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ORIGINAL ARTICLE

Site flatfile of Korea meteorological administration's seismic stations in Korea

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Abstract
This study constructed a flatfile with the information useful to satisfy the site characterization requirements of Korea Meteorological Administration's seismic network, which was expanded significantly to 265 seismic stations following the 2016 Gyeongju Earthquake and the 2017 Pohang Earthquake in South Korea. Seismic response parameters, including the average seismic shear-wave velocity from the surface to a depth of 30 m (V_{S30}), the depth of the engineering bedrock (H), and the mean V_S of soils above the engineering bedrock ($V_{S,Soil}$), were collected for each seismic station using existing available data and were obtained via direct in situ tests and explorations, including borehole drillings, downhole tests (DHTs), and surface seismic tests (multichannel analysis of surface waves [MASW]). To ensure the comprehensive coverage of all observation sites, terrain- and geological-map-based proxy techniques were applied to all stations. In addition to currently operational seismic stations, data on closed stations were collected and included as much as possible to enhance the accuracy of the seismic observational data at those points. For the 265 seismic stations, 28% of the representative V_{S30} values were obtained from geophysical investigations, such as DHTs and MASW, whereas 60% were collected using geotechnical in situ methods, such as boring and standard penetration tests. Twelve percent of the representative V_{S30} data were estimated using seismic records or proxy-based techniques. Finally, all observation sites were classified according to three engineering site classification systems: two internationally accepted V_{S30}-based National Earthquake Hazards Reduction Program codes and an H- and $V_{S,Soil}$-based Korean code.

Keywords Korea meteorological administration seismic network · Site flatfile · V_{S30} · Site classification · Geotechnical information

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1 Introduction

Many countries and pan-governmental organizations operate seismic monitoring networks to protect their properties and citizens. According to the International Seismological Centre (http://www.isc.ac.uk), the International Registry of Seismograph Stations comprises over 26,000 seismic stations registered in over 130 global, national, and regional networks; the actual number is estimated to be much higher if considering unregistered stations. Seismic stations are critical for issuing alerts in the early stages of an earthquake, and their seismographic data are utilized for estimating and mitigating seismic hazards as well as for tectonic studies.

Geological and geophysical characteristics on the location of seismic stations have a major impact on seismic records. As confirmed by the Mexico City Earthquake (Seed et al. 1988) and the Loma Prieta Earthquake (Borcherdt and Glassmoyer 1992), the effects on seismograms of shallow ground characteristics should be well identified and utilized (Sokolov et al. 2012). In most cases, the impedance contrast between the bedrock and the soft soil layer (Manandhar et al. 2016), lateral heterogeneities, and topographical features (Felicetta et al. 2017) could amplify earthquake motions and dominate every other effect (Bard 1998).

When the characteristics of a site are obtained, they can be used for studies relating to site effects, including early warnings of earthquakes with intensity prediction, ground-motion prediction equations (GMPEs), seismic hazard maps, site amplification (seismic response parameter) maps, and site classifications specified in seismic design codes. For this purpose, site flatfiles or databases have been established to facilitate the more detailed use of seismic records in major earthquake-prone countries, namely, Italy (Gorini et al. 2010; Capua et al. 2011; Felicetta et al. 2017; D'Amico et al. 2021), the U.S. (Ancheta et al. 2014; Seyhan et al. 2014; Yong 2016), Turkey (Akkar et al. 2010; Sandıkkaya et al. 2010), Greece (Theodulidis et al. 2004), Switzerland (Poggi et al. 2017), Taiwan (Kuo et al. 2012; Kwok et al. 2018), and Japan (Kinoshita 1998; Aoi et al. 2004). Even at the level of international organization (i.e., Observatories and Research Facilities for European Seismology [ORFEUS]), the dissemination of standardized station metadata including engineering site information is the original focus of their initiative (Cauzzi et al. 2021).

Site attributes necessary for reliable site characterization could be acquired based on direct measurements such as in situ investigations or geophysical prosepctions. In addition, auxiliary (or main) applications of empirical estimation are also possible based on wide-area information on surface geology and topographic slope. For seismic stations, the site attributes and local site amplification can be evaluated additionally by utilizing observational data (noise or strong motion) containing the site effects. Among the site attributes, time-averaged shear wave velocity (V_S) over 30 m (V) is the most representative indicator for the site identification. Since its appearance in 1990, it has been widely used due to its universality, simplicity, and cost-effectiveness, that is, 'summarized' information (Bergamo et al. 2021). Recently, in Europe, although cost and difficulty of acquisition are different, the following 7 most relevant indicators have reached an agreement that can be used reliably for seis$_{S30}$mic stations' characterization (Cultrera et al. 2021): fundamental frequency (f_0), V_S profile, V_{S30}, depth of seismological and engineering bedrock, surface geology and soil class. The indicators could be utilized solely or in a list, and when used in an appropriate combination, the amplification characteristics can be distinguished better (Bergamo et al. 2021).

The Korea Meteorological Administration (KMA; https://necis.kma.go.kr/) is responsible for national earthquake-related matters and operates a real-time seismic monitoring and analysis network. The seismographic network was expanded from two observatories in 1978 to six in 1980 before it underwent rapid modernization during the 1990s (KMA 2001; Park et al. 2011). In 1999, the observation equipment was changed to digital instrumentation, allowing recordings the 2016 Gyeongju Earthquake (M_L 5.8) (Kim et al. 2016a, b) and the 2017 Pohang Earthquake (M_W 5.4) (Gihm et al. 2018; Kim et al. 2018a, b); the two largest earthquakes to have occurred since 1978. Following the 2016 earthquake, the number of stations was rapidly increased from 156 (KMA 2017) to 265 (KMA 2021), and their distribution is shown in Fig. 1. The geotechnical characteristics of some stations have been obtained directly via in situ tests and investigations (Rhie 2015; Sun et al. 2016), or they have been inferred from seismic records based on P-wave seismograms (Kim et al. 2020) and horizontal-to-vertical spectral ratio (HVSR) (Ahn et al. 2021) techniques; however, a comprehensive site flatfile that covers the entire network has not been established to date.

