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A statistical investigation to determine dominant frequency of layered soil profiles

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Fundamental period
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ABSTRACT

Energy based seismic design getting attraction since it accounts for all structural (hysteretic behavior of structural members), earthquake (amplitude, duration and frequency content) and soil (bearing capacity, frequency content) characteristics. To develop an efficient energy based seismic design procedure, accurate determination of the fundamental periods of the soil deposits is crucial. Hence, several analytical, numerical and approximate methods were suggested in the literature to find out fundamental periods of layered soil profiles. However, practitioners tend to use the simplest and the roughest methods, generally. In this particular research, a statistical study was performed to find out the best fit coefficient for the total travel time having minimum standard deviation. In the analyses, the calculated fundamental periods of 459 different soil profiles are compared with the results of almost exact analytical equations. Resultantly, the equation generally preferred by the practitioners is improved. It is proved that the improved equation has higher accuracy with lowest standard deviation and higher correlation. Therefore, using the improved equation to determine fundamental period of the layered soil profiles is highly suggested.

1. INTRODUCTION

Energy-based seismic design is a promising procedure in structural and earthquake engineering since it accounts for all soil, structure and earthquake characteristics, (Güllü et al. 2019). Moreover, energy is a scalar quantity, which makes modal combinations easier. To develop an efficient energy-based design procedure, determining the dominant frequencies of soil deposits is crucial. It is also well-known for conventional design procedures that local geological conditions (especially near surface soil deposits) has a direct effect on vulnerability of structures against strong ground motions (Sextos et al. 2018). Greater input energy will be imparted to the structures having similar frequencies with the soil layers i.e. the structure will be exposed to resonance. As an example, it was reported that low- and mid-rise buildings in the Katmandu Valley almost unaffected by great 2015 Gorkha, Nepal earthquake since long period nature of the earthquake (Goda et al. 2015).

Characteristics of seismic waves (e.g. amplitude, frequency content) alter during the propagation of the wave through heterogeneous soil deposits. This phenomenon is primarily dependent on modal characteristics of the layered soil profiles. Particularly, amplification is dominant in the vicinity of the fundamental frequency of the soil deposit (Vijayendra et al. 2014).

Even though investigating the strong ground motion records is an easier and suitable way to determine the fundamental period of a soil site, finding data for any place is not possible. Hence, different procedures have been proposed in the literature for this purpose (Dobry et al.,1976; Gazetas, 1982; Zhao, 1996, 1997; Hadjian 2002; Vijayendra et al. 2014; Urzua et al., 2017; Wang et al.,2018).

Dobry et al. (1976) evaluated several numerical and approximate procedures to determine fundamental periods of layered soil profiles. The numerical method, namely Rayleigh method, provide almost exact results comparing to measured fundamental periods. However, it is fairly complex for more than two layers. Hence, a simplified version of the method was proposed by supposing constant soil density for the layers. In this method, single iteration is sufficient to catch modal shape and fundamental period of the soil profiles, Eqs. (1a-c).

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$$X\left(i+1\right)=X\left(i\right)+\frac{H-H_{mi}}{V_i^2}H_i \tag{1a}$$

$$\omega^2=4\frac{\sum\left[H-H_{mi}\right]^2\dfrac{}{V_i^2}H_i}{\sum\left[X\left(i\right)+X\left(i+1\right)\right]^2 H_i} \tag{1b}$$

$$T=\frac{2\pi}{\omega} \tag{1c}$$

In the equations, H is total depth to engineering bedrock, H_i and H_{mi} are height and the mid-depth of the i^{th} layer. Additionally, $X(i)$ and $X(i+1)$ are the first-mode shape at the top and bottom of the i^{th} soil layer.

A simple approximate method for two-layer soil which yields acceptable results was also suggested by Madera (1970). Dobry et al. (1976), improved this analytical and graphical solution considering constant density for multilayer soil profiles. Combined fundamental period for a two-layer profile, $T_{a\text{-}b}$, can be calculated by Eq. (2). In the equation ρ and h are stand for soil density and height, respectively. T_a and T_b are the fundamental periods of each soil layers.

$$\tan\left(\frac{\pi}{2}\frac{T_a}{T_{a-b}}\right)\tan\left(\frac{\pi}{2}\frac{T_b}{T_{a-b}}\right)=\frac{\rho_b h_b T_a}{\rho_a h_a T_b} \tag{2}$$

where $T_a=4\dfrac{H_a}{V_a}$ and $T_b=4\dfrac{H_b}{V_b}$.

For the application of the method to a multi-layered soil, firstly T_{a-b}^{1-2} of the top two layers should be calculated. Then, the combined fundamental period of the top three layers ($T_{a-b}^{1,2-3}$) can be calculated by considering the top two layers as a single layer with efficient fundamental period of T_{a-b}^{1-2}. Fundamental period of the multi-layered soil profile ($T_{a-b}^{1,2-n}$) can be obtained easily by repeating the process till the bottommost soil layer. Hadjian (2002) improved the Madera's method (Madera 1970) applying some algebraic manipulations on Eq. (2) and proposed a non-graphical solution.

Although the numerical methods provide accurate results, employing them is a tedious and time-consuming task for practitioners. Thus, several simple and rough methods were generated by researchers. Many practitioners preferred using Eq. (3) to determine fundamental periods of the soil profiles due to its simplicity. In the equation, H is height of soil column on the engineering bedrock, V_{avg} is weighted average shear wave velocity of the soil layers.

$$T=4\frac{H}{V_{avg}} \tag{3}$$

Increasing the accuracy of Eq. (3) through a statistical study is the rational of this paper. To serve this purpose 459 layered soil profile data is analyzed. Since the *Simplified Rayleigh method* has a remarkable accuracy (Dobry et al. 1976), results of the method were considered as *"true"* values. A novel and simple equation with lower standard deviation and higher correlation is suggested.

2. Materials and Method

The data provided by KiK-net of Japan is utilized here as the material. In the method, *true* dominant frequencies of the soil profiles, which is calculated by Eqs. (1a-b), compared with the results of varied coefficients of Eq. (3). Consequently, the coefficient having the smallest standard deviation is proposed for the quick and robust determination of the fundamental periods of the soil profiles. Details of the data set and analyzing procedures are described in the following sub-sections.

