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RESEARCH ARTICLE

Fuzzy inference system model for the spectrum characteristic periods of the Türkiye Building Earthquake Code (2007)

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Abstract

Seismic design codes define response spectra with crisp numerical classifications of seismic parameters, which mainly affect the spectrum's shape and determination of seismic design loads. The efficiency of structural safety and construction costs depends on the optimum design and accurately determined seismic forces. As presented in the seismic design codes, several parameters are utilized to calculate the seismic design forces with response spectra. This study proposes a rule-based fuzzy inference system (FIS) model with fuzzy set numbers to determine the relevant parameters. By defining the soil profile thickness and shear wave velocity as inputs, the model generates the spectrum characteristic periods specified in the Türkiye Building Earthquake Code (TBEC 2007). The response spectra of twenty different samples with the FIS and crisp models were generated and compared to assess the model's superiority. Unlike crisp seismic code classifications, the proposed FIS model accounts for imperfections in soil group selection and topmost soil layer thickness, offering a more realistic representation of uncertainties and proving to be an effective tool for addressing linguistic vagueness in seismic response spectra analysis. The comparison between fuzzy and crisp output seismic parameters revealed significant differences in response spectra shape and spectrum intensity values. The FIS model-generated spectra were more conservative in certain building locations, while in others, they provided similar or lower values, suggesting potential cost savings in design. The FIS model demonstrates its efficacy in producing more accurate and robust designs by considering the uncertainties inherent in the problem. Furthermore, this approach has the potential to be extended to study seismic parameters of other design codes, although further research is required to comprehensively explore its capabilities and limitations.

1. Introduction

Structural engineering design and evaluation against seismic events necessitate typically seismic design codes and code-based provisions for the response spectra to impose seismic loads during structural analysis [1-2]. The input parameters utilized for response spectra production in seismic design include factors such as soil profiles, seismic zones, seismic coefficients and site classes. The aforementioned spectra-responsive parameters significantly impact seismic design forces, which play a crucial role in the appropriate structural

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system member designs, materials, dimensions and types. The accuracy of the parameter adaptation for response spectra generation is essential for ensuring project structural safety and construction costs. While seismic design codes often provide crisp parameter classifications, the impact of fuzzification, particularly when guided by expert supervision, provides membership degrees for factors such as structural safety and construction costs [3-5]. In real-world scenarios, fuzzification of seismic coefficients can alter the shape of the response spectrum and provides a plausible variation range in the calculated seismic loads. Thus, it is necessary to compare the results of different cases, including crisp model values and fuzzy inference system (FIS) outputs, to assess the impact of fuzzification on the response spectrum's shape and the corresponding seismic design loads. This comparison can help to determine the optimal method for achieving better design performance, which is crucial for ensuring seismic safety and cost-effectiveness. Since the seismic forces consist of higher-order vagueness, fuzzy logic accounts for a more rational method to predict and minimize the uncertainties in calculations.

The subsequent studies provide an overview of the essential principles of FIS model applications, including fuzzy logic fundamentals and how FISs can be utilized to address verbal uncertainties, complexities, complications, and vagueness [6-12]. As described in the following paragraph, several recent studies have incorporated fuzzy logic methods to combine seismic effects and/or response spectra with FIS models.

Mellal [13] developed a new approach that combined fuzzy set theory and a nonlinear numerical model to determine seismic response spectra for soil columns. The modified FIS method in the study allowed for the rapid derivation of response spectra by applying fuzzy arithmetic to certain input parameters. In a separate study, Wadia-Fascetti and Güneş [14] utilized statistical models to incorporate fuzzy logic and quantify uncertainties inherent in structural response as a result of ground motions. They also compared their proposed models with current design codes and suggested further implementation methods. Ansari and Noorzad [15] proposed a method based on fuzzy mathematics to express the effects of uncertainties in certain dynamic analysis parameters such as damping, mass, stiffness, and input excitation on the response spectra of seismic activity in lowlands. Marano et al. [16] incorporated fuzzy theory and a probabilistic approach to define a ground motion model to generate a fuzzy classical stochastic response spectrum evaluation in linear systems. In their study, the input structural parameters' variability was considered and compared with other available non-probabilistic approaches in the literature.

