RESPONSE SPECTUM SHAPES IMPLIED BY EARTHQUAKES IN TURKEY: COMPARISONS WITH DESIGN SPECTRA

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Abstract

Currently the design spectrum shape in many standards and codes intended for building applications is defined by spectral accelerations for short (~0.2 s) and long (~1 s) periods. Both of these hazard-driven values are determined for assumed bedrock conditions at the site of interest, and then modified by multiplicative factors to account for the properties of the topmost 30 m of soil and the intensity of the input ground shaking that represent nonlinearity in the soil column. The traditional, quasi physics driven, empirically based approach involving pre-emptively shifting to longer periods of the constant velocity fall-off boundary that takes into account the accentuated nonlinear behavior of softer soil formations during ground shaking has been abandoned. This article calls attention to conflicts between spectra from actual recordings at a number of stations of the national strong motion network of Turkey with the design spectra for the same location and same site characteristics as given by the national seismic hazard map. The actual ground motions recorded in stations of the national strong motion network of Turkey (operated by AFAD) are used for this purpose. The events with magnitudes in the ranger 5.5 – 7.4 that occurred during 1976 - 2021 are selected from the national strong motion database. The stations are arranged with respect to site class designations in the national regulation. For records obtained there, the response spectra are calculated. Then the design spectra for exactly the same coordinates and site conditions are taken from the national seismic hazard map. We find that the design spectrum in the new Turkish Regulation does not consistently recognize the constant velocity, longer period demand that the ensemble of past earthquakes represents. This may foreshadow unsafe designs for the building stock in the country, but the quantification of this aspect must await comparison of actual design exercises because the regulations that harbor the spectral shapes themselves have been revised.

KEYWORDS: Earthquake, Corner Periods, Site Specific Design Spectra, Strong Motion Database

Introduction

A principal focus of engineering seismology during the course of the last fifty years has been the correct prediction of the various indicators that lead to safer design for elements of the built environment. Initially the interest focused on peak ground acceleration because this was at the time widely acknowledged to be a parameter that best correlated with the destructive power of an earthquake. Indeed, the first studies by Housner (1959) or Newmark and his co-investigators (both summarized in Housner and Jennings, 1982 and Newmark and Hall, 1973, 1982) for defining a design spectrum for use by engineers in designing structural systems capable of resisting the effects of earthquakes that were yet to occur focused on that parameter.

Early research relied on a meager collection of strong motion records to arrive at average global conclusions that the design profession could use in their work. These usually omitted the additional panoply of variables that are currently included in virtually all GMMEs. With the exponential increase of ground motion recordings from a very wide range of magnitudes, distances, styles of faulting, recording site conditions it has become possible to examine these models in excessive detail. But the huge increase of the ground motion database has not been matched by the predictive capability of the increasingly more elaborate equations using that database. Each new earthquake produces ground motions that are at some variance with existing models because that motion is influenced by an intricate combination of source, path and site properties (Douglas, 2019; Kaklamanos et al., 2021). Matched against the performance of first generation GMMEs, improvement toward narrowing the gap between empirical reality and predicted ground shaking e.g., Boore et al. (2014) has been achieved. Still, reduction of the disaccord between measurements and predictions remains a challenge for strong ground motion seismology.

Arriving at a satisfactory design basis for seismic safety requires not only a reliable means to foretell what the motion at the bedrock level is likely to be at a site, but also a supplementary tool to foretell how the motion at depth will be modified as it travels through the various strata of softer soil layers underlying the structure to be built near the surface. Site response is the process of analyzing how waves at depth are tempered as they propagate upwards toward the foundation level of the supported structure. Some degree of nonlinearity in earth materials during this process is present, and the concern is to determine how much of an effect it will produce on the eventual ground motion that is input to the supported structure.

A ground-breaking assessment of site-dependency of ground motions was articulated by Seed et al. (1976). Using a library of over one-hundred ground motion time series, mostly from earthquakes in western US, this study showed the "*clear differences in spectral shapes for different soil and geological conditions, indicating the need for consideration of these effects in selecting earthquake-resistant design criteria*" as seen in Figure 1. Such differences had of course been mooted and empirically noted at much earlier times (Kaklamanos et al. 2021). As the stiffness of the underlying geologic strata, quantified by several customary measures was reduced, the constant velocity roll-off period increased, and the amplification of the spectral acceleration appeared to abate in the period range of interest for many buildings (0.2 s - 1.5 s).

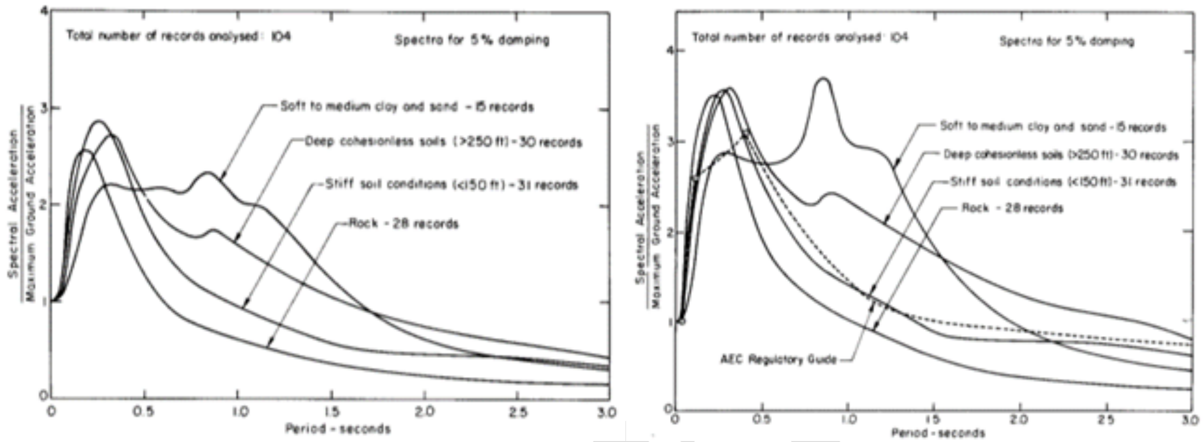

Figure 1. (a) Average acceleration spectra, (b) 84 percentile acceleration spectra for different site conditions. (Adapted from Seed et al (1976))

In the notation of UBC-1994 with V denoting the base shear force which is given in Equation 1 and the soil factor S in the interval $1.0 \leq S \leq 2.0$

$$V = \frac{ZIC}{R_w} W \quad \text{where} \quad C = \frac{1.25S}{T^{2/3}} \leq 2.75 \qquad (1)$$

The lower value of S was for rock-like or very stiff soils, typically with $V_{s30} > 750$ m/s and the upper value was valid for soil profiles with a weighted V_{s30} of < 150 m/s (currently small differences exist in the latest issues of IBC). The implication of Eq. (1) is that for S1 the roll-off period is 0.31 s and for S4, 0.87 s.

The four broadly characterized classes of soil that official design requirements have represents a checkered record, and when arrayed against the requirements that call upon them it is difficult to judge how they should transition into one another among different national documents. In this article we will call $V_{s,30} > 750$ m/s as “rock,” $375 < V_{s,30} < 750$ m/s as “very stiff soil,” $180 < V_{s,30} < 375$ m/s as “stiff soil” and $V_{s,30} < 180$ m/s as “soft soil or clay.” This four-layered crude classification takes on different designations among different documents (B – E or S1 – S4), but their exact attributes and names are unimportant for this article. This style of site characterization has continued in the evolution of UBC, IBC and ASCE7 updates. The wording of the Turkish regulations has followed a similar path.