In this study, we present a site flatfile for the KMA seismic monitoring network (Network code ‘KS’ by the International Federation of Digital Seismograph Network [FDSN]). Geotechnical, geological, and geomorphological data from individual seismic stations were used to calculate seismic response parameters such as V_{S30}, the depth of the engineering bedrock (H), and the mean V_S of soils above the engineering bedrock ($V_{S,Soil}$) because with the V_{S30} recognized almost as an international standard, the latter two are serve as important seismic response parameters in areas where engineering bedrock is dominant at shallow depths, as is found across Korea (Manandhar et al. 2018; Cho et al. 2021). Existing available data were collected and analyzed, and direct in situ tests and investigations (including borehole drillings, downhole tests [DHTs], and surface seismic tests) were conducted focusing on some stations that have not been surveyed. To obtain V_{S30}, this study utilized surface proxy-based methods (such as the slope gradient) along with local geology for stations where direct tests and exploration were not conducted. Additionally, the engineering bedrock depth (H) and the $V_{S,Soil}$ were calculated; these values can serve as seismic

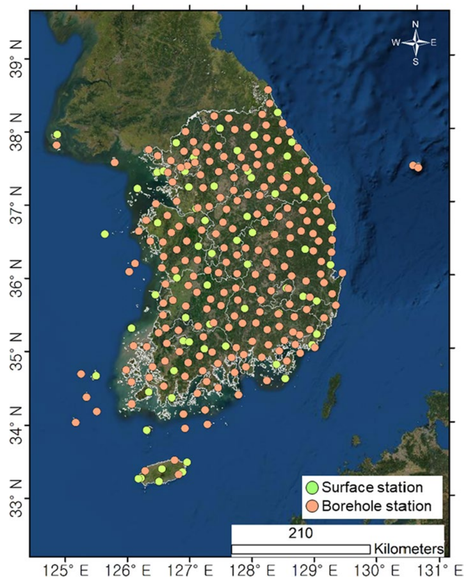


Fig. 1 Map showing all 265 seismic stations of the Korea Meteorological Administration in operation

response parameters in areas where engineering bedrock is dominant at shallow depths, as is found across Korea (Manandhar et al. 2018; Cho et al. 2021). Finally, all the stations were classified according to both international and Korean seismic design codes.

2 Review of site databases for national and international seismic networks

The Pacific Earthquake Engineering Research Center established a site database of seismic stations (Seyhan et al. 2014) as part of its NGA-West2 project (Bozorgnia et al. 2014) for the development of next-generation attenuation (NGA) relationships for active tectonic regions, such as in the Western U.S. This undertaking resulted in major advances in the estimation of global seismic hazards, with the site database playing an important technical role. The NGA-West2 site database contains information on site conditions for 4,147 strong-motion stations located mainly in California, Japan, Taiwan, China, and the Mediterranean region. The measured V_{S30} values from 2,013 stations were obtained, and the rest were estimated using proxy-based relationships (Seyhan et al. 2014).

A similar scheme, the NGA-East project (Goulet et al. 2017), was established for the stable continental regions of Central and Eastern North America. A database containing the site conditions at seismic stations (Goulet et al. 2014) was also released; it included the measured V_{S30} values for 84 out of 1,379 stations (6%), which were compiled from various open-literature sources. The V_{S30} values for the remaining 1,295 stations were estimated using the P-wave seismogram method (Kim et al. 2016a, b) and proxies, including surface geology, terrain, ground slope, and hybrid slope geology. However, in the NGA-East project, the low number of strong-motion sites with geophysical measurements contrasts with the situation in active crustal regions (i.e., NGA-West2) where measured V_{S30} values are available for approximately half of all stations (Goulet et al. 2014; Seyhan et al. 2014).

A reference database for seismic ground motions in Europe (RESORCE) was compiled using European station metadata with the intention of providing a single pan-European strong-motion databank for use in engineering seismology and earthquake engineering applications (Akkar et al. 2014). The main local and regional networks were obtained from Italy (the Italian accelerometric archive [ITACA]; Luzi et al. 2008), Turkey (the Turkish national strong-motion project; Akkar et al. 2010; Sandıkkaya et al. 2010), and Greece (the Hellenic Accelerogram Database; Theodulidis et al. 2004). Of the 1,540 strong-motion stations included in the inventory, the V_{S30} values for 423 stations were obtained using site characterization studies (i.e., in situ measurements), whereas the site classifications for 627 stations were inferred from local geological conditions (Akkar et al. 2014). The Engineering Strong-Motion Database (ESM, Luzi et al. 2016), which has been updated and expanded to include the Middle East, provides information on 3,575 stations (https://esm-db.eu; last accessed 2022, March), expanded from the initial 2,080 stations (Lanzano et al. 2019). Direct V_S profile from geophysical prospections are provided for about 20% of the stations, and site category or V_{S30} estimated/evaluated by surface geology information and topographic slope by Wald and Allen (2007) is provided for 77% of the stations (Lanzano et al. 2019).

ITACA, the Italian strong-motion database, is the largest and most active in Europe and includes data from networks in Italy and the surrounding areas (Luzi et al. 2008). In line with its goal to improve the characterization of recorded sites from geological and geophysical perspectives and to provide seismic classification (Felicetta et al. 2017), ITACA completed site classifications for 99.7% of 1,450 stations in accordance with Eurocode 8 (CEN 2005; D'Amico et al. 2021). The V_{S30} values for 21% of stations were derived from measured 1D velocity profiles, whereas 71% were based on surface geological data. In cases of missing velocity profiles or geological maps (8%), the V_{S30} values were estimated using empirical correlations with topographic slopes (D'Amico et al. 2021) in accordance with three main thematic levels (Felicetta et al. 2017).

In 1991, the Taiwan Strong-Motion Instrumentation Program (TSMIP) installed 680 free-field stations (Liu et al. 1999) in Taiwan, which is part of the Asian Ring of Fire. Since then, this number has increased to 820 (http://egdt.ncree.org.tw/; last accessed 2021, April). Following the 1999 Chi-Chi Earthquake in Taiwan, the National Center for Research in Earthquake Engineering started to work on the Engineering Geological Database for TSMIP (EGDT), which is a program for characterizing TSMIP stations (Kuo et al. 2012; Kwok et al. 2018). The EGDT includes site characterizations (comprising surface investigations and logging measurements) for 439 stations (Kuo et al. 2012). Since then, additional investigations have been conducted, and information on 465 stations is now provided through the EGDT's website (http://egdt.ncree.org.tw/; last accessed 2021, April). For approximately half the stations where in situ tests for site characterization were not conducted, the results of proxy- or seismic-record-based V_{S30} estimation techniques (Lin et al. 2014, 2016; Kwok et al. 2018) have been reflected in the EGDT since 2018 (http://egdt.ncree.org.tw/).