Şen [17] presented a fuzzy-logic-based computation model for the hazard categorization of existing buildings for the seismic hazard evaluation by rapid visual methods. The FIS presented in his paper demonstrated a robust application of fuzzy theory for the assessment of pre-earthquake resistance identification of buildings. Additionally, Şen [18] proposed another supervised fuzzy classification method for identifying hazard categories of individual buildings using different membership functions (MFs). Heidari and Khorasani [19] utilized the Adaptive Neural Network Fuzzy Inference System (ANFIS) to produce synthetic earthquake accelerograms that comply with specific response spectra. The proposed approach takes advantage of ANFIS's learning capabilities to establish a reverse mapping from response spectra to seismic records. It includes a set of illustrative recorded accelerograms to demonstrate the effectiveness of the proposed method. Ozkul et al. [20] introduced a fuzzy degrading model that accurately predicted inelastic displacement ratios of reinforced concrete structures in dynamic analyses, thereby helping to designate the most appropriate classical method to find the displacement ratios of degrading systems. Bektaş and Kegyes-Brassai [21] presented a fuzzy logic-based soft rapid visual screening (SRVS) method as an alternative to conventional rapid visual screening (RVS) methods to assess existing building stocks in earthquake-prone zones. The proposed method is developed based on the examination of 40 unreinforced masonry (URM) buildings data acquired as a consequence of the 2019 Albania earthquake. It aims to identify building safety levels using computer algorithms such as machine learning, fuzzy logic, and artificial neural networks. They established rules, MFs, necessary transformation and defuzzification procedures to construct the fuzzy logic-based SRVS method. Although Nahhas [22] previously developed a similar method for generating code-compliant seismic response spectra using a fuzzy model, there are no studies in the literature on acquiring seismic parameters by fuzzy logic for response spectra.

While various fuzzy logic-based methodologies, such as hybrid fuzzy, adaptive neuro-fuzzy inference system (ANFIS), fuzzy cognitive mapping (FCM), and fuzzy decision tree (FDT), are available for clustering multiple data, their efficiency varies. For instance, fuzzy cognitive maps (FCMs) and neuro-fuzzy inference systems (NFIS) are commonly employed for clustering purposes [23]. FCMs also serve as effective decision-making tools in data management [24-25]. Al-Fahdawi and Barroso [26] introduced adaptive neuro-fuzzy and simple adaptive control methods for three-dimensional coupled buildings under bi-directional seismic excitations. Ghani et al. [27] investigated earthquake-induced liquefaction behavior of fine-grained soils using an artificial intelligence-based hybridized model employing the adaptive neuro-fuzzy inference system. Mehrabi et al. [28] utilized intelligent fuzzy-based hybrid metaheuristic techniques to predict the seismic response of fiber-reinforced concrete columns. Tombari and Stefanini [29] proposed a hybrid fuzzy-stochastic approach for one-dimensional site response analysis, considering probability models for seismic input and fuzzy intervals for soil uncertainties. Guo et al. [30] assessed the seismic vulnerability of reinforced concrete structures using fuzzy theory and global vulnerability curves. Fuzzy logic-based methods offer the advantage of capturing logical relationships between input and output variables, surpassing crisp logic methodologies. Moreover, these approaches help mitigate numerical and lexical uncertainties through training and testing stages, leading to more reliable verification and validation results. However, a limitation of adaptive neuro-fuzzy inference systems is their partially black-box behavior concerning the internal generation mechanism of the system.

The primary objective of this study is to develop a Fuzzy Inference System (FIS) model using fuzzy sets, fuzzy membership functions (MFs) and fuzzy rules for certain soil profile input parameters. Many structures in Türkiye were designed considering the provisions of the previous seismic design code, the Türkiye Building Earthquake Code (TBEC 2007) [31], which was updated in 2018. Since the TBEC 2007 [31] was not prepared with any uncertainty, such as the probabilistic approach, fuzzy logic is functional to reflect the effect of imprecisions and vagueness alike. In this paper, the soil parameters of the response spectrum defined in the TBEC 2007 [31] are fuzzified to express the inherent vagueness using a fuzzy-based FIS modelling approach. Engineers and experts commonly use traditional crisp classifications and mathematical equations from seismic design codes to adopt a response spectrum for calculating seismic forces in structural analysis and assessment procedures. The proposed method has the potential to be adapted and applied to generate response spectra for other seismic codes with accuracy and precision improvements.