2.1. Data set

Since reaching a soil data set of Istanbul could not be possible after many attempts those were made to related division of the municipality, the detailed layered soil profile data provided by KiK-net (Kiban Kyoshin Network) of Japan (National Research Institute for Earth Science and Disaster Resilience) were utilized. KiK-net has 698 stations, and uniformly cover Japan with an average station-to-station distance of about 20 km.

Generally, fundamental periods of layer soil profiles were calculated by considering the engineering bedrock has a shear wave velocity of 760 m/sec (Ghofrani et al. 2013, Zhao et al. 2015, Wang et al. 2018) or 700 m/sec (Zhao et al., 2006; Zhao and Xu, 2013). In this study, bedrock is considered to be the depth where shear wave velocity reaches to 760 m/sec.

The data set was filtered according to following conditions in line with Wang et al. (2018);

- The data should be obtained by drilling up to engineering bedrock
- There should be at least two soil layers within the soil depth.
- Minimum shear wave velocity is accepted as 100 m/sec since low values of shear wave velocity may occur due to instrumental errors.

After filtering the data set, 459 KiK-net soil profiles were chosen to utilize in the analyses. The layered soil profiles which are *not* utilized in this study are listed in Appendix-1.

2.2. True determination of fundamental periods

Assuming constant density for the soil layers is an important characteristic of the Simplified Rayleigh method. The assumption considerably simplify the problem and it is possible to reach almost exact results by just one single iteration. According to Dobry et al. (1976), Simplified Rayleigh method differs only a few percent from the correct value. Thus, the results of the method can be accepted as true values for fundamental period calculations of layered soil profiles.

The parameters of the method (*V_i*, *H_i*, *H* and *H_{mi}*) are considered layer by layer starting from the bottom of the soil profile. At the lower boundary of the bottommost layer, *X_i* is taken as zero i.e., $X_i = X_1 = 0$. Once all *X_i* values are computed by Eq. (1a), fundamental circular frequencies of the soil profile can be calculated by Eq. (1b). Then, it can be converted to the period, easily. Fundamental period calculation of the soil profiles ABSH03 and CHBH06 by means of Simplified Rayleigh method, are given in Table 1. In the third column of the table, total depths (*H*) of the soil profiles are given. The fourth and fifth columns are the depth of each layer (*H_i*) and depth of center of each layer (*H_{mi}*). The seventh column is the measured shear wave velocity of the layers. Other columns are calculated by using the data given in these columns.

Table 1. Fundamental period calculation examples by simplified Rayleigh method.

Sta. ID	Layer #	H (m)	H_i (m)	H_{mi} (m)	$H-H_{mi}$ (m)	$V_{s,i}$ (m/s)	X_i ($\times10^{-4}$)	$(X_i+X_{i+1})^2\times H_i$ ($\times10^{-7}$)	$(H-H_{mi})^2\times H_i/V_{s,i}^2$ ($\times10^{-4}$)
ABSH03	1	12	6	3	9.00	640	1.318	1.042	11.865
	2		4	8	4.00	310	2.983	7.402	6.659
	3		2	11	1.00	100	4.983	12.693	2
							Σ=	21.13781	20.52496
								ω (Hz)=	*62.321*
								T (sec)=	*0.101*

Sta. ID	Layer #	H (m)	H_i (m)	H_{mi} (m)	$H-H_{mi}$ (m)	$V_{s,i}$ (m/s)	X_i ($\times10^{-2}$)	$(X_i+X_{i+1})^2\times H_i$ ($\times10^{-1}$)	$(H-H_{mi})^2\times H_i/V_{s,i}^2$ ($\times10^{0}$)
CHBH06	1	165	35.00	17.50	147.50	460	2.44	0.208	3.599
	2		38.00	54.00	111.00	440	4.619	1.893	2.418
	3		38.00	92.00	73.00	400	6.352	4.574	1.266
	4		36.00	129.00	36.00	360	7.352	6.761	0.36
	5		13.00	153.50	11.50	200	7.726	2.956	0.043
	6		5.00	162.50	2.50	180	776.45	1.2	0.001
							Σ=	17.592	7.687
								ω (Hz)=	*4.181*
								T (sec)=	*1.503*

2.3. Statistical Study

Fundamental period values of 459 KiK-net stations are calculated by a fully-automatic MATLAB code which was developed in this study. The fully automatic algorithm calculates the *true* fundamental periods based on Simplified Rayleigh method, initially. Secondly, the predicted fundamental periods for each *i^{th}* total travel time coefficient of average shear wave velocity are calculated. The difference of the true and predicted periods is nominated as the residuals. Henceforth, standard deviations of the residuals of 459 KiK-net data are calculated for each coefficient between 2.0 to 5.0 with 0.01 increments. The coefficient having the minimum standard deviation for residuals with highest correlation coefficients is considered to be the best-fit coefficient. Totally, 459×301=138159 calculations are performed in the content of this study. It is worth to note that in the mostly preferred equation by practitioners, the coefficient of the total travel time of shear wave was 4, see Eq. (3).

Hereafter, relative difference (*Rel. Dif.*) for each data is calculated by Eq. (4) where *$T_{calculated}$* and *T_{true}* correspond to determined fundamental periods of the soil layers by different coefficients of Eq. (3) and Simplified Rayleigh method, Eq. (1c), respectively.

$$\text{Rel. Dif.} = \frac{\left|T_{calculated} - T_{true}\right|}{T_{true}} \tag{4}$$

Relative differences and their mean values of the original and proposed equations are also compared in the study.

3. RESULTS

Variation of the standard deviations of residuals with the coefficients for travel time of average shear wave (from bedrock to surface) is depicted in Figure 1.