In Japan, a fundamental survey and observation plan for earthquake research was established following the 1995 Hyogoken–Nanbu Earthquake (Aoi et al. 2004). The National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan operates the Kyoshin Net (K-NET) (Kinoshita 1998) and the Kiban Kyoshin Network (KIK-NET) as part of this plan. K-NET comprises 1,045 stations where an accelerometer is installed on a free surface, whereas KIK-NET comprises 697 stations with seismographs installed both on the surface and at the bottom of boreholes (at depths of $\geq$ 100 m). With 1,742 operational observatories (Zhu et al. 2021), the two networks provide uniform national coverage with inter-station intervals of approximately 20–25 km (Aoi et al. 2011). NIED's website provides the soil condition data (including V_S profiles) for all K-NET stations and for 664 KIK-NET stations (> 95%) (https://www.kyoshin.bosai.go.jp/; last accessed 2021, April).

Currently, various derivative studies are underway using unrivaled, powerful earthquake observation infrastructure and observed seismic records from Japan related to site amplification characteristics, empirical relationships between site test results and V_S, factors affecting engineering site classification, GMPEs, site amplification factors, and probabilistic seismic hazard analyses (Zhu et al. 2021). This is possible for two reasons: first, the data are available to researchers in Japan and worldwide, and second, the site conditions were fully characterized to consider local site effects that were included in the observed records at seismic stations. Ultimately, the accumulation of related research becomes the impetus for the revision of design codes, such as USGS's U.S. National Seismic Hazard Model (NSHM). The NSHM is a major influence on the seismic provisions of U.S. codes for buildings, bridges, railways, defense facilities, and other structures. It is updated periodically, and in the latest revision (Petersen et al. 2020), the site functions of the ground-motion models, soil amplification factors, V_{S30} maps, etc., were updated with consideration of the results of studies involving NGA-West2 and NGA-East.

Table 1 summarizes the status of site characterizations at seismic stations belonging to the aforementioned local and regional (or project) seismic networks by securing V_{S30} or not. The number of stations for which site characterization has been completed is shown separately for direct measurements, based on geophysical explorations or geotechnical

Table 1 Site characterization status of strong-motion stations included in each regional seismic network by securing V_{S30}

Network or project	Regions	No. of stations	Site characterization by V_{S30}		Reference or website URL
			Measurement*	Estimation**	
NGA-West2	California, Japan, Taiwan, China, and the Mediterranean	4149	2013 (49%)	2134 (51%)	Seyhan et al. (2014)
NGA-East	Central and Eastern North America	1379	84 (6%)	1295 (94%)	Goulet et al. (2014)
RESORCE	pan-Europe	1540	423 (27%)	627 (41%)	Akkar et al. (2014)
ESM	pan-Europe	2080	471 (23%)	1609 (77%)	Lanzano et al. (2019)
		3575	677 (19%)	2740 (77%)	https://esm-db.eu/
ITACA	Italy and surrounding areas	1450	21%	79%	D'Amico et al. (2021)
TSMIP	Taiwan	820	465 (57%)	352 (43%)	egdt.ncree.org.tw/
K-NET & KIK-NET	Japan	1742	656 (38%)***	1742 (100%)	Zhu et al. (2021) kyoshin.bosai.go.jp/

*Measurements by downhole, crosshole, SPS logging, surface wave, and standard penetration test (SPT) N-V_S relationships

**Estimations by proxy relationships based on ground slope, surface geology and terrain, seismic-record-based techniques such as HVSR, microtremor array and receiver function analyses

***Note that the V_S profile for about 95% of the stations is secured, but most of the K-NET stations do not have V_S logging for depths deeper than 20 m in situ test, and for empirical estimations based on both proxies (e.g., local geology and geomorphology) and seismic records (e.g., HVSRs, microtremor array measurements and receiver functions) along with the total number of stations in each network.

3 Site flatfile construction of KMA's seismic network

Efforts have been made to obtain the site characteristics of seismic stations within the KMA network. Rhie (2015) conducted in situ tests and explorations at 58 stations using drilling, DHTs, and surface seismic tests. Although that study reported V_{S30} values, it did not specify the method used for each station. Sun et al. (2016) reanalyzed the raw data from those tests and reported V_{S30} values for 53 stations based solely on borehole drilling and seismic DHTs. In addition to direct site investigations and explorations, recent studies have estimated V_{S30} values based on seismic records obtained from stations. Kim et al. (2020) used the P-wave seismogram method: the average shear-wave velocity for a certain depth (V_{SZ}) can be estimated using the ratio of radial to vertical components in initial P-wave velocity seismograms, which can be converted to V_{S30} using an empirical relationship (Kim et al. 2020). This was verified using the site investigation results from 42 surface stations and was applied to an additional 91. Ahn et al. (2021) used the semi-empirical relationship between natural frequency (f_p) (selected from HVSR) and V_{S30} (i.e., the f_p–V_{S30} model) to estimate V_{S30} values for 70 KMA surface stations. The site information containing site response parameters (such as V_{S30}) is required for all operational KMA seismic stations. However, due to the shutdown or relocation of operations, the results from some stations that underwent the aforementioned site investigations or estimation techniques are invalid for the current seismic network. Furthermore, as the results of V_{S30} estimation techniques based on P-wave seismograms and HVSRs are limited only to surface stations, the stations with seismographs installed at the bottom of boreholes (hereinafter: borehole station) were excluded.

A site flatfile was established for all seismic stations in the KMA network. It covers 265 observavory sites currently in operation and includes 28 closed sites. Table 2 shows the results of only 24 stations (the low number is due to a lack of space) based on the ascending order of station codes currently in operation. The data for all stations are provided in the electronic supplementary material (Online Resource 1). In other words, Table 2 is an example of some stations in Online Resource 1. As shown in Table 2, site characterizations for each individual station were performed by separately listing the seismic response parameters, including V_{S30}, H, and $V_{S,Soil}$, according to the acquisition techniques used. V_{S30} is differentiated from direct measurements from drilling or exploration and estimations based on proxies and seismic records. Because the acquisition of H and $V_{S,Soil}$ requires a V_S profile, the application of existing V_{S30} estimation techniques via an empirical correlation is limited. Based on the acquired parameters, observatory sites are classified into V_{S30}-based NEHRP site classes (BSSC 1997, 2020) and/or H- and $V_{S,Soil}$-based site classes in Korea (MOLIT 2018). Among four parameters in the site flatfile, the three, such as V_{S30}, H and site class, are included in the 7 most relevant indicators for reliable seismic station's characterization recently derived through consensus of the scientific community (Cultrera et al. 2021). Along with H, the $V_{S,Soil}$ is also used as an important site indicator in the Korean Peninsula, where the majority sites are similar to the characteristics of site class E (5 m < H < 20 m) in Eurocode 8 (Lee et al. 2012; Manandhar et al. 2018; Kim et al. 2018a, b; Cho et al. 2021).