The normalized spectral shapes in UBC (1994) shown in Figure 2 constituted a demonstration of how the design community responded to the findings by Seed et al. (1976). We discuss this in terms of the requirements that apply to the equivalent static procedure because that measure best characterizes the thinking behind the quantification of the force to be used in routine design. No such refinement applied to the equivalent earthquake force procedure. Two properties of customizing spectral shapes for use in code requirements are shown in Figure 2: The period marking the end of the constant acceleration region (T_s in current ASCE7 verbiage, and renamed as T_B in the Turkish Regulation) shifts to longer periods, ranging between 0.4-0.9 s, but the amplification of the maximum ground acceleration in the shape is constant at 2.5 across the period range for all soil profiles. Larger amplifications occurring in profiles subjected to smaller spectral accelerations is a nuance that is absent in Figure 2. That nuance came in the next issue of UBC (1997) but the amplification ratios were anchored to the Z values characterizing the then still existing Zone Factors. A correction was made for the code in that the variation of the spectral acceleration beyond T_o, defined as $C_a/2.5C_a$ with C_a and C_v defining amplification factors for short (0.2 s) and long (1.0 s) period parts of the acceleration spectrum. For increasing ground acceleration amplitudes (implied by seismic zone factors rather than computed hazard ordinates) both C_a and C_v display a decreasing trend. Past the transition period for constant velocity, spectral acceleration was now inversely proportional to T rather than some power of it, in harmony with the mathematically correct expression.

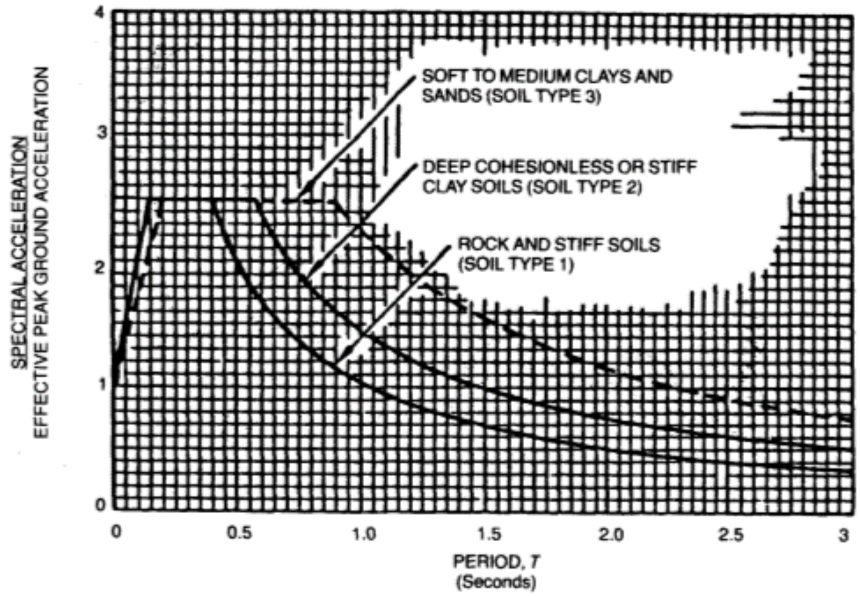

Figure 2. Normalized Spectral Shapes, UBC94

Evolution and refinement of site amplification factors that currently appear in seismic design standards may be traced to Borcherdt (1994, 2012) and Seyhan and Stewart (2014). ASCE7-16 that serves as the source document for IBC has developed a simple procedure for arriving at the design spectrum. Two spectral ordinates are defined for short (0.2 s) and long (1.0 s) periods for a given site, typically from a mapped seismic hazard study for a ground motion that has a 2 percent probability of occurrence during a 50-year long time window. These are termed S_s and S_l, respectively. Then, site effects are introduced by modifying S_s and S_l as follows:

$$S_{MS} = F_a S_S \quad \text{and} \quad S_{Ml} = F_v S_l \tag{2}$$

The factors F_a and F_v are modifiers that depend on site characteristics and hazard levels as given in Table 1 and Table 2. Whereas earlier vintage tables for F_a listed the value across Site Class B as 1.0 throughout, changes in the V_{s30} definition of that class reduced it to 0.9. Horizontal interpolation is permitted. In both tables the asterisk denotes sites where ASCE7 requires specific site-specific studies to be performed.

Table 1. Short Period Site Coefficient Fa, ASCE7-16 / TBER (2018)

Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at Short Period					
	$S_s \le 0.25$	$S_s = 0.5$	$S_s = 0.75$	$S_s = 1.0$	$S_s = 1.25$	$S_s = 1.5$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.9	0.9	0.9	0.9	0.9	0.9
C	1.3	1.3	1.2	1.2	1.2	1.2
D	1.6	1.4	1.2	1.1	1.0	1.0
E	2.4	1.7	1.3	* (1.1)	* (0.9)	* (0.8)
F	*	*	*	*	*	*

Table 2. Long Period Site Coefficient F_v, ASCE7-16 / TBER (2018)

Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at Long Period					
	$S_l \le 0.1$	$S_l = 0.2$	$S_l = 0.3$	$S_l = 0.4$	$S_l = 0.5$	$S_l = 0.6$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.8	0.8	0.8	0.8	0.8	0.8
C	1.5	1.5	1.5	1.5	1.5	1.4
D	2.4	2.2	2.0	1.9	1.8	1.7
E	4.2	* (3.3)	* (2.8)	* (2.4)	* (2.2)	* (2.0)
F	*	*	*	*	*	*

The Turkish Earthquake Regulation for Buildings, TERB (2018), that went into effect in 2019 lists F_a values that are identical to the ASCE7-16 entries except that the last three columns of the row for Site Class E has been modified as shown by the underlined numerals in parentheses. We do not know the provenance of those entries. A similar, seemingly arbitrary, modification has been made for the last five columns for F_v in the Turkish Regulation for Site Class E, given in Table 2.

Armed with the modified S_{MS} and S_{Ml} values the design response spectrum is drawn as shown in Figure 3 below with $S_{DS} = 0.67\ S_{MS}$ and $S_{Dl} = 0.67\ S_{Ml}$ and $T_s = S_{Dl} / S_{DS}$ and $T_o = 0.2\ T_s$. The simplifications are necessary for routine applications, but when they spill over to the domain of target spectrum matching they may imply unsafe design implements. TBER (2018) does not use the two-thirds reduction for S_{DS} and S_{D1} because the hazard level is defined for a repeat period of 475 years.