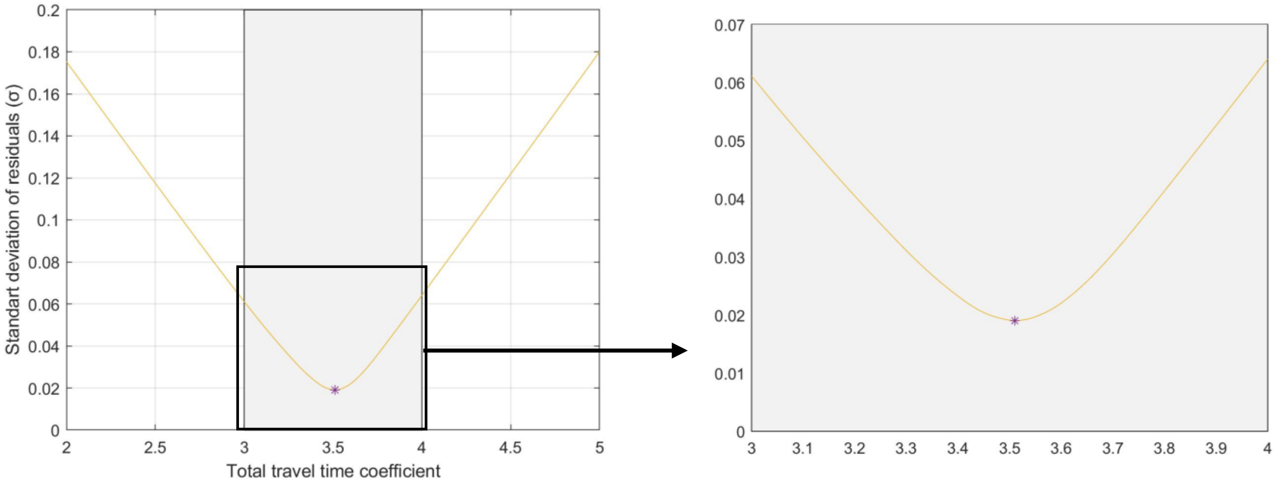


Figure 1. Variation of the standard deviation of the residuals for diverse total travel time coefficients of V_{avg}

The minimum standard deviation is obtained to be 0.019 for the coefficient of 3.51. Changing the coefficient of the equation simply with 3.51 will yield significantly lower standard deviation (~%336) and increase the reliability of the equation.

Mean value and standard deviation of the residuals are given in Table 2 for the coefficients of 3.51 and the original value of 4.00.

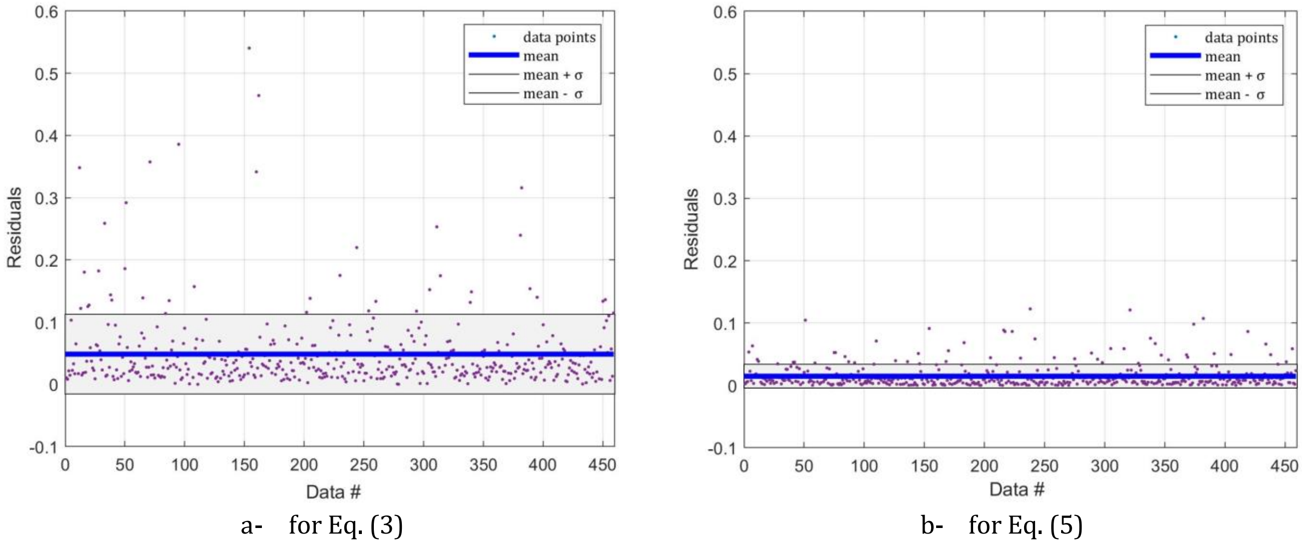
Table 2. Mean value and standard deviations of the residuals obtained by the proposed and original coefficients.

Equation	Mean value	Standard deviation
3.51 H/V_s	0.0147	0.0191
4.00 H/V_s	0.0487	0.0641

The correlation coefficient calculated for the *true* periods and the periods determined for the case of total travel time of shear velocity coefficient of 3.51 was found to be 0.998. The obtained correlation coefficient between the two series is extremely high. Therefore, Eq. (5) is proposed to determine fundamental periods of the layered soil profiles.

$$T = 3.51\frac{H}{V_{avg}} \tag{5}$$

In the second step, absolute residuals of each data point are plotted for the coefficients of 3.51 and 4.00 in Figures 2a-b. In the figures, mean value ± one standard deviation ranges are also depicted with gray color. Using the coefficient of 3.51 instead of 4.00, considerably reduced the scattering area of the residuals. Additionally, highest absolute residuals are obtained as 0.12 for the proposed coefficient and 0.54 for the original coefficient of 4.00.



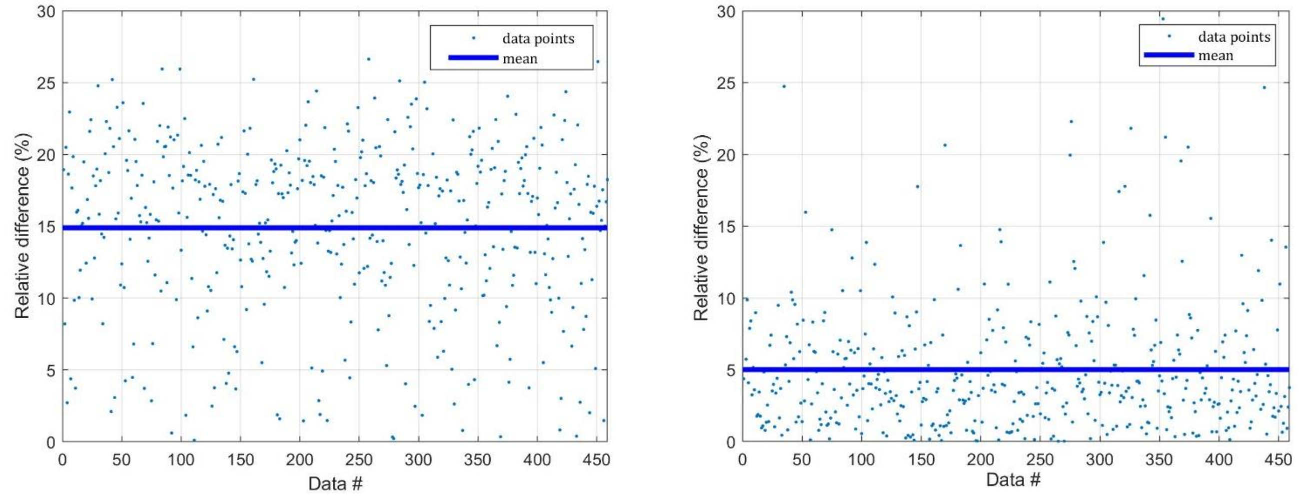
a- for Eq. (3)

b- for Eq. (5)