2. Türkiye Building Earthquake Code (2007) provisions

In many countries worldwide, including Türkiye, the seismic design of multi-story buildings is heavily influenced by the prevailing earthquake codes and standards established by the respective national authorities. These codes are periodically reviewed and updated to incorporate the latest advancements in seismic engineering research and practices. However, it is important to note that the implementation of updated codes takes time, and as a result, many existing buildings have been designed and constructed based on previous versions of the seismic design provisions.

Turning our focus specifically to Türkiye, a significant portion of the country's building stock comprises structures that were designed and constructed in accordance with the Türkiye Building Earthquake Code (TBEC) of 2007 [31]. This code represented the state-of-the-art seismic design practices at the time of its publication and played a crucial role in enhancing the seismic resilience of structures throughout the country. Nevertheless, as seismic engineering knowledge and understanding continue to evolve, it is essential to periodically reassess the performance of buildings designed under earlier codes to ensure their continued safety and resilience in the face of potential earthquakes. Ongoing efforts are being made by researchers, engineers, and regulatory bodies to improve seismic design standards and practices, taking into account the lessons learned from past earthquakes and advancements in the field of structural and earthquake engineering.

2.1. Response spectra

The spectral acceleration coefficient, $A(T)$, is taken as a basis for the determination of seismic loads in TBEC 2007 [31]. The structural analysis response spectrum is formed by acquiring the elastic spectral acceleration coefficient, $S_{ae}(T)$, which is the ordinate of the response spectrum corresponding to the product of $A(T)$, and the gravitational acceleration, g. A_0 is the effective ground acceleration coefficient, I is the building importance factor, and $S(T)$ is the spectrum coefficient. Thus, response spectra are the $S_{ae}(T)$ -T graphs that should be considered in the seismic analysis of structures, where T stands for the period values. An example response spectrum according to the TBEC 2007 [31] is shown in Fig. 1. The relationships between all the variables explained in this paragraph are given by the following formulations in TBEC 2007 [31].

$$A(T) = A_0\, I\, S(T) \tag{1}$$

$$S_{ae}(T) = A(T)\, g \tag{2}$$

2.1.1. Effective ground acceleration coefficient, A_0

The effective ground acceleration coefficient, A_0, is obtained through the earthquake zone of the building, which is found according to the earthquake zone map presented in Fig. 2. There are five main earthquake zones, which are based on the locations of the active fault lines, namely Zones 1, 2, 3, 4 and 5. Colours on the map differ considering high-risk (red) to low-risk (white) potential. For example, the red zones on this map show Zone 1, and the yellow zones show Zone 3 locations.

Four different effective ground acceleration coefficients A_0 are defined in TBEC 2007 [31], as shown in Table 1. Since no value is presented for Zone 5, the Zone 4 value can be used for the buildings in Zone 5.

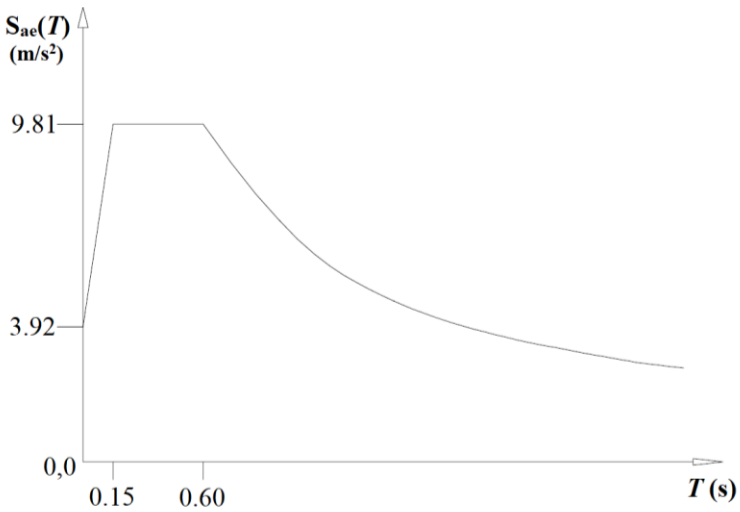


Fig. 1. An example response spectrum, according to TBEC 2007 [31]