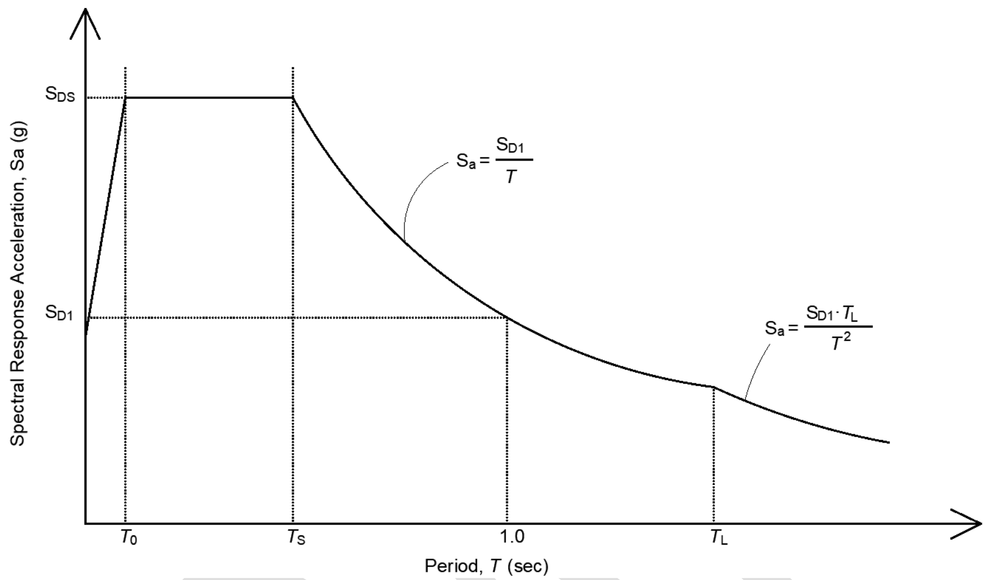

Figure 3. Design Response Spectrum (Figure has been reproduced from ASCE7-16)

Implicit in Figure 3 is the assumption that S_{D1} for softer soil profiles will be larger as shown in Table 2 for F_v, and therefore T_s will shift to larger values. But T_s is now somewhat divorced from its physical site properties, and comes from probabilistically computed information. Despite differences between design and response spectra a legitimate question then becomes: does empirical data support the expectation implied by the regulation-dictated design spectrum, or do the vagaries, both of aleatory and epistemic character, of probabilistically calculated spectral values rule out that a priory wisdom? This question is valid because site-specific design spectra should display a more than passing resemblance to the spectra of ground motions recorded where they have been recorded. Specifically, egregious discrepancies between code specified shapes and actual ground motion shapes for the same site should not exist.

We test the validity of that requirement by using data from the Turkish National Strong Motion Network (Gülkan, et al. 2007, Gülkan, 2011). The procedure we follow is to use strong motion records from stations of the National Network, and to compute the acceleration response spectrum of these time series without any scaling. Site characteristics of each station in the national system have been established through a program of geophysical investigations during the period 2003-2008. We mount on the same frame the design spectrum for that very site's coordinates and its geological description. The national hazard map permits design based on 43, 72, 475 and 2475 year return periods for different requirements of TBER. An interactive web page will draw any of these spectra for both horizontal and vertical directions for engineers to use in design. The list of stations and earthquake ground motions recorded there is listed in Appendix A.

The design spectrum for a given annual probability of occurrence (usually expressed as return period) of a future event can thus be obtained according to prescriptive guidelines given the computed short and long period spectral acceleration ordinates, but given the short and long period spectral acceleration ordinates of an earthquake that has already occurred does not necessarily lead to the corresponding return period of the corresponding ground motion (Gülkan, 2013). Flagrant conflict between them would imply a fundamental issue that must be resolved. To this end we present collectively and in the same order as in Appendix A the design spectra for four return periods in the Turkish Regulation and the corresponding response spectra for 5 percent damping in Appendix B of the digital supplement to this paper.

EVOLUTION OF THE SPECTRAL SHAPE SPECIFIED IN TURKISH REGULATIONS

A word is in order at this point concerning the evolution of the spectral shapes that successive updates of the Turkish Regulation have prescribed. This brief account is partly excerpted from Gülkan (2000).

The first seismic building regulation issued after the creation of the Ministry of Reconstruction and Resettlement is dated 1961. The title of the regulation was cumbersome: "Regulation for Buildings to Be Built in Disaster Areas" (the title survived with minor changes in wording until 2019). Where they existed municipal governments were designated as enforcers of the regulation, an experience that turned out to be an illusion. The text ignored the dynamic character of seismic design, and did not provide any guidance on the distribution of the base shear or its dependence on the building period or the effects of local geology. We will not consider this document further.

Following the 1967 earthquake in Mudurnu Valley-Adapazarı revised Regulation was issued in 1968 (TER 1968). In addition to the customary detailing and construction requirements this document contained an improvement over its predecessor because the base shear coefficient C was made a function of the calculated fundamental period of the building, and the inverted triangular distribution of the story level lateral forces was formulated. In terms of the basic magnitude of the lateral force, little was changed. The base shear coefficient $C = C_0 \alpha \beta \gamma$ where C_0 is the zone factor that we may interpret as the indicator of hazard varied for three zones from 0.06 to 0.02. The coefficient α was called the "soil" factor, and varied between 0.8 – 1.2, increasing for soft soil condition descriptions, β was the importance factor, and equaled 1.5 for critical facilities including all public assembly buildings and 1.0 for most others. The factor γ was the dynamic coefficient, and for a period $T < 0.5$ s, it equaled 1.0. For $T > 0.5$ s, $\gamma = 0.5/T$. This way, the constant velocity fall-off in the acceleration spectrum (T_s or T_B in current parlance) was fixed for a period of 0.5 s.

The 1975 (TER, 1975) issue of the Regulation addressed a conflict in the number of seismic zones, and brought many additional requirements in the design and detailing of reinforced concrete buildings. This update was influenced partly by the SEAOC "Blue Book," the California design requirements of the time. One important revision was the increase of the basic base shear coefficient for the highest hazard Zone 1 from 0.06 to 0.10, a 67 percent increase. The remaining zones were also proportionately increased. The 1975 regulation (TER 1975) is generally considered to be an adequate seismic regulation for its time. The design spectrum is displayed in Panel (a) of Figure 4 where the rightward shift of the various curves is in harmony with soil classification. The constant velocity roll-off periods ranged from about 0.45 s (Type I) to 1.0 s (Type IV). The penultimate revision of the Regulation became effective in 1998, accompanied, for the first time, by a probabilistically determined hazard map of zones. The Regulation was augmented in 2007 with the inclusion of retrofit requirements, but the part dealing with the equivalent static force was unchanged. The design spectrum is shown in Panel (b) of Figure 4. In the interest of a "safety margin" the decay of the spectral coefficient with increasing period was formulated as $T^{0.8}$. This contravenes the structural dynamics principle and both the 1968 and the 1975 Regulations (TER 1975, 1998) but it imitated the UBC-1994 stipulation except that the power of T in the denominator was fixed arbitrarily at 0.8. The corner periods T_A and T_B were tabulated *a priori*, in keeping with former versions (Table 3). Regulation was next changed in 2019 as in ASCE7-16 but the reference return period was made the ubiquitous number 475 years, rather than two-thirds of the 2475-year ordinate. The description of the procedure for arriving at the design spectrum is summarized in Figure 4. Note that, except for notation, it is identical to ASCE7-16 (Akansel et al., (2021).