Figure 2. Calculated absolute residuals

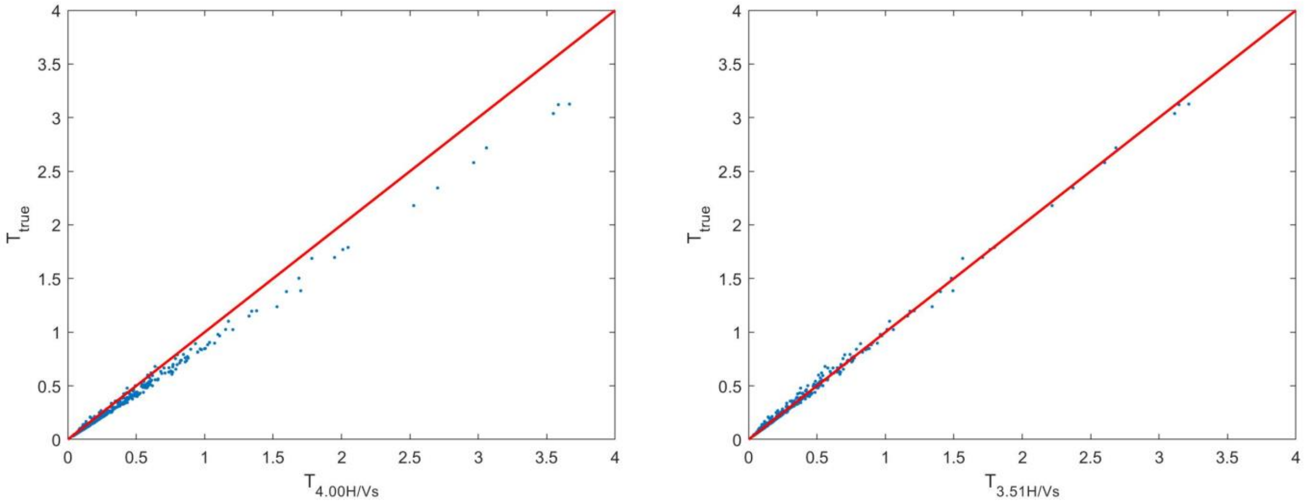
These statistical results show that the newly proposed equation, Eq. (5), provides better correlation with the true results. To be able to show the difference of proposed formula and the original one, relative differences of Eqs. (3) and (5) with respect to Simplified Rayleigh method are illustrated for the all stations considered in this study, Figure 3. Average relative difference is reduced to almost 5% from 15% by using Eq. (5).

Finally, the predicted dominant periods are compared with the true ones in Figure 4. As it was expected, soft soils have longer fundamental periods while the value is quite shorter for stiff soils. It is clear that the proposed equation has superior performance to capture *true* dominant period.



a- for Eq. (3) b- for Eq. (5)

Figure 3. Calculated relative differences



a- for Eq. (3) b- for Eq. (5)

Figure 4. Comparisons of the previous and the proposed equations with *true* period

Based on the performed statistical analyses, it can be said that the proposed equation, Eq. (5), yields more concrete results with similar simplicity.

4. CONCLUSION

Fundamental period of the layer soil profiles is a crucial parameter for the earthquake resistant design of structures and energy based seismic design. Due to the difficulty of applying numerical methods to the calculation of fundamental periods of soils, many simple formulas exist in the literature for practitioners. The roughest and the simplest equation, Eq. (3), is mostly preferred by the practitioners. Although this formula may give adequate results for some specific cases, it has a great standard deviation and approximately 15% error in average. In this study, a statistical study is applied to find out a better coefficient for total travel time (H/V_{avg}) by utilizing the KiK-net database of Japan. The proposed formula gives better results with smaller standard deviation, higher correlation coefficient and it has only 5% mean relative difference with respect to true results. Moreover, the proposed equation has the same simplicity with the existing equation. Hence, using the proposed equation instead of the existing one is highly suggested. It is worth to remind that the study based on solely the KiK-net data. So, an amount of discrepancy may arise for some specific soil profiles which is not represented in this data set.

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APPENDIX Soil data which is not utilized in the study