Table 2 Site conditions of strong-motion stations in Korea Meteorological Administration's seismic network (full details are provided in Online Resource 1)

Station code (current)	Station code (historical*)	V_{S30} (m/s)							H (m)				$V_{S,Soil}$ (m/s)				Site class		
		Measurements				Estimations			Measurements				Measurements						
		Exploration		Boring		Seismic records		Proxy	Exploration		Boring		Exploration		Boring		NEHRP		MOLIT 2018
		DHT	MASW	SPT	Geo layers**	HVSR (Ahn et al. 2021)	P-wave (Kim et al. 2020)	Slope	DHT	MASW	SPT	Geo layers	DHT	MASW	SPT	Geo layers	1997	2020	
ADO2	–	792	–	415	829	–	757	836	8.0	–	> 30	5.0	384	–	NA	295	*B*	*BC*	S_2
ADOA	–	632	490	697	827	–	–	836	4.0	> 30	9.0	4.1	192	NA	433	246	*C*	*C*	S_3
AGSA	–	–	–	–	854	–	–	836	–	–	–	4.3	–	–	–	280	*B*	*BC*	S_2
AMD	–	–	–	–	–	1,015	612	836	–	–	–	-	–	–	–	-	*B*	*B*	NA
ANMA	ANM	–	–	–	703	407	654	480	–	–	–	9.5	–	–	–	353	*C*	*BC*	S_2
ASNA	–	–	–	–	742	–	–	836	–	–	–	6.0	–	–	–	273	*C*	*BC*	S_2
BAR2	BAR	–	–	–	–	246	408	162***	–	–	–	-	–	–	–	–	*D*	*D*	NA
BAU	YSU	740	804	529	509	718	811	836	4.0	10.0	15.0	12.3	207	463	390	271	*C*	*BC*	S_3
BGDB	–	–	–	–	176	–	–	400	–	–	–	52.0	–	–	–	277	*E*	*DE*	S_4
BKWA	–	–	–	–	474	–	–	836	–	–	–	16.0	–	–	–	305	*C*	*C*	S_2
BLGA	–	–	–	–	628	–	–	836	–	–	–	11.0	–	–	–	331	*C*	*C*	S_2
BLLA	–	–	–	–	516	–	–	836	–	–	–	16.5	–	–	–	346	*C*	*C*	S_2
BOGA	–	–	–	–	427	–	–	690	–	–	–	24.0	–	–	–	366	*C*	*CD*	S_4
BON2	BON	–	–	–	–	–	693	836	–	–	–	–	–	–	–	–	*C*	*BC*	NA
BOSB	–	212	–	140	171	–	–	480	> 30	–	> 30	82.0	NA	-	NA	380	*D*	*DE*	S_4
BSAA	–	–	–	–	901	–	–	480	–	–	–	5.0	–	–	–	356	*B*	*BC*	S_2
BURB	–	–	–	–	463	–	–	836	–	–	–	13.2	–	–	–	255	*C*	*C*	S_3
BUS3	BUS, BUS2	–	–	–	–	1,115	753	836	–	–	–	–	–	–	–	–	*B*	*B*	NA
BUSA	-	–	–	–	620	–	–	836	–	–	–	17.0	–	–	–	443	*C*	*C*	S_2

Table 2 (continued)

Station code (current)	Station code (historical*)	V_{S30} (m/s)							H (m)				$V_{S,Soil}$ (m/s)				Site class		
		Measurements				Estimations			Measurements				Measurements						
		Exploration		Boring		Seismic records		Proxy	Exploration		Boring		Exploration		Boring				
		DHT	MASW	SPT	Geo layers**	HVSR (Ahn et al. 2021)	P-wave (Kim et al. 2020)	Slope	DHT	MASW	SPT	Geo layers	DHT	MASW	SPT	Geo layers	NEHRP 1997	NEHRP 2020	MOLIT 2018
BUYB	BUY	–	–	–	–	447	467	836	–	–	–	–	–	–	–	–	*C*	*C*	NA
CEA2	CEA	–	–	–	–	1,151	706	836	–	–	–	–	–	–	–	–	*B*	*B*	NA
CEJA	CEJ	287	–	306	805	-	-	836	> 30	–	27.0	16.0	NA	–	306	604	*D*	*D*	S_4
CGAA	–	–	–	–	568	–	–	570	–	–	–	15.0	–	–	–	363	*C*	*C*	S_2
CGDA	–	–	–	–	686	–	–	690	–	–	–	11.0	–	–	–	378	*C*	*BC*	S_2

*Historical station code is regarded as the same location as the current station code (It is excluded if the historical code is similar to but farther than the reference distance.)

**Soil layers with assumed representative V_S values for each soil layer (Sun et al. 2012)

***Application of the local-geology-based proxy method (Kim et al. 2018a, b) for stations near the Military Demarcation Line on the Korean Peninsula

Site characterization parameters of the seismic stations in this study, were obtained for some stations directly from geotechnical in situ tests, geophysical explorations, and proxy-based estimations, whereas for other stations they were extracted from existing literature. The data sources can include boring logs, standard penetration test (SPT) *N* logs, V_S profiles through geophysical seismic tests, and determined/estimated V_{S30} values. Table 3 summarizes the number of stations for which the different data are available; the number of stations may overlap within an individual reference or with another reference, i.e., several techniques may have been used at some stations over the years. For site characterization, efforts were made to acquire at least one parameter for each seismic station. When multiple results for one parameter are derived by overlapping application of several acquisition techniques for one station, measurements were prioritized over estimations in engineering site classifications (Seyhan et al. 2014; Felicetta et al. 2017). For instance, if a DHT result was presented, the values were used for site classifications. The following subchapters contain details of the acquisition process (in this study or in other literature) of each seismic parameter given in Online Resource 1 and Table 2.