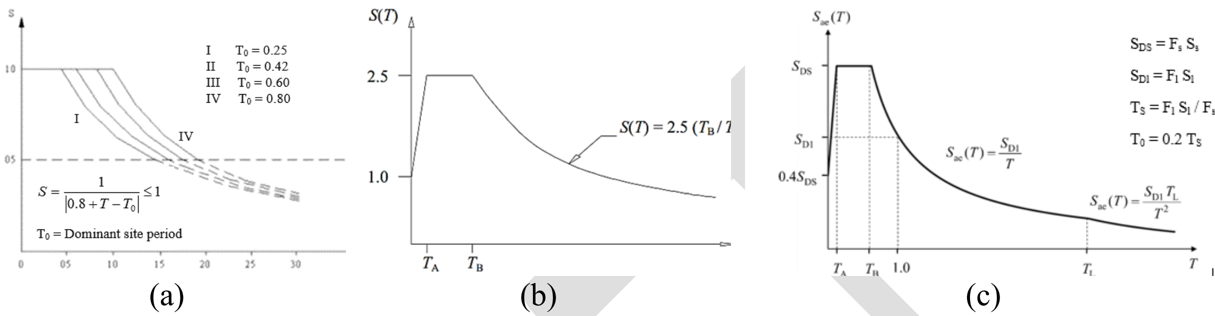

Figure 4. (a) Spectral coefficient in the (a) 1975, (b) 1998, 2007, (c) 2018 Turkish Building Earthquake Regulation

Table 3. Corner periods per TER (1998)

Local Site Conditions	T_A (seconds)	T_B (seconds)
Z1	0.1	0.3
Z2	0.15	0.4
Z3	0.15	0.6
Z4	0.2	0.9

Assuming that the soil profile descriptions between the 1975 and 1998 issues match exactly (they don't, but for purposes of this discussion they can be assumed roughly to correspond) then the roll-off periods have been revised as given in Table 4.

Table 4. T_B comparison between 1975 and 1998 (2007) Regulations

Soil Type (1975)	T_B, s		Soil Type (1998)	T_B, s
I	0.45		Z1	0.3
II	0.62		Z2	0.4
III	0.8		Z3	0.6
IV	1.0		Z4	0.9

We examine the suitability of the most recent shape in Panel (c) of Figure 4 by using selected acceleration time series from the database of the National System in Turkey and drawing their response spectra. We overlay these curves with design spectra for several return periods for precisely the same coordinates and same soil classes as extracted from the national hazard map. We posit that, while response and design spectra don't serve the same purpose, there needs to be a loosely confirmatory similarity between their shapes. No one knows the return period for a given response spectrum drawn for a particular ground motion, and there exists no metric to judge the goodness of that response spectrum for the design spectrum of the site where its time series has been recorded.

On each panel of Figure 5, we mount the four different return period design spectra per TBER captured at each particular station.

DATABASE

The information listed in Table A.1 of Appendix A forms the basis of this article. We list the National Network station information including their names, station designations, coordinates, site classes, epicentral distance and earthquakes and their dates that triggered the transducer in that station. Our focus is on ground motion records with PGA larger than 0.1 g. The corresponding color-coded soil types are given in Figure 6 and the maximum recorded PGA values of the stations are given in Figure 7. The highest PGA values recorded at Stations 1402, 4504 and 4107 are 807 cm/ s^2, 700 cm/s^2 and 612 cm /s^2 located at Bolu, Demirci and İzmir during the 1999 Düzce, 2011 Simav and 1999 Kocaeli earthquakes, respectively.

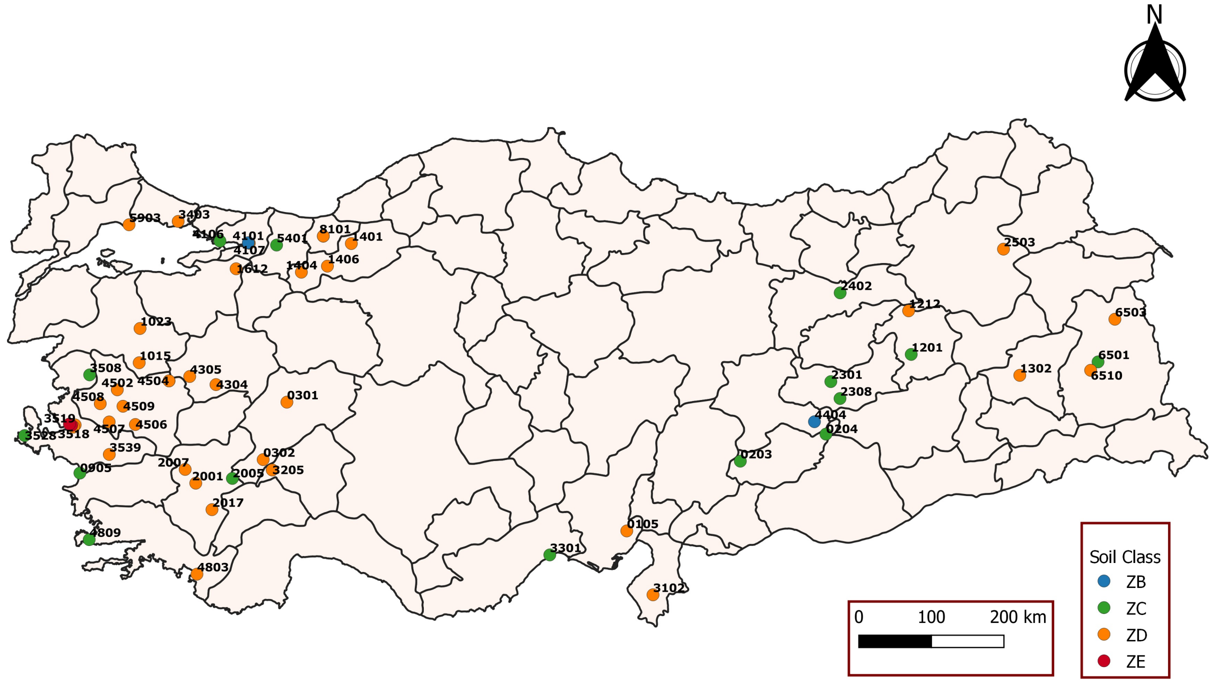

Figure 5. Soil Types of the stations given in Appendix A, Table A.1.