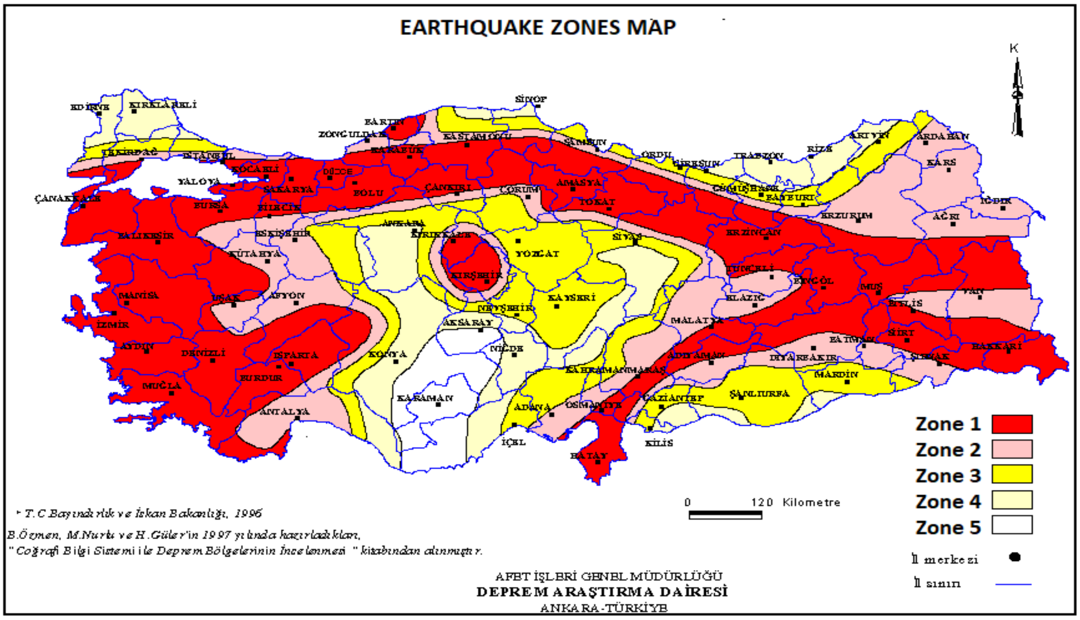


Fig. 2. Earthquake zones map of Türkiye [32]

Table 1. Effective ground acceleration coefficients, A_0 [31]

Earthquake Zone	A_0
1	0.40
2	0.30
3	0.20

2.1.2. Building importance factor, I

The building importance factor, I, is determined according to the purpose of occupancy or the type of the building. Table 2 shows the building importance factors defined in the code for different types of buildings.

2.1.3. Spectrum coefficient, $S(T)$

The spectrum coefficient, $S(T)$, is determined depending on the local soil profile and the building's natural period, T. The response spectrum shape is dependent mainly on spectrum coefficients. Its shape in terms of spectral coefficients is given in Fig. 3, which is formed according to the following three mathematical expressions. Here, T_A and T_B correspond to the spectrum characteristic periods given in Table 3, depending on the local soil classes based on the detailed classification.

$$S(T) = 1 + 1.5\frac{T}{T_A} \qquad (0 \leq T \leq T_A) \tag{3}$$

$$S(T) = 2.5 \qquad (T_A \leq T \leq T_B) \tag{4}$$

$$S(T) = 2.5\left(\frac{T_B}{T}\right)^{0.8} \qquad (T_B \leq T) \tag{5}$$

Table 2. Building Importance Factors, I [31]