Table 3 References for site characterizations of Korea Meteorological Administration's seismic stations. The corresponding number of stations in each reference is divided according to the acquisition techniques: boring logs, geophysical explorations, and methods that acquires only the V_{S30} value

References		No. of target seismic stations									
		Total	Log		V_S profile			V_{S30}			
			Boring	SPT *N*	DHT	S-PS	Surface	DHT	HVSR	P-wave	Proxy
KMA reports on boring investigation and seismic instruments installation services	2012	12	12								
	2013	5	5		***		5				
	2014	6	6			6					
	2015	16	16		14	6	16				
	2016	13	12		6	6	13				
	2017	74	74		50	24	6				
	2018	69	69		54	15					
Rhie 2015		58	56	51				58****			
Sun et al. 2016		53						53			
Kim et al. 2020*		91(42)**								133	
Ahn et al. 2021*		70							70		
This study		27	14	11	14		19				
		265						Local-slope-based →			253
								Local-geology-based →			12

*Unlike other references, the two studies that estimated V_{S30} using seismic records also included estimates of historical station codes (based on the time of publication) at the time the seismic records were produced

**(In parentheses) Kim et al. (2020) also reported the results of the V_{S30} estimation for stations where V_{S30} already exists as a result of geophysical exploration for bias correction

***(Within bold box) Although the 2013–2018 reports state that seismic tests (such as DHT, S-PS, and surface wave testing) were performed, only the V_S profiles for rock layers were recorded for checking the engineering bedrock for installing seismographs in boreholes. Furthermore, the results of surface wave tests were provided in 2D images, making it impossible to obtain the original data

****Rhie's (2015) report states that V_{S30} was obtained for 58 stations using the DHT and multichannel analysis of surface wave (MASW) techniques in parallel, but the techniques applied to each station are not distinguished

Before moving on to the detailed sections, it is necessary to mention the naming policy for the KMA's seismic stations. The KMA has continued its naming policy of linking a station code to its historical observatory management, such as changes in equipment and the observational environment. Borehole stations are appended with A and B at the end of their specific station codes (e.g., OOOA or OOOB). This is applicable to newly established borehole stations and when existing surface stations are converted to borehole stations (e.g., CHO CHOA). The letter A is added only when an accelerometer is installed in a borehole, and B is included when a broadband velocity seismograph is incorporated. For surface stations, a number is added to the existing code when an instrument (a digitizer or seismograph) is changed (e.g., ADO ADO2). Generally, these naming policies are followed, but there are cases in which the station code changes even though the location of the station remains the same because of the construction of new stations in the surrounding area (e.g., YSU BAU). Because the naming policy does not consider the transfer of a station to a nearby location, it is not possible to check the location transfer using only the change history of the code. Therefore, it is necessary to select and utilize valid site characterization data based on differentiating between past and present stations with similar codes but different locations; i.e., verification is required as to whether the site characterization data could be used for similar station codes by matching a valid code at the time of the in situ test, exploration, and estimation. The second column of Table 2 contains historical station codes that could be regarded as the same location as the station currently in operation. The difference in distance that can be regarded as the same location is set to 100 m based on the longitude and latitude for each code. Note that the criterion is arbitrarily set for the purpose of maximizing the use of existing data without considering any lithological conditions. The site characterization data obtained individually for past or present station codes can be used simultaneously to analyze the seismic records produced by both code types.

3.1 Geotechnical in situ tests

Although geotechnical in situ tests mainly involve boring-related investigations, SPTs have been applied to some stations. As in Table 3, the results are included in the KMA reports from 2012 to 2018, Rhie (2015) and this study. The current study conducted boring investigations for 14 stations, and SPT results were obtained for 11 of them. With the exclusion of some overlapping results and the results for closed stations, 225 and 57 valid boring and SPT results, respectively, were obtained (collected and measured, see Table 3) for the operational stations. When multiple boring results exist for one station, priority is given to the boring result obtained at the time the station was installed. Because the boring and SPT results are given by depth (i.e., log), they can be converted to V_S profiles. The converted profile can be used not only for V_{S30} but also for H and $V_{S,Soil}$ determinations using bedrock definitions (stratum with a $V_S > 760$ m/s, [MOLIT 2018]).

The V_S profile can be obtained by using information from boring logs or from SPT measurements. For the first case, a representative V_S value can be assigned to each layer of the boring log, following what is suggested for Korea by Sun et al. (2012). The representative V_S for weathered rock is 651 m/s. The value of 1,276 m/s is given for rock layers harder than soft rock; therefore, the H value based on the geolayers in Table 2 is determined as the depth at which the rock layers harder than soft rock appear in accordance with the bedrock definition ($V_S > 760$ m/s). This is consistent with the results of Sun (2014) for maintaining conservatism in cases where only boring logs exist without direct V_S acquisition (Cho et al. 2021).

In the other case, the stratum-specific N–V_S relationships proposed by Sun et al. (2013) were applied to convert SPT N values to V_S. If the N value does not exist to a depth of 30 m (because of the shallow bedrock characteristics found in Korea), depth-dependent V_S values of up to 30 m can be extrapolated empirically on the basis of the deepest converted V_S and shape curve proposed by Sun (2015). Fifty of the selected 57 observatories fall into this category. Here, the deepest SPT N value is important, and it differs depending on the obtained stratum. Twenty-eight stations have the deepest SPT N in their soil layers, whereas 22 stations have the deepest SPT at the initial appearance depth of rock layers, such as weathered and soft rock. This difference significantly influences the determination of both V_{S30} and bedrock depth ($V_S > 760$ m/s).

3.2 Geophysical explorations

The data contained in the bold box in Table 3 were not utilized in the preparation of Online Resource 1 and Table 2. This is because these data refer to the stations where geophysical explorations (including DHT, S-PS, and surface wave tests) have been conducted, but either the surface V_S was not reported or the results were provided only as 2D images. Rhie (2015) describes that V_{S30} was derived using DHT and surface wave tests without providing a V_S profile and without distinguishing between the two methods; therefore, it cannot be specified which method was applied to each station. However, Sun et al. (2016) reanalyzing the original DHT data for 53 of the 58 stations of Rhie (2015).

In this study, we obtained further V_S profiles by performing DHTs at 14 stations and conducting multichannel analyses of surface waves (MASWs) at 19 stations. The two techniques were both applied to seven of these stations. The DHT results were interpreted using the modified interval method (Kim et al. 2004). Finally, for the 72 stations currently in operation, having V_S profiles through geophysical explorations (such as DHT and MASW), it was possible to determine the H and $V_{S,Soil}$ values presented in Online Resource 1 and Table 2. There are four stations for which only V_{S30} values have been obtained.