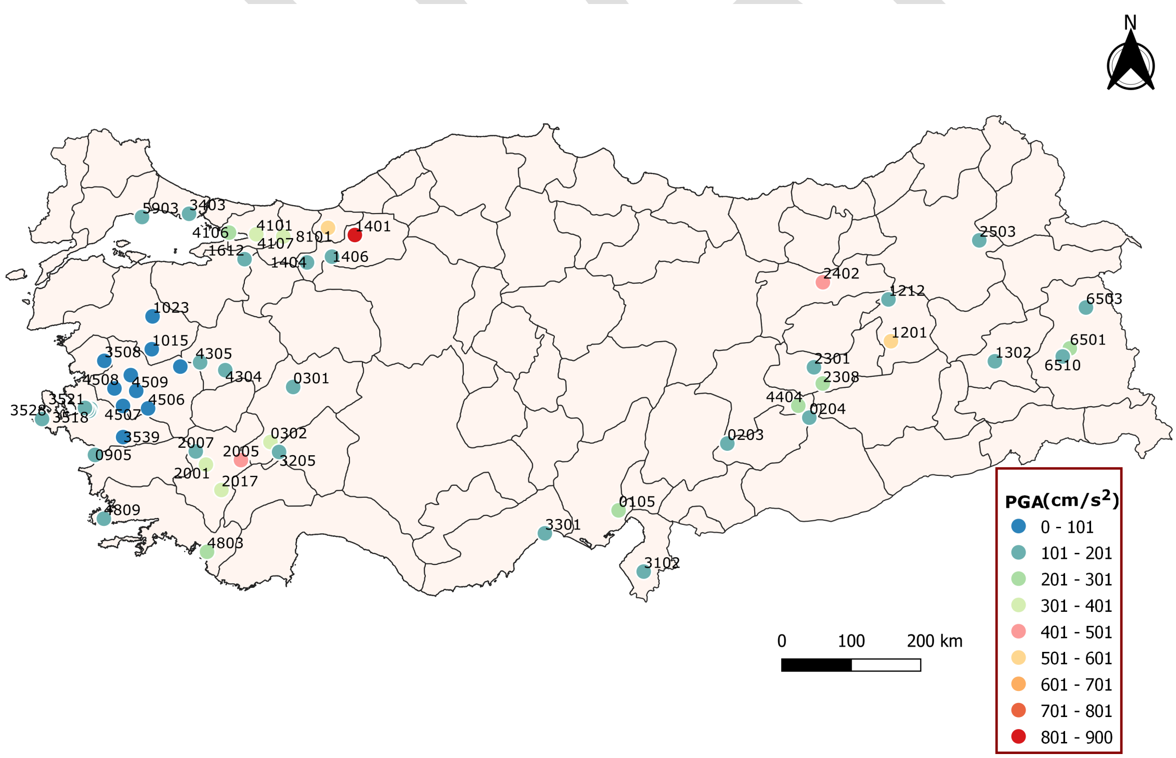

Figure 6. Maximum PGA values recorded at the stations given in Appendix A, Table A.1.

The basic challenge is, given magnitude, distance and the site geology can we come up with a model that tells us in broad terms what ground shaking to expect during a future earthquake? Is that confirmed by physical evidence? This is of crucial importance in achieving the safety objectives of rational design in addition to providing and explanation of the complex chain of events that cause an earthquake to nucleate and waves move away from the source. The processes that occur in the crust of the earth are poorly known, however, and do not lend themselves to formulations based on the fundamental natural laws of science. This has forced engineers and earth scientists to resort to statistics in the hope that future earthquakes will mimic past ones in some way. They do, statistically speaking, but each earthquake still harbors enough differences from our collection of instruments of predictive power to foreshadow what ground motion will occur at a given point given an earthquake nearby. A compendium assembled by Douglas (2018) is instructive in displaying the magnitude of the intellectual capital that has been invested in ground motion modeling equations (GMMEs).

COMPARISON WITH MEASURED SPECTRA

A fanciful question may now be framed as follows. If the response spectra from recorded ground motions at each station listed in Appendix A were to be compared with the design spectra for the same geographical location for the same four levels that TBER (2018) says it will be on average every pre-specified number of year windows over very long periods of time for the same soil class of that station, then how similar are these curves? In Figure 7, this comparison is given at 10 selected stations whose cells have been accentuated in Appendix A. We refrain from up- or down-scaling the measured ground motion time series so that the spectra match at some period. Figure 7 is devoted to a visual answer to this question. Both sets of curves share the same scales, but the focus is on how well the design spectral shape implies the measured spectra. The Izmit

(Station 4501) and Düzce (8101) stations have two different records from two different earthquakes. The two different events seem to yield similar spectral shapes and higher Sa values past T_B among themselves. The shift in the T_B can also be observed but that bears no similarity to the design spectra for the same locations. Owing to lack of space we only show a limited number of curves in Figure 7 and the rest of the figures for the selected stations are given in Appendix B of the digital supplement of this paper.

The sizeable number of curves in Appendix B shows that there is period conflict between implied spectral demands according to the current Turkish Regulation and the measured earthquake ground motions. In the 0.9 s – 1.6 s range that discord is strongest. This range corresponds to the first period of many of the 8 – 15 story buildings in the stock that is being developed today. Extrapolation of this observation leads to an important question that begs an answer: if all buildings during the next thirty years are designed using the spectral shape in the Turkish Regulation of 2019 (TBER, 2018) do we run the risk of exposing part of the future building stock to possible deficient capacity in the long period range? Amplification factors F_s and F_l that omit dependence on ground motion frequency are partially responsible for that anomaly. The conflict may be explained also by recalling that S_{DS} and S_{Dl} are the medians of a roughly normally distributed dispersion where variability of the random disturbance is different across elements of the vector. Their distribution is heteroscedastic. The variability in S_{DS} and S_{Dl} must be different, so considering upper and lower one-sigma ranges of the short and long period spectral acceleration ordinates leads to nine different estimates of T_S (or T_B). Then the transition from the constant acceleration to the constant velocity part of the spectrum becomes diffused, unlike the earlier neatly pre-ordained, profile-dependent periods. An added source for the conflict may be the variable values for F_a (or F_S) and F_v (or F_l) that decrease with increasing S_s and S_l that are partly judgmental (Borcherdt, 2012).

