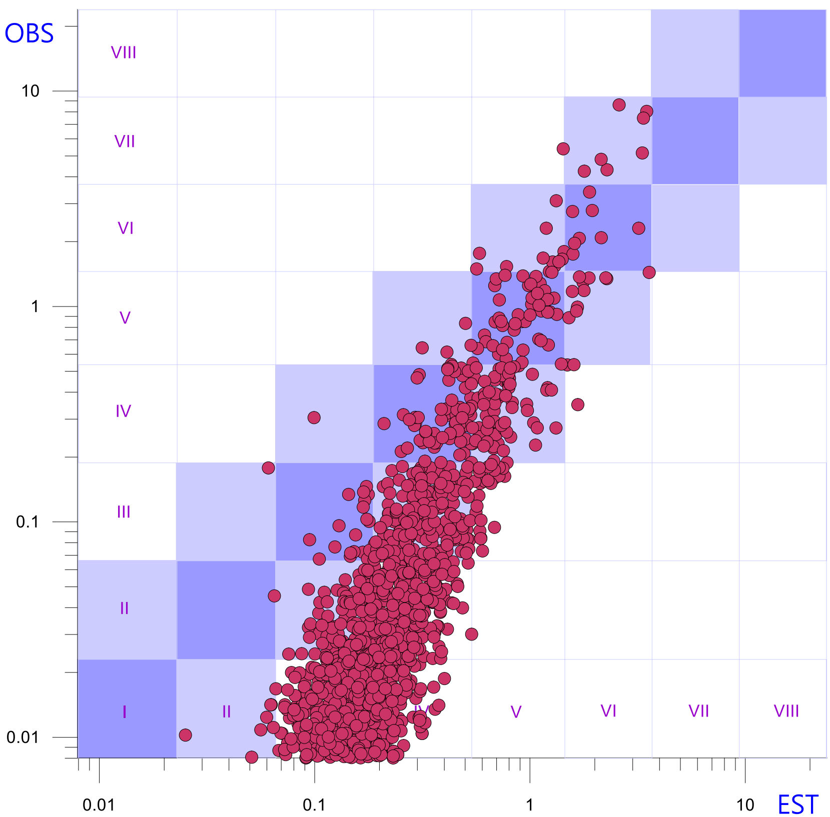
- **Generates pseudo station records by interpolation of PGV, PA, Pv, and Pd observations into 0.01 x 0.01 spatial grids on the Korean Peninsula.**



PGV(cm/sec) Pa(cm/sec^2) Pv(cm/sec) Pd(cm)

Performance of Onsite EEW in Case 4

- **Comparison of PGVs(Binned pseudo records of M5.8,1Hz HPF) and evaluation of performance**
  - Averaged PGV estimated through simple linear regression ; **f(Pa) + g(Pv) + h(Pd) = 3 x PGV**