The Purpose of Occupancy or Type of the Building	Building Importance Factor, I
1. The buildings to be used first priority after an earthquake and the buildings containing hazardous materials: a) The buildings required to be utilized immediately after the earthquake (Hospitals, dispensaries, healthcare centres, fire stations and facilities, post office departments and other telecommunication facilities, transportation stations and terminals, power generation and distribution facilities; provincial halls, county and municipality administration buildings, first aid and emergency planning stations). b) The buildings containing or storing toxic, explosive and flammable materials 1	1.5
2. Intensively and long-term occupied buildings and the buildings preserving valuable goods: a) Schools, other educational buildings and facilities, dormitories and hostels, military barracks, and prisons. b) Museums.	1.4
3. Intensively and short-term occupied buildings: Sports facilities, cinemas, theatre and concert halls.	1.2
4. Other buildings: The buildings without the above definitions. (Residential and office buildings, hotels, and building-type industrial structures)	1.0

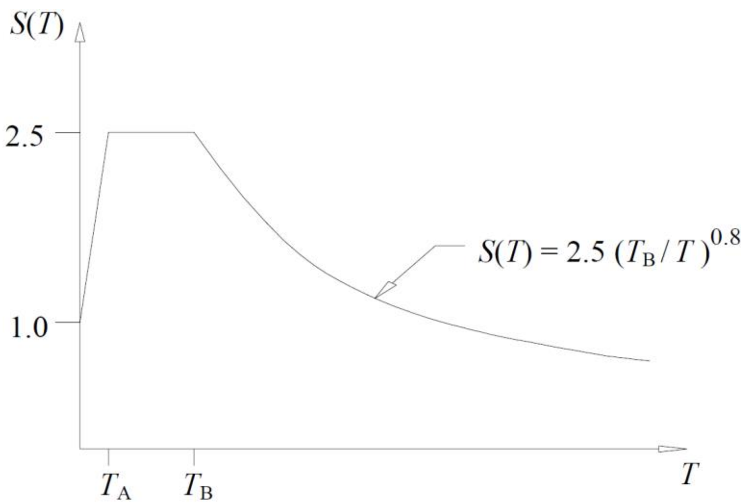


Fig. 3. Spectrum coefficients of the response spectrum [31]

Table 3. Spectrum characteristic periods, T_A and T_B [31]

Local Soil Class	T_A	T_B
Z1	0.10	0.30
Z2	0.15	0.40
Z3	0.15	0.60
Z4	0.20	0.90

2.2. Local soil classification

Four different local soil classes are defined in TBEC 2007 [31] for considering the seismic properties of the soil profile under the structures as Z1, Z2, Z3 and Z4. Determination of the local soil classes is mainly based on two different parameters, namely, the soil group (soil type) and the thickness of the foundation soil layer. Thus, if the soil profile of the building location is determined in terms of these variables, the local soil class and corresponding spectrum characteristic periods are then found under the light of the previous section.

TBEC 2007 [31] provides two tables for the determination of these soil conditions. Table 4 is for the soil groups definition as (A), (B), (C) and (D) according to the standard penetration (N/30) test results, relative density, unconfined compressive strength and shear velocity. One of the most distinctive and predominant variables among the soil group specification is the shear wave velocity, which is accepted globally as the seismic behaviour and hazard risk of soils' determinant value. In this study, it is considered as the input for the determination of the soil group. Table 5 shows the topmost soil layer thickness values. The thickness threshold values consist of 10 m, 15 m, and 50 m. If the soil group and the topmost layer thickness are determined, then the local soil class is found in this table.

Table 4. Soil groups

Soil Group	Description of the Soil Group	Standard Penetration (N/30)	Relative Density (%)	Unconfined Compressive Strength (kPa)	Shear Wave Velocity (m/s)
(A)	**1.** Massive volcanic rocks and unweathered solid metamorphic rocks, stiff cemented sedimentary rocks	-	-	> 1000	> 1000
	2. Very dense sand, gravel	> 50	85-100	-	> 700
	3. Hard clay and silty clay	> 32	-	> 400	> 700
(B)	**1.** Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity	-	-	500-1000	700-1000
	2. Dense sand, gravel	30-50	65-85	-	400-700
	3. Very stiff clay, silty clay	16-32	-	200-400	300-700
(C)	**1.** Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity	-	-	< 500	400-700
	2. Medium-dense sand and gravel	10-30	35-65	-	200-400
	3. Stiff clay and silty clay	8-16	-	100-200	200-300
(D)	**1.** Soft, deep alluvial layers with high groundwater level	-	-	-	< 200
	2. Loose sand	< 10	< 35	-	< 200
	3. Soft clay and silty clay	< 8	-	< 100	< 200