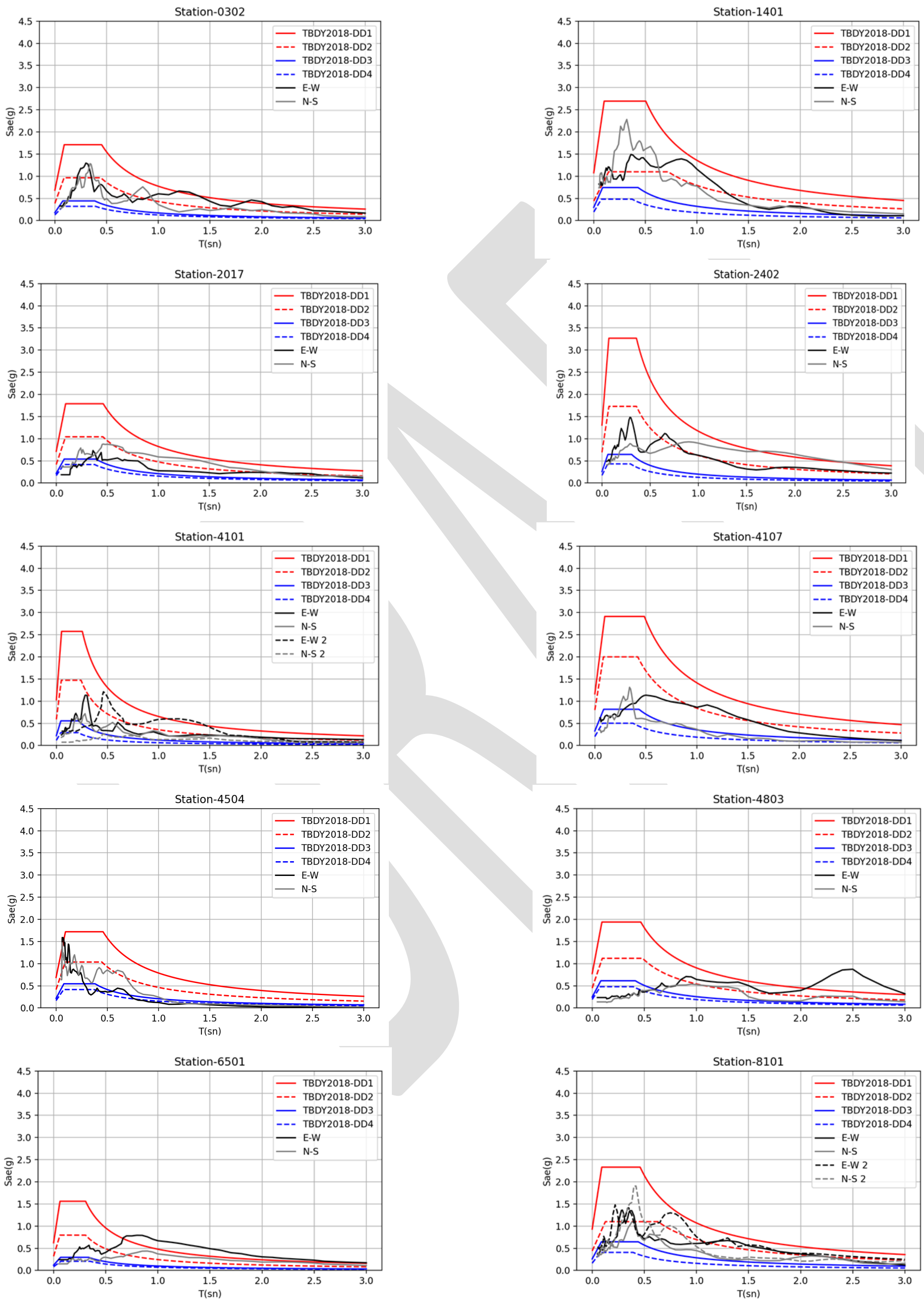

Figure 7. Spectral accelerations at 10 selected stations and DD1 to DD4 design spectra according to TBER (2018) (Dinar (0302); Bolu (1401); Acıpayam (2017); Erzincan (2402); İzmit (4101, Kocaeli); İzmit (4107); Demirci (4504); Fethiye (4803); İpekyolu (6501); Düzce (8101)

We refrain from up- or down-scaling the measured ground motion time series so that the spectra match at some period. Appendix B, a digital supplement of this paper, is devoted to a visual answer to this question. Both sets of curves share the same scales, but the focus is on how well the design spectral shape mimics and covers the measured spectra. A substantial number of the curves show that there is period conflict between implied spectral demands according to the current Turkish Regulation and the measured earthquake ground motions. In the 0.9 s – 1.6 s range that conflict is strongest.

DISCUSSION AND CONCLUSIONS

Every earthquake harbors its own subtle messages. We need to learn to interpret them for better protection of the public. In this narrative, we have focused on the design implications of the ground acceleration records at hand from the national network in Turkey. A new seismic Regulation has gone into effect at the beginning of 2019, and it is an opportune time now to evaluate some of its properties as an instrument of structural design. Of course, seismic design requirements don't all relate to the narrow band of items that deal with the spectral properties of future ground motions, but ultimately, they control a good many of those requirements in some complex way. As end users of our observations we cannot drape a gauze over our eyes and hope that the design spectrum shape will correspond to the response spectrum of a future earthquake. Instead, we must compare what nature has said to us with our anticipation of codified wisdom in technical documents. We find evidence that the design spectrum in the new Turkish Regulation (and ASCE7-16 on which it is based) may miss the longer period demands of earthquakes yet to occur. The design spectrum for a short return period is related to a different set of possible nearby fault ruptures than one that is governed by the foretold ground motions for longer return period events that nucleate elsewhere. One standard shape fails to cover both of these eventualities. We note also that for T_B = 1 s we must have $S_{DS} = S_{DL}$, but no station site in Turkey has a design spectrum that fits that condition. But urban sites do exist. A corollary of this is that, deep alluvial basin sites are dangerously exposed as confirmed by the October 30, 2020 off Sisam (Samos) earthquake. This might lay a trap for future designs.

There may be other plausible causes of the dissimilarity, but we surmise that the compounded uncertainty in weaving together ingredients of a hazard map represented by S_s, S_l, and adding F_s and F_l to come up with a design spectrum may be an unwarranted simplification because dissimilar ingredients are blended together. The topic needs further investigation that must include actual sample design comparisons among the regulations that have been included here for reference. The revision for the shape of the spectrum is reflected in different ways in the designs performed according to them because requirements for other facets of the design process have themselves been subjected to changes as well. This examination has not included that aspect. Regardless of how attractive a hazard map looks to the eye, if the design spectra it engenders don’t match facts most of the time then it may not serve as a reliable design instrument. The quest for the Holy MacGuffin is not answered by the newly developed hazard map for Turkey. Despite older age, we suggest that earlier Regulation requirements for pushing T_B pre-emptively to longer values represents a better idea.

ACKNOWLEDGMENTS

The ground acceleration records recovered from the Turkish National Strong Motion Network have been incorporated into this report as courtesy of AFAD, the Natural Disaster and Emergency Management Authority of Turkey. Authors are grateful to Ozan Öğünç and Mehmet Artun Baki for their help at the arrangement of the ground motion data and the spectrum plots.

DIGITAL SOURCE:

The list of stations with 0.1g and higher PGA is given in Table A.1 of APPENDIX A. The visuals that complement Figure 7 can be viewed or downloaded from link: https://bit.ly/31JEvxa.

References

AFAD (2020) https://tadas.afad.gov.tr/

ASCE/SEI (2016). Minimum design loads for buildings and other structures, ASCE7-16. American Society of Civil Engineers/Structural Engineering Institute, Reston, VA.

Boore, D. M., J. P. Stewart, E. Seyhan, and G. M. Atkinson (2014). NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes, Earthquake Spectra 30(3), pp. 1057-1085.

Borcherdt, R.D. (1994). Estimates of Site-Dependent Spectra for Design (Methodology and Justification), Earthquake Spectra, 10(4), pp. 617-653.

Borcherdt, R.D. (2012). V_{S30} – A Site-Characterization Parameter for Use in Building Codes, Simplified Earthquake Resistant Design, GMPEs, and ShakeMaps, Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal.

Douglas, J. (2019). Ground motion prediction equations 1964-2018. Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK (available online at https://www.strath.ac.uk/staff/douglasjohndr/).

Guéguen P., Bonilla F., Douglas J. (2018). Comparison of Soil Non-Linearity (In-Situ Stress-Strain Relation and G/Gmax Reduction) Observed in Strong-Motion Databases and Modelled in Ground Motion Prediction Equations, Bulletin of the Seismological Society of America, doi:10.1785/0120180169.

Gülkan, P. (2000). Building Code Enforcement Prospects: Failure of Public Policy. Chap. 15 of 1999 Kocaeli, Turkey, Earthquake Reconnaissance Report, Supplement A to Volume 16, Earthquake Spectra, December, pp. 351-367.

Gülkan, P. (2011). The Turkish National Accelerometric Network: 1973-2010, in *Accelerometric Data Exchange and Archiving*, Ed. S. Akkar, P. Gülkan and T. Van Eck, Elsevier.

Gülkan, P. (2013). A Dispassionate View of Seismic Hazard Assessment. Seismological Research Letters, (84)3: 413-416.

Gülkan, P., U. Çeken, Z. Çolakoğlu, T. Uğraş, T. Kuru, A. Apak, J.G. Anderson, H. Sucuoğlu, M. Çelebi, D.S. Akkar, U. Yazgan, A.Z. Denizlioğlu (2007). Enhancement of the National Strong Motion Network in Turkey, Seismological Research Letters, (78)4: 429-438.

Housner, G. W. (1959). "Behavior of Structures during Earthquakes," Proc. ASCE, **85**, October.

Housner, G. W. and Jennings, P. C. (1982). Earthquake Design Criteria, Earthquake Engineering Research Institute, Berkeley, Calif., 1982.