logPGV = 0.482(±0.001)logPa - 0.400(±0.001) stdv = 0.154 R^2 = 0.915

logPGV = 0.524(±0.001)logPv +0.442(±0.002) stdv = 0.173 R^2 = 0.893

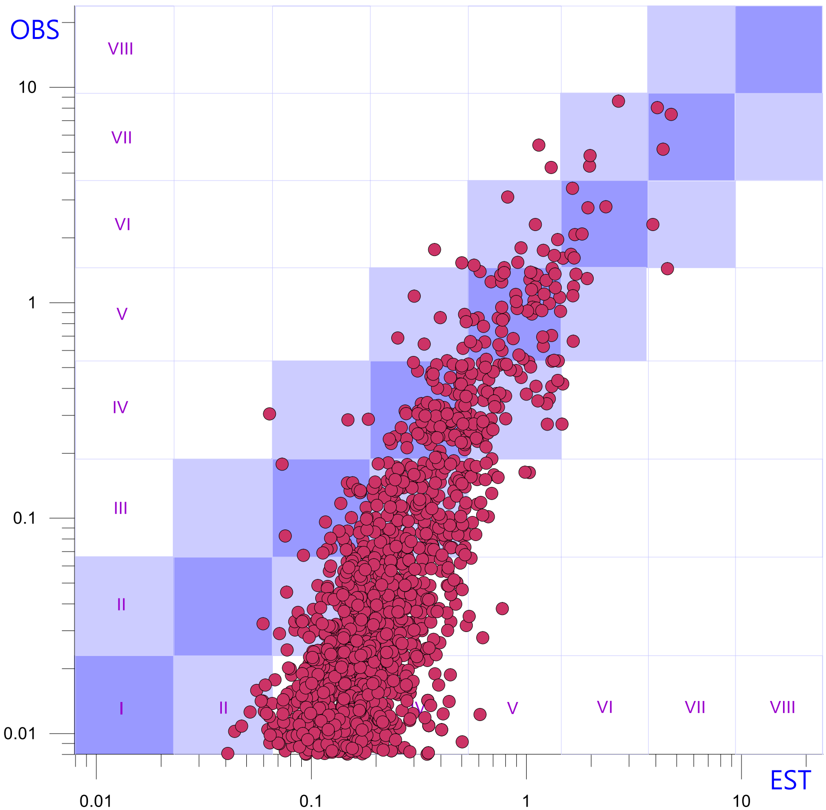
logPGV = 0.549(±0.001)logPd +1.063(±0.003) stdv = 0.190 R^2 = 0.871

MMI	False	Success	Total	Suc. Ratio	Binning EA
1	1276	359	1635	21.96	13(13)
2	270	136	406	33.50	462(462)
3	25	214	239	89.54	44,693(7,000)
4	3	144	147	97.96	49,899(7,000)
5	0	63	63	100.00	11,271(7,000)
6	0	20	20	100.00	7,251(7,000)
7	1	7	8	87.50	715(715)
8	0	0	0		total(used)
9	0	0	0		
10	0	0	0		

- Comparison of PGV observations and prediction of M5.4 earthquake through simple linear regression for 1Hz HPF applied M≥3.0 seismic records binned by MMI grade.
- Successful ratios of MMI I and II are extremely low because available records are insufficient but they have no need to warn.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Performance of Onsite EEW in Case 4

- **Comparison of PGVs(Binned pseudo records of M5.8,1Hz HPF) and evaluation of performance**
  - PGV estimated through multiple regression ; **F(Pa, Pv, Pd) = PGV**



logPGV = -0.524 + 0.876 logPa - 0.892 logPv + 0.492 logPd

stdv = 0.144 R^2 = 0.9251

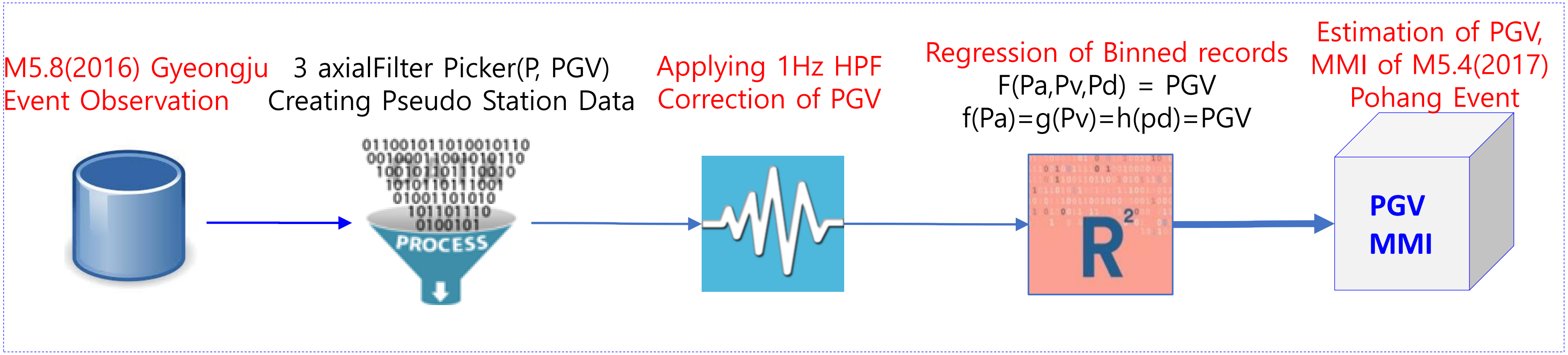
MMI	False	Success	Total	Suc. Ratio	Binning EA
1	1434	201	1635	12.29	13(13)
2	220	186	406	45.81	462(462)
3	17	222	239	92.89	44,693(7,000)
4	3	144	147	97.96	49,899(7,000)
5	1	62	63	98.41	11,271(7,000)
6	2	18	20	90.00	7,251(7,000)
7	2	6	8	75.00	715(715)
8	0	0	0		total(used)
9	0	0	0		
10	0	0	0		