3.3 Seismic records

As a method based on seismic records at only surface stations, the results of the V_{S30} estimation from two studies using P-wave seismograms (Kim et al. 2020) and the HVSR technique (Ahn et al. 2021) were used to construct the flatfile (Online Resource 1 and Table 2). It should be noted that this study produced no direct results. Both studies estimated V_{S30} for past and present station codes. The past station codes refer to codes that are currently closed or that are not currently in operation due to changes in the code names. If the past station code was renamed in the same location, the result is considered to be valid for the updated (present) code also. Where estimates exist for the past and current station codes without location transfers, the suggested values for the latest code are presented. On the basis of the stations currently in operation, both the P-wave seismogram method and the HVSR approach produced valid V_{S30} values for 81 stations (46 surface type and 35 borehole type) and 41 stations (29 surface type and 12 borehole type), respectively. The difference in the number of stations between the two methods. While Kim et al. (2020) also presented V_{S30} estimates for the stations (having geophysical exploration data) used for verification of the P-wave seismogram method in Korea, Ahn et al. (2021) did not provide an estimate for the stations used to tune the f_p–V_{S30} model.

3.4 Proxies

Despite performing collective site characterizations using the aforementioned methods, no relevant values were obtained for some stations. This study used slope- and geology-based proxies in parallel to exhaustively estimate V_{S30} values for all 265 stations, as proxy-based V_{S30} estimations help in predicting the geomorphological and geological formation of subsurfaces (Table 3). To provide surficial terrain information, a digital elevation model (DEM) with a 5 × 5 m (approximately 0.15 arcsec) was archived from Korean radar mission projects and was applied primarily to determine the local slope–V_{S30} relationship (Sun et al. 2018). Local-geology-based proxies (Kim et al. 2018a, b) were derived from a 1:50,000 geological map (https://data.kigam.re.kr/mgeo; last accessed 2021, May) for 12 stations where the DEM is omitted close to the Military Demarcation Line on the Korean Peninsula. However, because the proxies only determine the V_{S30} range on the basis of site classification, the median V_{S30} value for each site class level is provided.

4 Statistics of site characteristics for KMA's seismic stations based on the flatfile

Table 4 presents the status of the site information collected in the flatfile, according to the number of stations where V_{S30} values were obtained using seven acquisition methods for all 265 operational observatories excluding the closed observatories (Online Resource 1 and Table 2). Five techniques (DHT, SPT, boring, P-wave and proxy) provided the V_{S30} values for over 20% of the total number of stations. A representative V_{S30} value was chosen for those stations with multiple V_{S30} values, (Online Resources 1, Table 2): the methods with high reliability are listed to the leftmost column (measurements estimations), and this order corresponds to the priorities suggested by the site databases of NGA-West2 (Seyhan et al. 2014) and ITACA (Felicetta et al. 2017). The same procedure was applied for representative H and $V_{S,Soil}$ values. Out of the 265 representative V_{S30} values, 28% were determined by geophysical explorations and 60% by geotechnical tests. The two direct-measurement-based methods accounted for 88%, which is the highest compared with the site databases of other seismic networks (with the exception of KIK-NET, as shown in Table 1). When multiple results are listed for a single station, the differences can be ascribed to the acquisition

Table 4 Status of the constructed site database (Table 2) according to V_{S30} acquisition techniques

V_{S30} acquisition techniques	Geophysical		Geotechnical		Seismic records		Proxy
	DHT	MASW	SPT	Boring	HVSR	P-wave	
No. of stations obtaining V_{S30} by each technique (ratio to all stations)	60 (23%)	19 (7%)	57 (22%)	225 (85%)	41 (15%)	81 (31%)	265 (100%)
No. of stations utilized as a representative V_{S30} for each station (ratio to all stations)	60 (23%)	12 (5%)	4 (2%)	155 (58%)	14 (5%)	5 (2%)	15 (5%)

techniques, such as: (1) differences in accuracy and precision arising from each technique, (2) differences in drilling points (DHTs vs. boring and SPTs), (3) differences between drilling points and the position of geophone arrays (boring, SPTs, and DHTs vs. MASW), (4) differences in the expertise of those performing and interpreting geophysical explorations (DHTs and MASW), and (5) differences between theoretical backgrounds and real-world environments (e.g., surface slope and anisotropic underground conditions for P-waves and HVSRs).

The KMA seismic observatory sites were classified according to three site classification systems. The first two are internationally accepted V_{S30}-based NEHRP site classifications (BSSC 1997, 2020), and the third is included in the General Seismic Design code (MOLIT 2018), which was produced with consideration of the shallow bedrock characteristics found in Korea (Kim et al. 2018a, b). Because at least one V_{S30} value has been measured and/or estimated for all stations, the NEHRP site classifications are entirely possible. However, the MOLIT site classifications were not conducted for 35 stations (13%) where direct measurements were not performed or it was impossible to determine the H and $V_{S,Soil}$ values. Figure 2 shows the site class distributions of the KMA seismic observatory sites and distinguishes the three site classification methods according to the acquisition methods of the site response parameters. According to the NEHRP's 1997 classification, site classes *B*, *C*, *D*, and *E* (BSSC 1997) reveal distributions of 29%, 59%, 11%, and 1%, respectively, whereas according to NEHRP's 2020 (BSSC 2020) classification, the proportions of site classes *B*, *BC*, *C*, *CD*, *D*, *DE*, and *E* are 11%, 33%, 34%, 15%, 5%, 1%, and 1%, respectively. Site classes S_2, S_3, and S_4 (MOLIT 2018) reveal distributions of 57%, 11%, and 19%, respectively. Figure 3 shows the map about site class of KMA seismic observatory sites according to three engineering site classification systems.

Figure 4 presents distributions showing prioritized V_{S30} and applied number of V_{S30} acquisition techniques to each station based on the summarized information in Online Resource 1 (as described in Table 2). Methods for obtaining prioritized 265 V_{S30} values are distinguished (Fig. 4 [a]). When compared with the site class distributions by the two NEHRP codes (Fig. 2a and b), the V_{S30} distribution characteristics of the observatory sites follows closely the distribution by the recent code due to more subdivided site classes. Moreover, Fig. 4b depicts the number of V_{S30} acquisition methods applied to each station as aggregated from Online Resource 1. For the majority of the sites (151 stations), two methods were applied (a proxy-based method that derived a value for all stations and a method that used a boring log), whereas a total of 99 stations (37%) have V_{S30} values using more than three methods.

The depth of the engineering bedrock (H) is based on the appearance depth of a rock layer harder than weathered rock on a boring log (Sun 2014). Therefore, only the results for 225 stations for which boring logs were obtained (155 of these results were prioritized; see Table 4) were used for the histogram in Fig. 5a. For distributing $V_{S,Soil}$ values, the results from 60 stations that were determined using DHT, MASW, and SPT tests were utilized (Fig. 5b). Boring-log-based $V_{S,Soil}$ values were not used because the values were determined by empirically assigned strata V_S unlike other methods for determining $V_{S,soil}$ based on direct measurement.