Site Code	Site Name	Latitude	Longitude	Altitude (m)	Depth (m)	Prefecture	Seismo-graph	Notes
ABSH02	OKOPPE-W	44.4234	143.0264	38	113	HOKKAIDO	KiK-net06	
ABSH04	TAKINOUE-N	44.192	143.0767	134	200	HOKKAIDO	KiK-net06	
ABSH11	MEMAMBETSU	43.9144	144.1913	40	122	HOKKAIDO	KiK-net11B	
ABSH12	KOSHIMIZU	43.8566	144.4574	25	120	HOKKAIDO	KiK-net06	
AICH05	TOKONAME	34.8886	136.8763	50	401	AICHIKEN	---	suspension
AICH13	KIYOSU	35.2177	136.8509	5	741	AICHIKEN	KiK-net06	
AICH15	ASUKE	35.1392	137.3359	150	120	AICHIKEN	KiK-net11B	
AKTH02	NISHIKI-S	39.6634	140.5721	95	100	AKITAKEN	KiK-net06	
AKTH03	YAJIMA	39.2223	140.1283	145	103	AKITAKEN	KiK-net11A	
AKTH05	CHOKAI	39.0718	140.3185	275	200	AKITAKEN	KiK-net06	
AKTH07	KOSAKA	40.4563	140.8395	405	105	AKITAKEN	KiK-net06	
AKTH09	TASHIRO	40.2755	140.4596	45	101	AKITAKEN	KiK-net06	
AKTH10	ODATE	40.3002	140.5812	85	100	AKITAKEN	KiK-net06	
AKTH16	NISHISEMBOKU	39.545	140.3481	20	154	AKITAKEN	KiK-net06	
AKTH18	OMORI	39.3548	140.3869	65	100	AKITAKEN	KiK-net06	
AOMH01	OMA	41.5273	140.9127	10	100	AOMORIKEN	KiK-net06	
AOMH03	KAWAUCHI	41.234	140.9896	20	100	AOMORIKEN	KiK-net11C	
AOMH04	AOMORI	40.8524	140.6759	10	307	AOMORIKEN	KiK-net06	
AOMH08	AJIGASAWA	40.7618	140.3121	50	160	AOMORIKEN	KiK-net06	
AOMH11	TOWADAKO-W	40.58	140.995	240	100	AOMORIKEN	KiK-net06	
AOMH12	TOWADAKO-E	40.5846	141.1547	85	100	AOMORIKEN	KiK-net06	
AOMH13	HACHINOHE	40.5794	141.4451	10	150	AOMORIKEN	KiK-net11C	
AOMH16	SHINGO	40.4624	141.0923	315	150	AOMORIKEN	KiK-net06	
CHBH04	SHIMOSA	35.7966	140.0206	23	2300	CHIBAKEN	KiK-net06	
CHBH10	CHIBA	35.5458	140.2417	65	2000	CHIBAKEN	KiK-net06	
CHBH11	YORO	35.2867	140.1529	80	2000	CHIBAKEN	KiK-net06	
CHBH12	FUTTSU	35.3445	139.8554	3	2000	CHIBAKEN	KiK-net11C	
CHBH13	NARITA	35.8307	140.298	12	1300	CHIBAKEN	KiK-net06	
CHBH14	CHOSHI-C	35.7342	140.823	2	525	CHIBAKEN	KiK-net11A	
CHBH15	TATEYAMA-W	34.9591	139.7885	30	500	CHIBAKEN	KiK-net11A	
CHBH19	HASUNUMA	35.5943	140.5107	1	1630	CHIBAKEN	KiK-net06	
CHBH20	KAMOGAWA-S	35.0882	140.0997	28	306	CHIBAKEN	KiK-net11B	
EHMH01	TSUSHIMA	33.0556	132.5552	375	100	EHIMEKEN	KiK-net11A	
EHMH04	TAMBARA	33.9023	133.0658	15	200	EHIMEKEN	KiK-net11A	
EHMH12	UWA	33.427	132.5055	250	150	EHIMEKEN	KiK-net11B	
EHMH13	MISAKI	33.3719	132.1157	10	222	EHIMEKEN	KiK-net18	
FKIH01	EIHEIJI	36.0955	136.3617	65	100	FUKUIKEN	KiK-net06	
FKOH04	KAHO	33.5512	130.7451	60	100	FUKUOKAKEN	KiK-net18	
FKOH05	SAIGAWA	33.5293	130.9503	370	100	FUKUOKAKEN	KiK-net18	
FKOH06	BUZEN	33.5925	131.1348	35	303	FUKUOKAKEN	KiK-net11C	
FKOH10	UKIHA	33.2891	130.817	190	200	FUKUOKAKEN	KiK-net11B	
FKSH15	INAWASHIRO	37.6461	140.1735	757	100	FUKUSHIMAKEN	KiK-net06	
FKSH16	FUKUSHIMA	37.7643	140.3766	135	300	FUKUSHIMAKEN	KiK-net11A	
FKSH17	KAWAMATA	37.6636	140.5974	205	100	FUKUSHIMAKEN	KiK-net06	
FKSH20	NAMIE	37.4911	140.9871	12	109	FUKUSHIMAKEN	KiK-net06	
GIFH04	FURUKAWA	36.2448	137.1983	572	100	GIFUKEN	KiK-net11A	
GIFH05	SHOKAWA	36.0654	136.9479	839	100	GIFUKEN	KiK-net11A	
GIFH14	KAMITAKARA	36.2493	137.5174	810	100	GIFUKEN	KiK-net18	