International Conference of Building Officials (1994). Uniform Building Code, Whittier, CA 90601 USA.

International Conference of Building Officials (1997). Uniform Building Code, Whittier, CA 90601 USA.

Kaklamanos, J., A. Cabas, S. Parolai, and P. Guéguen (2021). Introduction to the Special Section on Advances in Site Response Estimation, Bull. Seismol. Soc. Am. 111, 1665–1676, doi: 10.1785/0120210152

Kalkan, E., and Gülkan, P. (2004). Site-dependent spectra derived from ground motion records in Turkey. Earthquake Spectra, 20(4), 1111-1138.

Loviknes, K., S. R. Kotha, F. Cotton, and D. Schorlemmer (2021). "Testing Nonlinear Amplification Factors of Ground-Motion Models," Bull. Seismol. Soc. Am. 111, 2121–2137, doi:10.1785/0120200386/

Newmark, N. M. and Hall, W. J. (1982). "Earthquake Spectra and Design," Earthquake Engineering Research Institute, Berkeley, California.

Seed, H.B., C. Ugas and J. Lysmer (1976). Site-Dependent Spectra for Earthquake-Resistant Design, Bulletin of the Seismological Society of America. Vol. 66, No. 1, pp. 221-243.

Seyhan, E. and Stewart, J.P. (2014). Semi-Empirical Nonlinear Site Amplification Factors from NGS West2 Data and Simulations, Earthquake Spectra, 30(3), pp. 1241-1256.

Turkish Building Earthquake Regulation (TBER) (2018). Turkish Building Earthquake Regulation, Disaster and Emergency Management Authority (AFAD), Ankara.

Turkish Building Earthquake Regulation (TBER) (2018). Turkish Building Earthquake Regulation, Disaster and Emergency Management Authority (AFAD), Ankara, Turkey.

Turkish Earthquake Regulation (TEC) (1968). Regulation for Buildings to Be Built in Disaster Areas, Ministry of Public Works and Settlement, Ankara, Turkey.

Turkish Earthquake Regulation (TEC) (1975). Regulation for Buildings to Be Built in Disaster Areas, Ministry of Public Works and Settlement, Ankara, Turkey.

Turkish Earthquake Regulation (TEC) (1998). Regulation for Buildings to Be Built in Disaster Areas, Ministry of Public Works and Settlement, Ankara, Turkey.

Veletsos AS, Newmark NM. (1964). Response Spectra for Single-Degree-of-Freedom Elastic and Inelastic Systems. Report No. RTD-TDR-63-3096, Vol. III, Air Force Weapons Laboratory, Albuquerque, NM.

APPENDIX A

Table A.1 The selected stations which have PGA larger than 0.1 g

Stations	Station Name	Long	Lat.	ZS	S_S DD1	S_S DD2	S_S DD3	S_S DD4	S_1 DD1	S_1 DD2	S_1 DD3	S_1 DD4	Event ID	Event Date	M	PGA (cm/s^2) NS	PGA (cm/s^2) EW	R_{jb} (km)	R_{rup} (km)	R_{epi} (km)	R_{hy} (km)
0105	Adana Ceyhan	35.82	37.03	ZD	1.3	0.6	0.2	0.2	0.3	0.2	0.1	0.0		27-06-1998 13:55	6.2	223.3	273.6	40.0	58.2	48.2	67.0
0203	Adıyaman Akçakaya	37.66	37.79	ZC	2.4	1.2	0.4	0.3	0.7	0.3	0.1	0.1		05-05-1986 03:35	6	114.7	76.0	23.9	24.0	29.2	29.6
0204	Gerger	39.03	38.03	ZC	1.7	0.9	0.3	0.2	0.4	0.2	0.1	0.1	457758	24-01-2020 17:55	6.8	94.3	110.1	30.9	30.9	36.8	37.7
0301	Afyonkarahisar Merkez	30.53	38.78	ZD	1.6	0.8	0.3	0.2	0.4	0.2	0.1	0.0	241600	03-02-2002 07:11	6.5	112.8	93.9	51.7	57.7	64.7	68.4
0302	Dinar	30.15	38.06	ZD	1.7	0.8	0.3	0.2	0.4	0.2	0.1	0.1	240861	01-10-1995 15:57	6.4	272.3	320.8	0.0	2.9	0.5	5.0
0905	Kuşadası	27.27	37.86	ZC	2.0	1.1	0.4	0.3	0.5	0.3	0.1	0.1	483762	30-10-2020 11:51	6.6	179.3	144.0	35.6	41.1	42.9	46.0
1201	Bingöl Merkez	40.50	38.90	ZC	2.8	1.6	0.6	0.4	0.8	0.4	0.2	0.1	236848	01-05-2003 00:27	6.3	501.4	297.5	2.2	5.8	11.8	15.5
1212*	Yedisu	40.54	39.44	ZD	2.9	1.7	0.7	0.4	0.9	0.5	0.2	0.1	475667	14-06-2020 14:24	5.7	177.6	93.1			16.7	
1302*	Bitlis Merkez	42.16	38.47	ZD	1.2	0.6	0.3	0.2	0.3	0.2	0.1	0.1	141933	23-10-2011 10:41	7	89.7	102.2	107.0	110.0	116.0	117.6
1401	Bolu Merkez	31.61	40.75	ZD	2.7	1.5	0.5	0.3	0.8	0.4	0.1	0.1	246572	12-11-1999 16:57	7.1	724.0	807.0	8.0	8.6	36.1	37.6
1404	Bolu Göynük	30.78	40.40	ZD	1.5	0.8	0.3	0.2	0.5	0.3	0.1	0.1	247730	17-08-1999 00:01	7.6	138.0	119.2	44.2	45.7	80.7	82.5
1406	Bolu Mudurnu	31.21	40.47	ZD	1.8	1.0	0.4	0.2	0.5	0.3	0.1	0.1	246572	12-11-1999 16:57	7.1	58.3	121.0	32.1	32.3	37.5	39.0
1612	İznik Merkez	29.72	40.44	ZD	1.7	0.9	0.3	0.2	0.5	0.3	0.1	0.1	247730	17-08-1999 00:01	7.6	91.9	123.3	33.2	34.8	40.3	43.8
2001	Denizli Çamlık	29.09	37.76	ZD	2.1	1.1	0.4	0.3	0.5	0.3	0.1	0.1		19-08-1976 01:12	6.1	348.5	290.4	6.4	17.9	9.9	22.1
2005	Çardak	29.67	37.82	ZC	1.7	0.9	0.3	0.2	0.4	0.2	0.1	0.1	444581	08-08-2019 11:25	6	423.2	273.9			8.0	
2007	Denizli Sarayköy	28.92	37.93	ZD	2.3	1.2	0.5	0.3	0.6	0.3	0.1	0.1	253439	26-07-2003 08:36	5.6	107.5	121.1	11.2	22.0	13.8	25.4
2017	Acıpayam	29.35	37.43	ZD	1.8	0.9	0.4	0.3	0.4	0.2	0.1	0.1	433515	20-03-2019 06:34	5.5	361.2	184.4			7.4	
2301	Elazığ Merkez	39.19	38.67	ZC	1.7	0.9	0.3	0.2	0.5	0.3	0.1	0.1	457758	24-01-2020 17:55	6.8	118.1	137.8	30.4	30.5	36.4	37.3
2308	Sivrice	39.31	38.45	ZC	2.8	1.5	0.5	0.3	0.8	0.4	0.1	0.1	457758	24-01-2020 17:55	6.8	235.8	292.8	17.9	17.9	23.8	25.1
2402	Erzincan Merkez	39.49	39.75	ZC	2.7	1.4	0.5	0.3	0.8	0.4	0.1	0.1	236369	13-03-1992 17:18	6.6	405.0	479.5	3.3	16.8	12.8	26.0
2503	Erzurum Horasan	42.17	40.04	ZD	1.3	0.7	0.3	0.2	0.3	0.2	0.1	0.1		30-10-1983 04:12	6.6	149.3	168.7	22.6	24.7	34.5	38.1
3102*	Antakya Merkez	36.16	36.21	ZD	2.1	1.1	0.3	0.2	0.6	0.3	0.1	0.1		22-01-1997 17:57	5.7	136.0	150.5	19.2	46.8	19.8	49.5
3205*	Keçiborlu	30.30	37.93	ZD	1.6	0.8	0.3	0.2	0.4	0.2	0.1	0.1	444581	08-08-2019 11:25	6	161.2	109.3			63.1	
3301	Yenişehir	34.60	36.78	ZC	0.7	0.3	0.1	0.1	0.2	0.1	0.0	0.0		27-06-1998 13:55	6.2	132.1	119.3	57.5	71.2	64.9	79.9
3403	İstanbul Küçükçekmece	28.76	41.03	ZD	1.8	1.0	0.4	0.2	0.5	0.3	0.1	0.1	247730	17-08-1999 00:01	7.6	118.0	89.6	55.9	56.0	105.2	106.6
3513	Bayraklı	27.17	38.46	ZD	2.1	1.1	0.4	0.3	0.5	0.3	0.1	0.1	483762	30-10-2020 11:51	6.6	106.3	94.7	64.6	67.8	72.0	73.9