- Comparison of PGV observations and predictions of M5.4 earthquake through multiple regression for 1Hz HPF applied M5.8 pseudo records binned by MMI grade.
- Successful ratios of MMI I and II are extremely low because available records are insufficient but they have no need to warn.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Case 5 ; Estimate M5.4 event using M5.8 event records

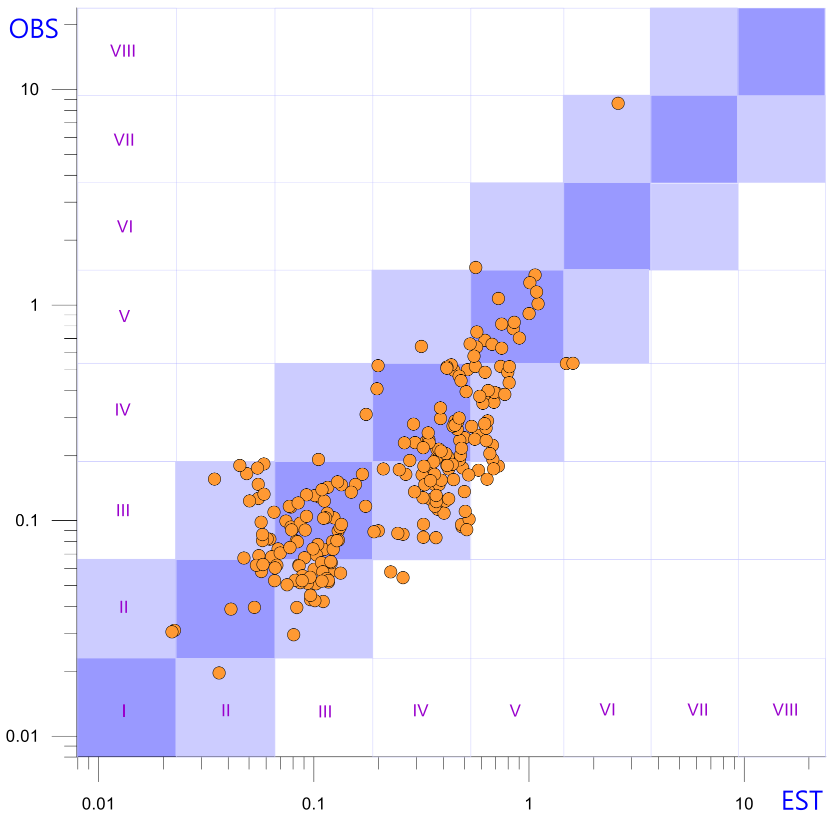
- Case 3 : **Estimate M5.4 Pohang event using pseudo records of M5.8 Gyeongju event.**

- M5.8 Gyeongju event(2016) produces virtual records of Pa, Pv, Pd, and PGV from a virtual station created by interpolation of observations into the Korean Peninsula. (Total 114,304 sets)
- Simple linear and multiple regression analysis between PGV and Pa, Pv and Pd using binned seismic records – 7,000 records were randomly selected and binned per MMI each except for MMI I and II.
- Estimate PGV of M5.4 Pohang event using pseudo records of Pa, Pv and Pd of M5.8 Gyeongju event.