GIFH16	ASAHI-N	36.094	137.3438	790	100	GIFUKEN	KiK-net18
GIFH18	MAZE	35.8991	137.1495	570	107	GIFUKEN	KiK-net11A
GIFH20	GERO-N	35.7991	137.2531	355	128	GIFUKEN	KiK-net18
GIFH21	MINAMI	35.6665	136.9618	170	200	GIFUKEN	KiK-net18
GIFH22	KANAYAMA	35.6682	137.1054	435	100	GIFUKEN	KiK-net18
GNMH05	ISESAKI	36.3143	139.1847	57	2000	GUNMAKEN	KiK-net11A
GNMH06	TATEBAYASHI	36.2441	139.5443	20	1203	GUNMAKEN	KiK-net06
GNMH07	TONE	36.6998	139.2104	646	200	GUNMAKEN	KiK-net11B
GNMH14	MIDORI	36.4931	139.3219	360	200	GUNMAKEN	KiK-net11A
HDKH03	MOMBETSU-E	42.5934	142.3521	160	106	HOKKAIDO	KiK-net06
HRSH03	MITSUGI	34.5183	133.1375	160	200	HIROSHIMAKEN	KiK-net11A
HRSH04	NUMAKUMA	34.3785	133.3493	25	200	HIROSHIMAKEN	KiK-net11A
HRSH12	HIROSHIMA	34.581	132.4295	360	150	HIROSHIMAKEN	KiK-net11C
HRSH17	TOGOUCHI	34.5716	132.2326	265	102	HIROSHIMAKEN	KiK-net11C
IBRH06	KITAIBARAKI2	36.8809	140.6545	395	100	IBARAKIKEN	KiK-net11
IBRH07	EDOSAKI	35.9521	140.3301	3	1200	IBARAKIKEN	KiK-net11A
IBRH08	TAIYO	36.1188	140.5621	40	1200	IBARAKIKEN	KiK-net06
IBRH09	JOHOKU	36.439	140.3559	50	106	IBARAKIKEN	KiK-net11C
IBRH15	GOZENYAMA	36.5566	140.3013	45	107	IBARAKIKEN	KiK-net11B
IBRH19	TSUKUBA	36.2137	140.0893	175	210	IBARAKIKEN	KiK-net06
IBRH21	TSUKUBA-S	35.9814	140.105	22	929	IBARAKIKEN	KiK-net06
IBUH03	ATSUMA	42.6486	141.8641	10	153	HOKKAIDO	KiK-net06
IKRH02	SHINSHINOTSU	43.2204	141.6523	10	127	HOKKAIDO	KiK-net06
ISKH01	SUZU	37.5266	137.2844	48	200	ISHIKAWAKEN	KiK-net06
ISKH02	YANAGIDA	37.3644	137.0413	121	102	ISHIKAWAKEN	KiK-net11C
ISKH06	SHIKA	37.0533	136.8206	20	200	ISHIKAWAKEN	KiK-net11A
IWTH03	IWAIZUMI	39.802	141.652	310	100	IWATEKEN	KiK-net11C
IWTH06	NINOHE-W	40.2611	141.1709	225	100	IWATEKEN	KiK-net06
IWTH07	KARUMAI	40.2705	141.5709	260	120	IWATEKEN	KiK-net06
IWTH09	KUJI-S	40.0861	141.712	240	100	IWATEKEN	KiK-net06
IWTH15	YAHABA	39.6148	141.0929	195	122	IWATEKEN	KiK-net06
IWTH17	KAWAI-N	39.6442	141.5977	305	103	IWATEKEN	KiK-net11C
IWTH20	HANAMAKI-S	39.3434	141.0473	106	156	IWATEKEN	KiK-net11C
IWTH24	KANEGASAKI	39.1979	141.0118	200	150	IWATEKEN	KiK-net11C
IWTH26	ICHINOSEKI-E	38.969	141.0013	125	108	IWATEKEN	KiK-net11C
IWTH27	RIKUZENTAKATA	39.0307	141.532	80	100	IWATEKEN	KiK-net11C
KGSH03	MIYANOJO	31.9812	130.4438	110	100	KAGOSHIMAKEN	KiK-net06
KGSH04	SENDAI	31.8374	130.3602	14	100	KAGOSHIMAKEN	KiK-net11C
KGSH05	KEDOIN	31.8699	130.4958	73	107	KAGOSHIMAKEN	KiK-net06
KGSH06	KORIYAMA	31.6988	130.4594	131	203	KAGOSHIMAKEN	KiK-net06
KGSH07	AIRA	31.714	130.6149	6	302	KAGOSHIMAKEN	KiK-net11C
KGSH08	OHSUMI	31.5618	130.9969	97	150	KAGOSHIMAKEN	KiK-net06
KGSH13	KANOYA	31.4005	130.8541	40	101	KAGOSHIMAKEN	KiK-net06
KGWH03	MIKI	34.27	134.1482	50	100	KAGAWAKEN	KiK-net11A
KGWH05	UCHINOMI	34.4572	134.3241	20	433	KAGAWAKEN	KiK-net11B
KKWH01	BIFUKA-N	44.5973	142.3036	61	111	HOKKAIDO	KiK-net06
KKWH03	BIFUKA-W	44.4732	142.2725	100	100	HOKKAIDO	KiK-net06
KKWH04	NAYORO	44.4376	142.4056	84	100	HOKKAIDO	KiK-net06
KKWH05	SHIMOKAWA-W	44.2921	142.6303	160	300	HOKKAIDO	KiK-net06
KKWH06	SHIMOKAWA-E	44.3207	142.7656	200	100	HOKKAIDO	KiK-net06
KKWH12	BIEI-E	43.5038	142.6006	450	207	HOKKAIDO	KiK-net11B

KMMH04	ASO	32.9514	131.0199	475	127	KUMAMOTOKEN	---	suspension
KMMH07	MISUMI	32.6234	130.5584	22	300	KUMAMOTOKEN	KiK-net11B	
KMMH11	ASHIKITA	32.2918	130.5777	100	300	KUMAMOTOKEN	KiK-net11B	
KMMH17	TAMANA	32.9873	130.5608	55	100	KUMAMOTOKEN	KiK-net11B	
KMMH18	ASO2	33.0031	131.0071	932	78	KUMAMOTOKEN	KiK-net11B	
KNGH10	YOKOHAMA	35.4991	139.5195	62	2000	KANAGAWAKEN	KiK-net06	
KNGH11	ATSUGI	35.404	139.3539	12	1800	KANAGAWAKEN	KiK-net06	
KNGH21	KIYOKAWA	35.4628	139.2146	455	210	KANAGAWAKEN	KiK-net11A	
KOCH02	GOHOKU	33.7079	133.3641	590	100	KOCHIKEN	KiK-net11A	
KOCH04	OTSUKI	32.8414	132.7066	55	100	KOCHIKEN	KiK-net11A	
KOCH05	IKEKAWA	33.6472	133.1444	260	100	KOCHIKEN	KiK-net11A	
KOCH06	NAKAMURA	33.0754	132.9524	31	100	KOCHIKEN	KiK-net11A	
KOCH09	KAHOKU	33.6748	133.8243	190	100	KOCHIKEN	KiK-net11B	
KOCH11	MUROTO	33.2866	134.1603	90	300	KOCHIKEN	KiK-net11B	
KSRH01	AKAN-N	43.4361	144.0844	431	106	HOKKAIDO	KiK-net11B	
KSRH02	AKAN-S	43.1142	144.123	30	105	HOKKAIDO	KiK-net06	
KSRH03	SHIBECHA-N	43.3848	144.6279	83	107	HOKKAIDO	KiK-net06	
KSRH04	SHIBECHA-S	43.2139	144.6804	30	240	HOKKAIDO	KiK-net11A	
KSRH06	TSURUI-E	43.22	144.4285	30	237	HOKKAIDO	KiK-net06	
KSRH07	TSURUI-S	43.1359	144.3274	38	222	HOKKAIDO	KiK-net11B	
KSRH08	SHIRANUKA-N	43.1603	143.8936	174	100	HOKKAIDO	KiK-net06	
KSRH09	SHIRANUKA-S	42.9856	143.9841	27	100	HOKKAIDO	KiK-net06	
KSRH10	HAMANAKA	43.2084	145.1168	31	255	HOKKAIDO	KiK-net11B	
KYTH04	MIYAMA	35.2685	135.5508	190	100	KYOTOFU	KiK-net18	
KYTH07	KUMIYAMA	34.8983	135.7461	11	800	KYOTOFU	KiK-net18	
MIEH08	MATSUSAKA	34.5424	136.5033	35	150	MIEKEN	KiK-net11B	
MYGH04	TOWA	38.786	141.3254	35	100	MIYAGIKEN	KiK-net06	
MYGH07	KAWASAKI	38.1802	140.6405	186	142	MIYAGIKEN	KiK-net11	
MYGH08	IWANUMA	38.1133	140.8441	10	100	MIYAGIKEN	KiK-net11C	
MYGH12	SHIZUGAWA	38.6416	141.4428	18	102	MIYAGIKEN	---	suspension
MYGH14	RIFU	38.34	140.9551	48	1034	MIYAGIKEN	KiK-net11	
MYZH05	NANGO	32.347	131.2668	353	100	MIYAZAKIKEN	KiK-net06	
MYZH06	TOGO	32.3607	131.4643	100	100	MIYAZAKIKEN	KiK-net11C	
MYZH09	SUKI	32.0421	131.0618	335	100	MIYAZAKIKEN	KiK-net11C	
MYZH16	NOBEOKA	32.506	131.6958	2	100	MIYAZAKIKEN	KiK-net06	
NARH02	TOTSUKAWA-E	33.9692	135.8574	480	100	NARAKEN	KiK-net11A	
NARH06	YAMAZOE	34.6413	136.0512	277	101	NARAKEN	KiK-net11A	
NGNH07	NAKANO	36.7434	138.376	378	200	NAGANOKEN	KiK-net06	
NGNH09	TAKESHI	36.2859	138.2491	605	100	NAGANOKEN	KiK-net06	
NGNH12	MINAMIMAKI	35.9696	138.4797	1320	206	NAGANOKEN	KiK-net06	
NGNH22	HASE	35.7946	138.0824	820	100	NAGANOKEN	KiK-net06	
NGNH27	SHINSHUSHIN	36.577	138.0479	505	102	NAGANOKEN	KiK-net06	
NGNH34	OHMACHI-C	36.5327	137.8201	825	106	NAGANOKEN	KiK-net06	
NGNH54	IIDA	35.4489	138.0058	1168	104	NAGANOKEN	KiK-net06	
NGSH02	SASEBO-N	33.2122	129.7652	140	112	NAGASAKIKEN	KiK-net18	
NGSH06	NAGASAKI	32.6999	129.8625	155	200	NAGASAKIKEN	KiK-net18	
NIGH01	NAGAOKA	37.4272	138.8876	85	100	NIIGATAKEN	KiK-net11A	
NIGH02	ASAHI	38.2799	139.5486	34	104	NIIGATAKEN	KiK-net06	
NIGH03	ARAKAWA	38.1327	139.4289	6	221	NIIGATAKEN	KiK-net06	
NIGH04	SEKIKAWA	38.1313	139.5428	78	100	NIIGATAKEN	KiK-net06	
NIGH05	SEIRO	37.9759	139.2788	7	147	NIIGATAKEN	KiK-net06	