Table A.1 (Cont.) The selected stations which have PGA larger than 0.1g

Stations	Station Name	Long	Lat.	ZS	S_S DD1	S_S DD2	S_S DD3	S_S DD4	S_1 DD1	S_1 DD2	S_1 DD3	S_1 DD4	Event ID	Event Date	M	PGA (cm/s^2) NS	PGA (cm/s^2) EW	R_{jb} (km)	R_{rup} (km)	R_{epi} (km)	R_{hy} (km)
3518	Konak	27.14	38.43	ZD	2.1	1.1	0.4	0.3	0.5	0.3	0.1	0.1	483762	30-10-2020 11:51	6.6	106.1	91.4	61.0	64.3	68.4	70.3
3519	Karşıyaka	27.11	38.45	ZE	2.1	1.1	0.4	0.3	0.5	0.3	0.1	0.1	483762	30-10-2020 11:51	6.6	150.1	110.0	61.8	65.2	69.2	71.2
3521	Karşıyaka	27.08	38.47	ZE	2.1	1.1	0.4	0.3	0.5	0.3	0.1	0.1	483762	30-10-2020 11:51	6.6	110.8	94.0	62.2	65.5	69.6	71.5
3528	Çeşme	26.37	38.30	ZC	1.9	1.0	0.4	0.3	0.5	0.2	0.1	0.1	483762	30-10-2020 11:51	6.6	117.6	149.3	50.8	54.8	58.2	60.5
4101	İzmit Kocaeli	29.92	40.77	ZB	2.9	1.6	0.6	0.3	0.8	0.4	0.2	0.1	247730	17-08-1999 00:01	7.6	163.7	228.3	0.6	3.9	3.4	17.3
4101	İzmit Kocaeli	29.92	40.77	ZB	2.9	1.6	0.6	0.3	0.8	0.4	0.2	0.1	248095	13-09-1999 11:55	5.8	73.7	318.3	8.7	12.4	13.8	17.3
4106	Gebze	29.45	40.79	ZC	2.4	1.3	0.5	0.3	0.7	0.4	0.1	0.1	247730	17-08-1999 00:01	7.6	264.8	141.5	4.9	6.2	42.8	46.0
4107	İzmit	29.93	40.76	ZD	2.9	1.7	0.6	0.3	0.8	0.5	0.2	0.1	248095	13-09-1999 11:55	5.8	341.1	611.5	1.5	7.6	3.3	10.9
4304	Gediz	29.40	38.99	ZD	2.3	1.2	0.4	0.3	0.6	0.3	0.1	0.1	128573	19-05-2011 20:15	5.7	92.3	103.9			31.5	
4305*	Kütahya Simav	28.98	39.09	ZD	2.1	1.1	0.4	0.3	0.5	0.3	0.1	0.1	128573	19-05-2011 20:15	5.7	71.2	115.6			10.0	
4404	Pütürge	38.87	38.20	ZB	2.8	1.5	0.5	0.3	0.8	0.4	0.1	0.1	457758	24-01-2020 17:55	6.8	193.6	228.4	18.6	18.6	24.6	25.8
4504	Demirci	28.65	39.04	ZD	1.7	0.9	0.4	0.3	0.4	0.2	0.1	0.1	128573	19-05-2011 20:15	5.7	625.8	699.8	35.4	40.9	39.0	46.0
4803	Fethiye	29.12	36.63	ZD	1.9	1.0	0.4	0.3	0.5	0.3	0.1	0.1	167145	10-06-2012 12:44	6	136.2	230.1			32.6	
4809	Bodrum	27.44	37.03	ZC	1.8	1.0	0.4	0.3	0.5	0.2	0.1	0.1	381491	20-07-2017 22:31	6.5	158.8	102.0			12.6	
5401	Adapazarı	30.38	40.74	ZC	2.9	1.7	0.7	0.3	0.8	0.5	0.2	0.1	246561	11-11-1999 14:41	5.6	197.1	322.5	10.4	11.3	11.2	13.5
5903*	Çorlu M.Ereğlisi	27.95	40.97	ZD	1.9	1.1	0.4	0.3	0.5	0.3	0.1	0.1	247730	17-08-1999 00:01	7.6	90.4	101.4	116.9	116.9	170.8	171.6
6501	İpekyolu	43.40	38.50	ZC	1.3	0.6	0.2	0.2	0.3	0.2	0.1	0.0	146290	09-11-2011 19:23	5.6	148.1	245.9			13.5	
6503*	Van Muradiye	43.76	38.99	ZD	1.4	0.7	0.3	0.2	0.3	0.2	0.1	0.1	141933	23-10-2011 10:41	7	178.3	168.8	33.1	11.6	42.2	46.3
6510*	Van Edremit	43.27	38.41	ZD	1.2	0.6	0.2	0.2	0.3	0.2	0.1	0.0	146290	09-11-2011 19:23	5.6	65.7	102.6			3.7	
8101	Düzce Merkez	31.15	40.84	ZD	2.3	1.3	0.4	0.3	0.6	0.4	0.1	0.1	247730	17-08-1999 00:01	7.6	314.3	365.9	46.0	46.2	101.2	102.7
8101	Düzce Merkez	31.15	40.84	ZD	2.3	1.3	0.4	0.3	0.6	0.4	0.1	0.1	246572	12-11-1999 16:57	7.1	400.1	512.9	0.0	9.7	5.3	11.7

* Soil type at stations 1212, 1302, 3102, 3205,4305, 5903, 6503 and 6510 are assumed as ZD.