3. Fuzzy model

A Fuzzy Inference System (FIS) model alternative, the Mamdani method [9-10], is employed to estimate spectrum characteristic periods (T_A and T_B) of the response spectra. The model has two input variables, namely the thickness (h_1) and the shear wave velocity (V_s) of the topmost soil layer, and outputs the spectrum characteristic periods, , T_A or T_B. The input and output variables are described in the form of fuzzy sets. After the fuzzification of input variables and writing down the fuzzy logic rule base between the inputs and outputs, the results appear in non-normal fuzzy set forms, which are defuzzified to obtain a crisp value for the spectrum characteristic periods. The process of generating spectrum characteristic periods using the FIS model involves a mechanism that combines expert opinions of input variables' fuzzy sets to output fuzzy sets through a fuzzy rule base. Considering the soil group and soil class, each rule in the fuzzy rule base establishes a connection between the fuzzy input sets and the spectrum characteristic periods, which are the outputs of the model.

The FIS model is implemented using MATLAB [33] software fuzzy logic controller tool due to its precision and practicality. Figure 4 shows the estimation mechanism of the proposed FIS model for both spectrum characteristic periods, T_A or T_B. While the model determines both period values, the output membership functions (MFs) and rule bases differ. The proposed model has adaptability potential and applicability to other seismic design codes beyond TBEC 2007 [31]. This could lead to more precise and accurate estimates of seismic variables used in the response spectrum generation.

3.1. Membership functions (MFs)

MFs with triangular and trapezium shapes are considered for each input and output variable in fuzzification procedures. The topmost soil layer thicknesses, h_1, are fuzzified by considering the related table of local soil classification given in the code, as described in Section 2.2. The transition between peak thickness values is determined by triangular-shaped fuzzy sets. The topmost soil layer thickness (h_1) MFs are given in Fig. 5 as "Very Low", "Low", "Medium", and "High".

Similarly, the soil groups are fuzzified by considering the shear wave velocity values as described in Section 2.2. The transition between peak shear wave velocity values is specified by triangular-shaped fuzzy sets. The shear wave velocity MFs connected to soil groups are shown in Figure 6 as "D", "C", "B", and "A".

Each spectrum characteristic period (TA or TB) is categorized according to four local soil classes in terms of fuzzy sets as "Z1", "Z2", "Z3", and "Z4" based on the code provisions in Section 2.2. The MFs of these outputs are shown in Fig. 7. Fig. 5-7 are for the input and output fuzzifications consisting of trapezium MFs for the initial and final sets, each with two triangular MFs in between.

Table 5. Local soil classes [31]

Local Soil Class	Soil Group and Topmost Soil Layer Thickness (h_1)
Z1	Group (A) soils Group (B) soils with $h_1 \le 15$ m
Z2	Group (B) soils with $h_1 > 15$ m Group (C) soils with $h_1 \le 15$ m
Z3	Group (C) soils with 15 m $< h_1 \le 50$ m Group (D) soils with $h_1 \le 10$ m
Z4	Group (C) soils with $h_1 > 50$ m Group (D) soils with $h_1 > 10$ m