Performance of Onsite EEW in Case 5

- **Comparison of PGVs of M5.4(Binned pseudo records of M5.8,1Hz HPF) and evaluation of performance**
  - Averaged PGV estimated through simple linear regression ; **f(Pa) + g(Pv) + h(Pd) = 3 x PGV**



logPGV = 0.482(±0.001)logPa - 0.400(±0.001) stdv = 0.154 R^2 = 0.915

logPGV = 0.524(±0.001)logPv +0.442(±0.002) stdv = 0.173 R^2 = 0.893

logPGV = 0.549(±0.001)logPd +1.063(±0.003) stdv = 0.190 R^2 = 0.871

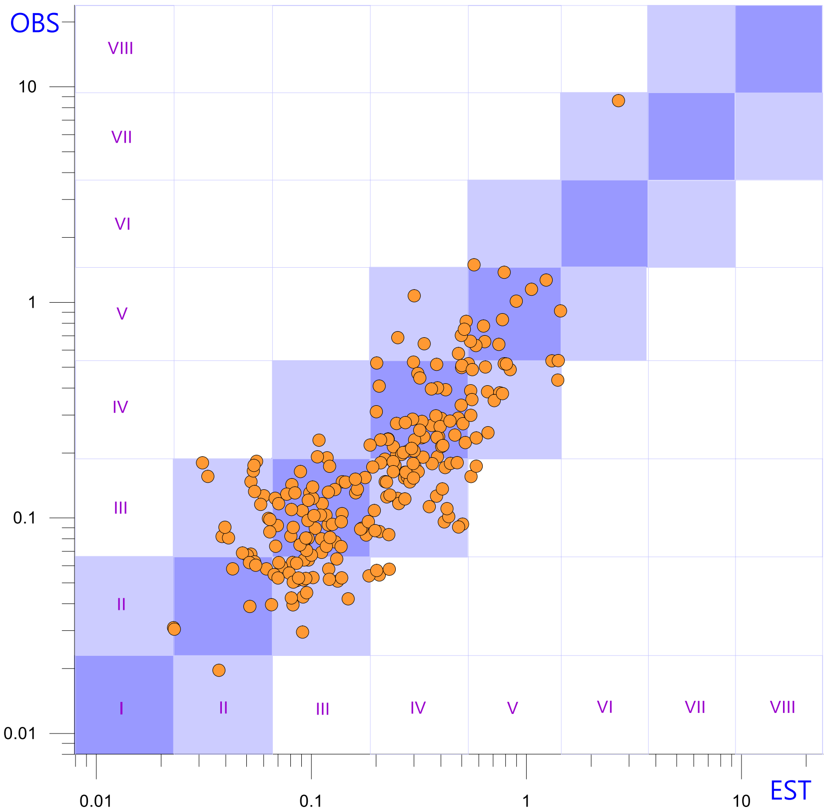
MMI	False	Success	Total	Suc. Ratio	Binning EA
1	0	2	2	100.00	13(13)
2	2	37	39	94.87	462(462)
3	4	106	110	96.36	44,693(7,000)
4	2	66	68	97.06	49,899(7,000)
5	0	18	18	100.00	11,271(7,000)
6	0	1	1	100.00	7,251(7,000)
7	0	1	1	100.00	715(715)
8	0	0	0		total(used)
9	0	0	0		
10	0	0	0		

- Comparison of PGV observations and prediction of M5.4 earthquake through simple linear regression for 1Hz HPF applied M≥3.0 seismic records binned by MMI grade.
- Successful ratios of MMI I and II are extremely low because available records are insufficient but they have no need to warn.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Performance of Onsite EEW in Case 5

- **Comparison of PGVs of M5.4(Binned pseudo records of M5.8,1Hz HPF) and evaluation of performance**