NIGH06	KAMO	37.6527	139.0676	30	100	NIIGATAKEN	KiK-net06
NIGH15	MUIKA	37.0533	138.9951	358	100	NIIGATAKEN	KiK-net06
NIGH19	YUZAWA	36.8114	138.7849	985	100	NIIGATAKEN	KiK-net11C
NMRH03	NAKASHIBETSU	43.5508	144.9665	30	228	HOKKAIDO	KiK-net11B
NMRH04	BEKKAI-E	43.3978	145.1224	30	216	HOKKAIDO	KiK-net11A
NMRH05	BEKKAI-W	43.39	144.8021	92	220	HOKKAIDO	KiK-net06
OITH01	YAMAGUNI	33.4122	131.0326	249	200	OITAKEN	KiK-net11B
OITH02	YAMAGA	33.4581	131.4429	165	100	OITAKEN	KiK-net11B
OITH05	NOTSUHARA	33.1525	131.542	160	100	OITAKEN	KiK-net11B
OITH06	TAKETA	32.9726	131.3984	260	103	OITAKEN	KiK-net11B
OITH09	UME-E	32.8486	131.6786	190	100	OITAKEN	KiK-net06
OKYH02	SETO	34.7501	134.0702	30	200	OKAYAMAKEN	KiK-net11A
OKYH07	SHINGO	35.0493	133.3169	564	100	OKAYAMAKEN	KiK-net18
OKYH10	KAMISAIBARA	35.2826	133.9263	495	200	OKAYAMAKEN	KiK-net11A
OKYH11	SHOO	35.0732	134.1162	129	200	OKAYAMAKEN	KiK-net11A
OKYH12	OHARA	35.0999	134.319	280	200	OKAYAMAKEN	KiK-net11A
OKYH13	HINASE	34.7283	134.2744	3	103	OKAYAMAKEN	KiK-net18
OKYH14	HOKUBO	34.9363	133.6205	218	100	OKAYAMAKEN	KiK-net18
OSKH01	TAJIRI	34.3977	135.2836	5	1505	OSAKAFU	KiK-net06
OSKH02	KONOHANA	34.6628	135.3896	7	2008	OSAKAFU	KiK-net11A
RMIH01	HORONOBE	45.0167	142.0795	30	100	HOKKAIDO	KiK-net06
RMIH02	TESHIO	44.8948	141.9251	10	107	HOKKAIDO	KiK-net06
RMIH03	EMBETSU	44.6359	141.8187	20	209	HOKKAIDO	KiK-net06
SAGH05	SHIROISHI	33.1806	130.1046	18	203	SAGAKEN	KiK-net18
SBSH01	FURUBIRA	43.2341	140.6228	28	100	HOKKAIDO	KiK-net06
SBSH02	TOMARI	43.0527	140.5017	25	100	HOKKAIDO	KiK-net06
SBSH03	AKAIGAWA	43.0842	140.8199	145	220	HOKKAIDO	KiK-net11B
SBSH04	KYOWA	42.9758	140.6219	20	200	HOKKAIDO	KiK-net06
SBSH05	KUCCHAN	42.95	140.8223	240	100	HOKKAIDO	KiK-net06
SBSH06	RANKOSHI	42.8309	140.4831	39	130	HOKKAIDO	KiK-net06
SBSH07	MAKKARI	42.763	140.8084	228	100	HOKKAIDO	KiK-net06
SBSH10	SHIMAMAKI	42.7797	140.1557	32	100	HOKKAIDO	KiK-net11B
SIGH01	TAGA	35.2383	136.3599	610	100	SHIGAKEN	KiK-net06
SIGH02	OHTSU	35.2482	135.8671	305	100	SHIGAKEN	KiK-net11A
SITH01	IWATSUKI	35.929	139.7349	8	3510	SAITAMAKEN	KiK-net11A
SITH03	HIDAKA	35.899	139.3843	51	1800	SAITAMAKEN	KiK-net06
SITH04	TOKOROZAWA	35.8028	139.5353	30	2000	SAITAMAKEN	KiK-net06
SITH05	KAMIIZUMI	36.1509	139.0504	150	100	SAITAMAKEN	KiK-net11A
SMNH10	MIHONOSEKI	35.5579	133.3004	9	200	SHIMANEKEN	KiK-net06
SMNH12	YOSHIDA	35.1634	132.8558	380	101	SHIMANEKEN	KiK-net06
SMNH14	MUIKAMACHI	34.3904	131.8925	249	100	SHIMANEKEN	KiK-net06
SOYH02	SARUFUTSU-S	45.2163	142.2254	5	100	HOKKAIDO	KiK-net06
SOYH03	WAKKANAI-W	45.2531	141.6334	8	137	HOKKAIDO	KiK-net06
SOYH04	WAKKANAI-E	45.2303	141.8806	30	203	HOKKAIDO	KiK-net06
SOYH06	TOYOTOMI	45.1019	141.7834	15	135	HOKKAIDO	KiK-net11A
SRCH03	HOROKANAI-S	43.9994	142.1258	155	100	HOKKAIDO	KiK-net06
SRCH04	NUMATA	43.8203	141.9397	100	105	HOKKAIDO	KiK-net06
SRCH08	SUNAGAWA	43.5138	141.909	30	122	HOKKAIDO	KiK-net06
SRCH09	KURIYAMA	43.0587	141.8063	30	122	HOKKAIDO	KiK-net06
SRCH10	YUBARI	42.993	142.0085	195	200	HOKKAIDO	KiK-net06
SZOH24	INASA	34.8343	137.6616	19	300	SHIZUOKAKEN	KiK-net11B