Fig. 2 Site class distributions of Korea Meteorological Administration's seismic observatory sites according to the acquisition method for site response parameters: **a** V_{S30}-based NEHRP 1997 site classifications for 265 stations; **b** V_{S30}-based NEHRP 2020 site classifications for 265 stations; **c** H- and $V_{S,Soil}$-based MOLIT site classifications for 230 stations

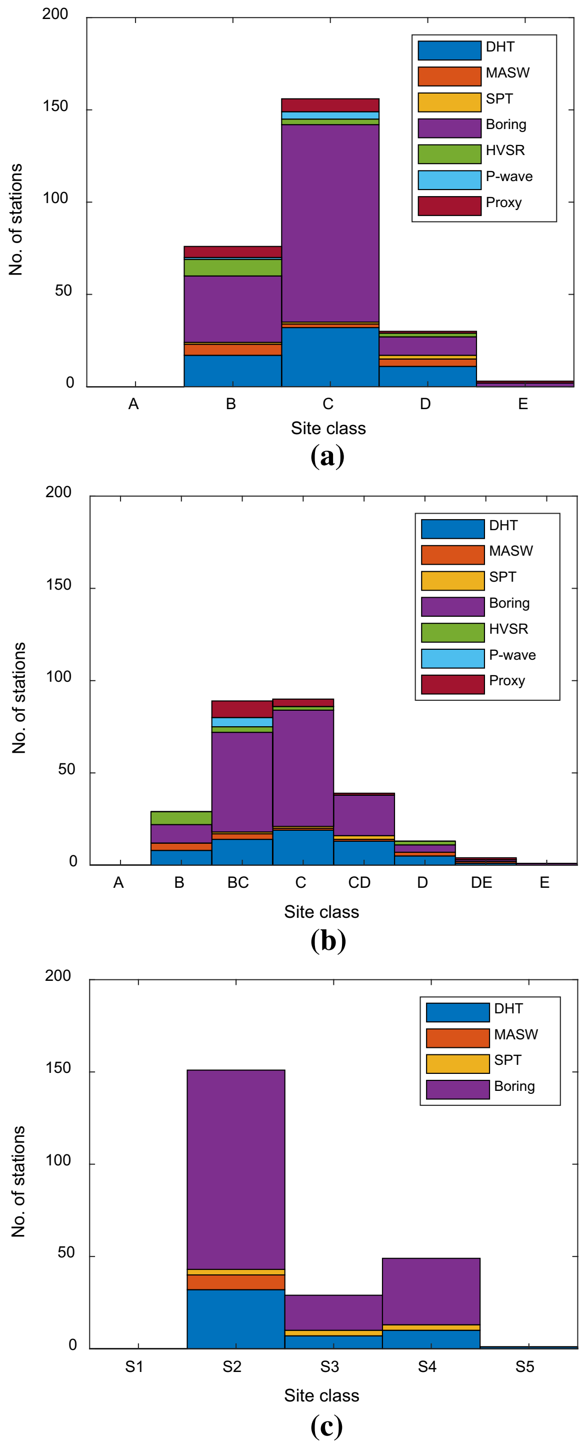
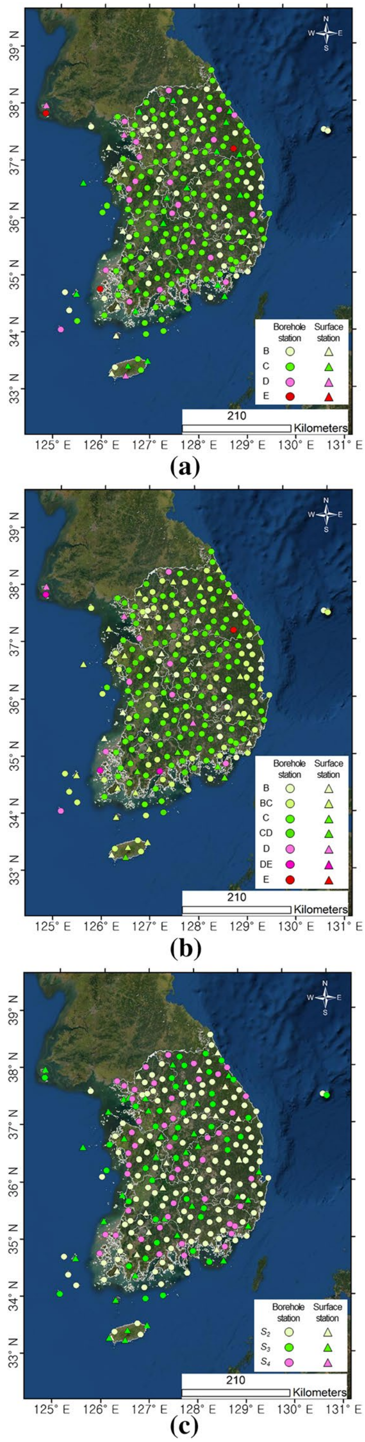


Fig. 3 Spatial distribution of site class of Korea Meteorological Administration's seismic observatory sites in operation according to the acquisition method for site response parameters: **a** V_{S30}-based NEHRP 1997 site classifications for 265 stations; **b** V_{S30}-based NEHRP 2020 site classifications for 265 stations; **c** H- and $V_{S,Soil}$-based MOLIT site classifications for 230 stations