  - PGV estimated through multiple regression ; **F(Pa, Pv, Pd) = PGV**



logPGV = -0.524 + 0.876 logPa - 0.892 logPv + 0.492 logPd

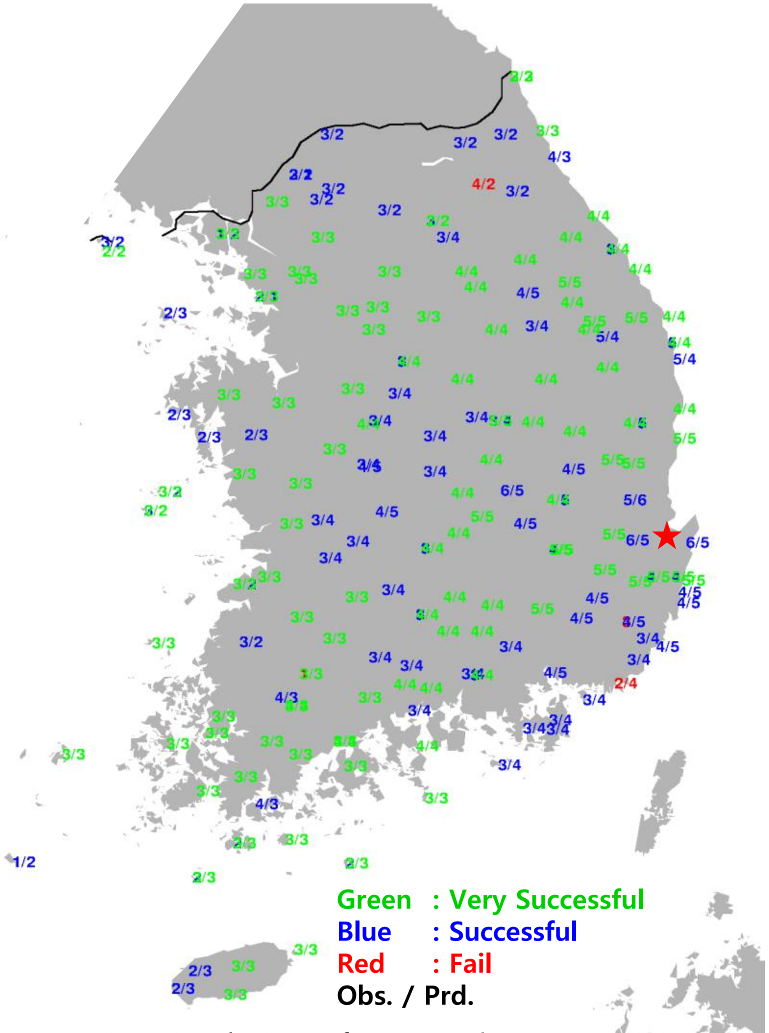
stdv = 0.144 R^2 = 0.9251

MMI	False	Success	Total	Suc. Ratio	Binning EA
1	1	1	2	50.00	13(13)
2	3	36	39	92.31	462(462)
3	2	108	110	98.18	44,693(7,000)
4	0	68	68	100.00	49,899(7,000)
5	0	18	18	100.00	11,271(7,000)
6	0	1	1	100.00	7,251(7,000)
7	0	1	1	100.00	715(715)
8	0	0	0		total(used)
9	0	0	0		
10	0	0	0		

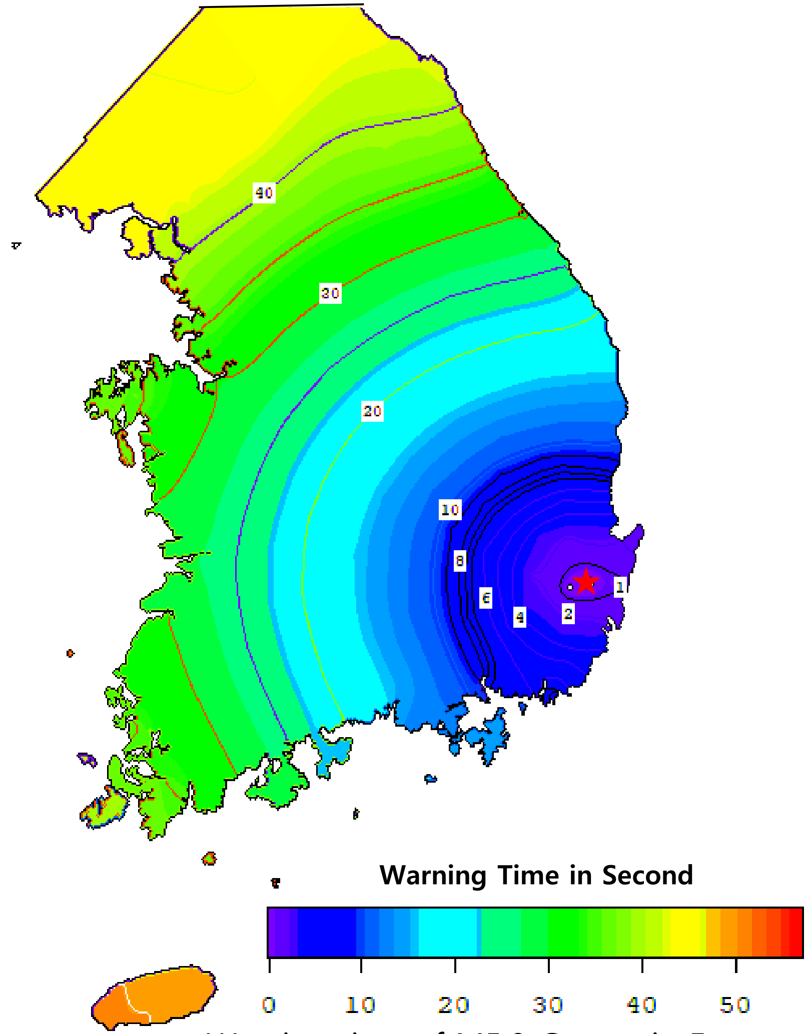
- Comparison of PGV observations and predictions of M5.4 earthquake through multiple regression for 1Hz HPF applied M5.8 pseudo records binned by MMI grade.
- Successful ratios of MMI I and II are extremely low because available records are insufficient but they have no need to warn.
- Judged successful ratio by the number of successful or false alarm within ±1 MMI scale.