SZOH26	FUKUROI	34.7948	137.9034	23	450	SHIZUOKAKEN	KiK-net06
SZOH41	MINAMIIZU	34.6749	138.834	60	109	SHIZUOKAKEN	KiK-net06
SZOH53	KAKEGAWA3	34.8768	138.0174	182	100	SHIZUOKA KEN	KiK-net11B
SZOH54	HATSUSHIMA2	35.0417	139.1685	20	110	SHIZUOKA KEN	KiK-net06
TCGH06	MOKA	36.4458	139.9509	70	1648	TOCHIGIKEN	KiK-net06
TCGH08	KURIYAMA-E	36.8828	139.6459	702	203	TOCHIGIKEN	KiK-net11A
TCGH11	IMAICHI	36.7084	139.7694	290	200	TOCHIGIKEN	KiK-net11A
TCGH13	BATO	36.7342	140.1781	135	140	TOCHIGIKEN	KiK-net11C
TCGH16	HAGA	36.548	140.0751	105	112	TOCHIGIKEN	KiK-net11A
TCGH17	FUJIHARA2	36.9853	139.6922	635	104	TOCHIGIKEN	KiK-net06
TKCH06	MEMURO	42.892	143.0603	97	227	HOKKAIDO	KiK-net06
TKCH07	TOYOKORO	42.8114	143.5203	9	100	HOKKAIDO	KiK-net06
TKSH02	SADAMITSU	34.0112	134.0918	190	100	TOKUSHIMAKEN	KiK-net11A
TKSH03	KOYADAIRA	33.8778	134.1294	640	201	TOKUSHIMAKEN	KiK-net11A
TKYH02	FUCHU	35.6539	139.4704	45	2753	TOKYOTO	KiK-net06
TKYH11	KOTO	35.6114	139.8125	6	3000	TOKYOTO	KiK-net11A
TKYH13	HINOHARA-S	35.7017	139.1275	360	100	TOKYOTO	KiK-net11B
TYMH02	DAIMON	36.7142	137.0378	5	212	TOYAMAKEN	KiK-net06
TYMH03	TOYAMA	36.7294	137.2627	8	580	TOYAMAKEN	KiK-net06
TYMH04	UOZU	36.7914	137.4689	154	100	TOYAMAKEN	KiK-net06
TYMH06	YATSUO	36.5711	137.1595	110	200	TOYAMAKEN	KiK-net06
WKYH04	SUSAMI	33.5559	135.5454	130	100	WAKAYAMAKEN	KiK-net11A
WKYH06	OTO	33.6948	135.5953	218	100	WAKAYAMAKEN	KiK-net11A
YMGH01	HOFU	34.0494	131.5618	35	200	YAMAGUCHIKEN	KiK-net11A
YMGH06	UBE	33.9893	131.3012	80	200	YAMAGUCHIKEN	KiK-net11A
YMGH12	MITO	34.2176	131.3597	150	102	YAMAGUCHIKEN	KiK-net06
YMGH16	KAMINOSEKI	33.826	132.104	65	106	YAMAGUCHIKEN	KiK-net06
YMNH08	NISHINOHARA	35.6895	138.734	375	1206	YAMANASHIKEN	KiK-net06
YMNH10	HAYAKAWA-N	35.5351	138.3087	695	107	YAMANASHIKEN	KiK-net11A
YMNH13	MINOBU	35.3509	138.4203	255	204	YAMANASHIKEN	KiK-net11A
YMNH14	TSURU-S	35.5115	138.9675	1010	250	YAMANASHIKEN	KiK-net11A
YMNH15	KAMIKUISHIKI	35.5323	138.6045	525	116	YAMANASHIKEN	KiK-net11A
YMNH16	KOFU2	35.7421	138.5653	595	256	YAMANASHIKEN	KiK-net06
YMTH01	TENDO	38.3841	140.3805	113	207	YAMAGATAKEN	KiK-net11A
YMTH02	YAMAGATA	38.2693	140.2583	130	150	YAMAGATAKEN	KiK-net11A
YMTH03	NANYO	38.1035	140.1553	278	114	YAMAGATAKEN	KiK-net11A
YMTH08	YAWATA	38.9701	140.0333	115	106	YAMAGATAKEN	KiK-net11A
YMTH14	NISHIKAWA-W	38.386	139.9916	465	103	YAMAGATAKEN	KiK-net11C

Author Contributions

Serkan Hasanoğlu: Development and application of MATLAB codes, writing, editing; **Ahmet Güllü**: Conceptualize, development of algorithms, evaluating the results, writing, editing.

Conflict of interest

The authors declare that there is no known conflict of interest.

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