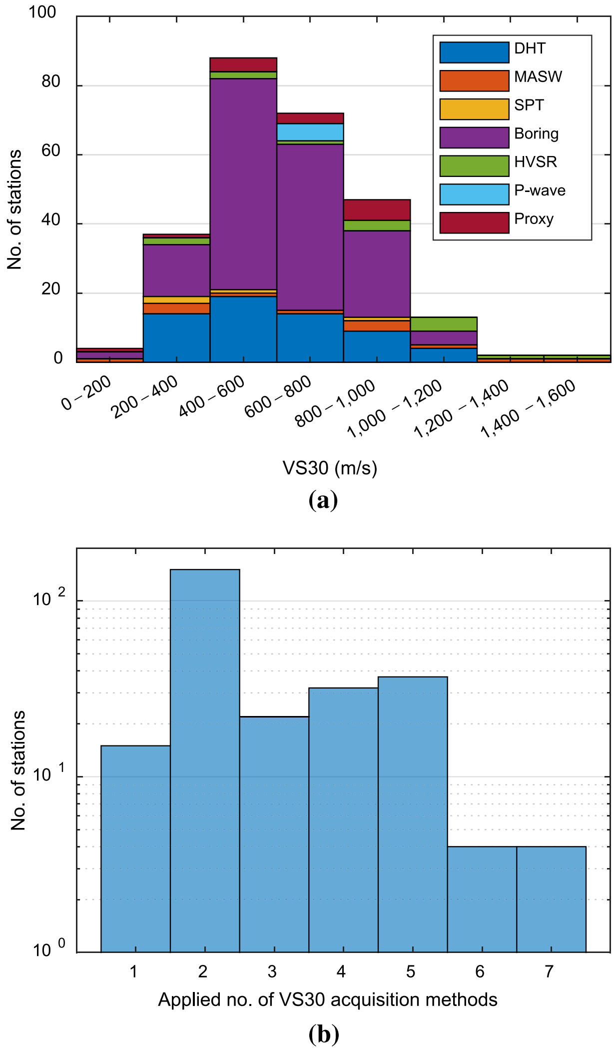
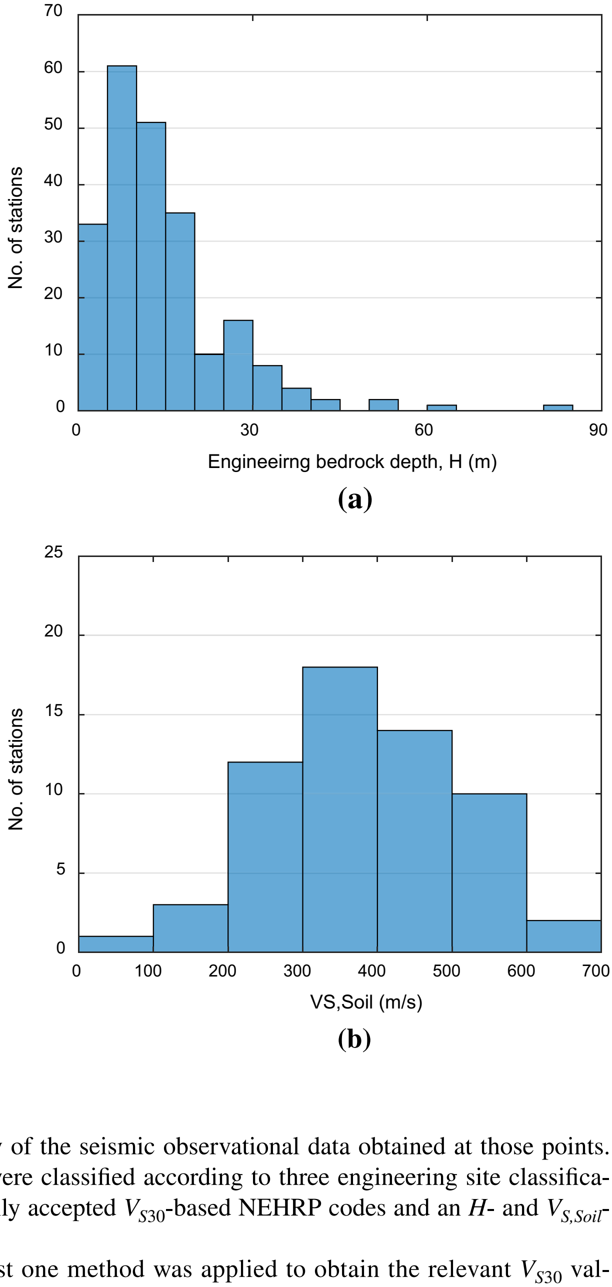


Fig. 4 Distributions of prioritized V_{S30} values and the number of V_{S30} acquisition techniques applied to each station at KMA 265 seismic stations currently in operation based on Online Resource 1: **a** Prioritized V_{S30} values; **b** Number of V_{S30} acquisition techniques applied to each station

5 Conclusions

This study constructed a site flatfile for the KMA seismic stations, which represent the production points of seismic observational data, with the objective of satisfying the network's site characterization requirements. The network significantly increased in size to 265 stations following the 2016 Gyeongju Earthquake and the 2017 Pohang Earthquake, which are the two largest earthquakes to have occurred in South Korea since 1978. Seismic response parameters, including V_{S30}, H, and $V_{S,Soil}$, were obtained for each seismic station by using existing available data and were derived from direct in situ tests and explorations, including borehole drillings, DHTs, and surface seismic tests. Additionally, geomorphological and geological dataset-based proxy techniques were applied to all stations to compensate for those observatory sites where no direct measurements were available. In addition to data from operational seismic stations, information on closed stations was collected and

Fig. 5 Distributions of H and prioritized $V_{S,Soil}$ at KMA 265 seismic stations currently in operation based on Online Resource 1: **a** H values from 225 boring results; **b** Prioritized $V_{S,Soil}$ values for 60 seismic stations from downhole tests, multichannel analyses of surface waves, and standard penetration tests



recorded to increase the utility of the seismic observational data obtained at those points. Finally, all observation sites were classified according to three engineering site classification systems: two internationally accepted V_{S30}-based NEHRP codes and an H- and $V_{S,Soil}$-based Korean code.

For all 265 stations, at least one method was applied to obtain the relevant V_{S30} values. Sixty-three percent of the stations had V_{S30} values that were acquired using one or two techniques (mainly based on proxy and/or boring logs), whereas three or more V_{S30} acquisition techniques were used for 37% of the stations. If multiple V_{S30} values were obtained at one station, a representative V_{S30} value was selected in the following order of the results of geophysical explorations, geotechnical in situ tests, seismic records, and proxy values for engineering site classification. The same procedure was applied for representative H and $V_{S,Soil}$ values. Out of the 265 representative V_{S30} values, 28%

were determined by geophysical explorations, including DHT and MASW, whereas 60% were obtained from geotechnical in situ tests, including boring and SPT. The two direct measurement techniques accounted for 88% of all methods used; this is the highest ratio compared with the site databases of other seismic networks with the exception of the Japanese KIK-NET database. However, because only 27% of geophysical explorations directly measured V_S, it is essential to increase this ratio in the future.

It is anticipated that the site flatfile will be used as a basic data source to inform further research on the uncertainty and variability of the results arising from the different acquisition techniques. More precise site characterizations of the stations could be performed through these further studies. Ultimately, it is suggested that the time at which the sufficient site characteristics are obtained (instead of when the installation of a seismograph is completed) should be considered as the time at which a station is completely established.

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Declarations

Conflict of interest We confirm that this manuscript represents original work that has not been published elsewhere and is not under consideration by another journal for publication. All authors have approved the manuscript and agree with its submission to the Bulletin of Earthquake Engineering. The authors declare no conflict of interest.

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