Onsite Simulation of Past Events

- **Warning performance and time of M5.4 Pohang event and M5.8 Gyeongju event.**



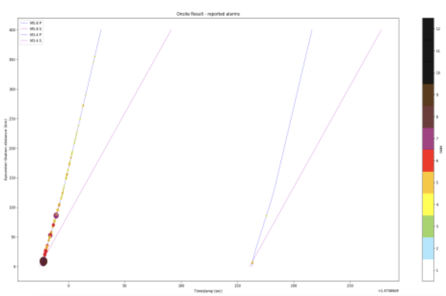
Onsite Simulation of M5.4 Pohang Event



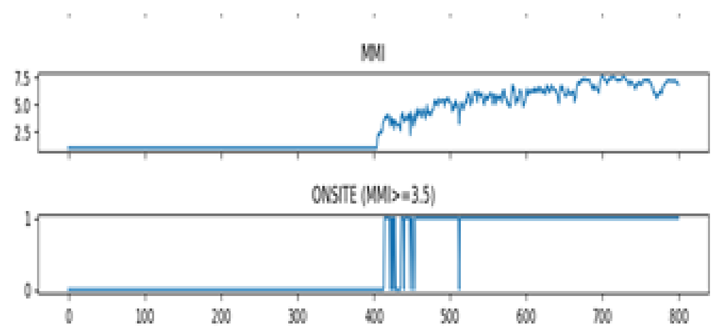
Warning time of M5.8 Gyeongju Eq.
(Time between Eq. happen and S wave arrival)

Summary

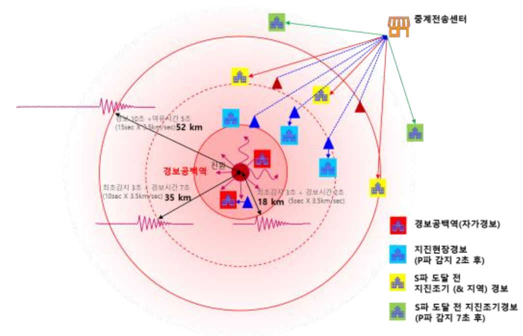
- Onsite EEWS is said to be useful for reducing blind zone and massive damages near epicenter when earthquake occurred.
- Five cases desktop tests of the on-site EEW was carried out using past 4 years seismic records in Korea.
- It was possible to detect P-waves features from seismic records using the Filter Picker rapidly and consistently.
- Useful empirical equations for the actual implementation of onsite EEWS and data sets have been arranged in Korea.
- To reduce wrong detections of P-waves and successful warning, machine learning techniques are now being applied.



Picking



Onsite estimation and judging



Warning