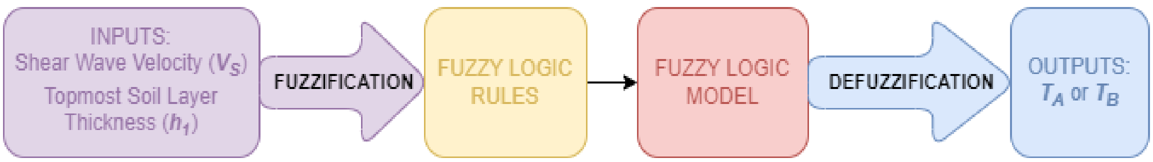


Fig. 4. FIS model's estimation mechanism

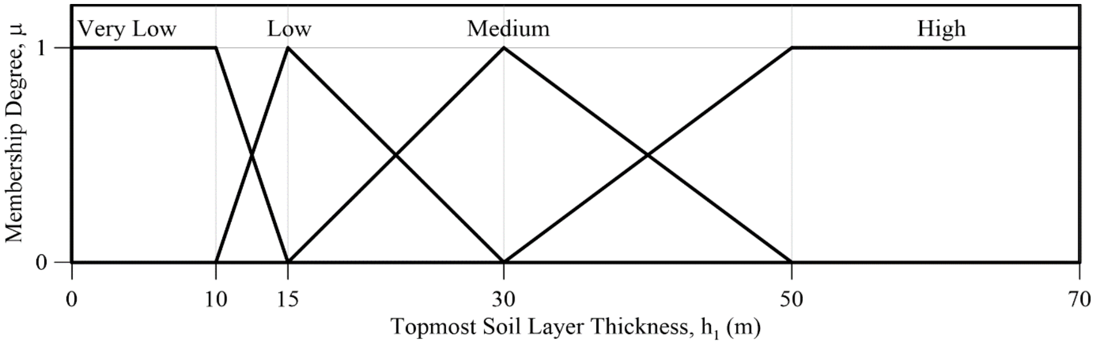


Fig. 5. Membership functions of topmost soil layer thickness (h_1)

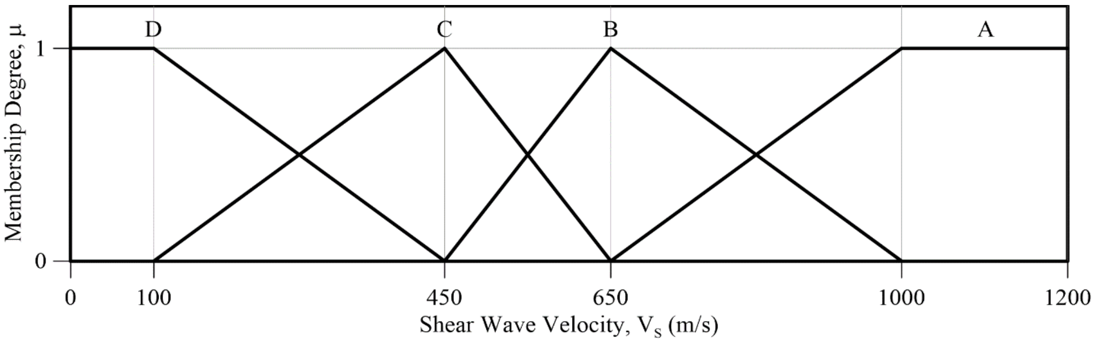
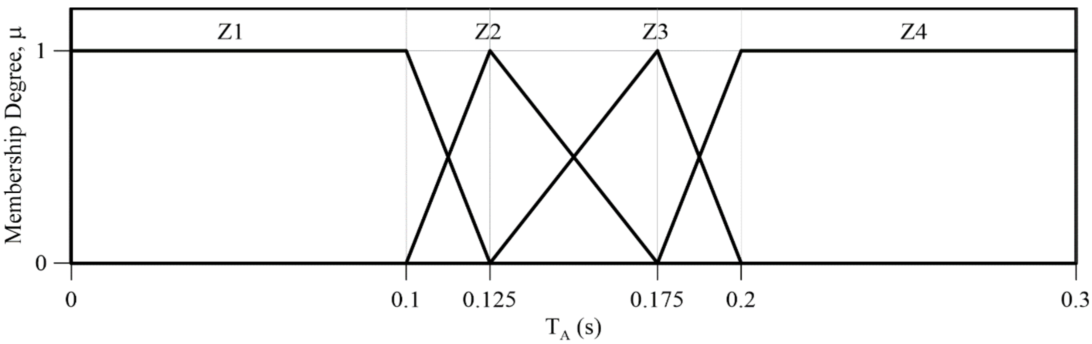
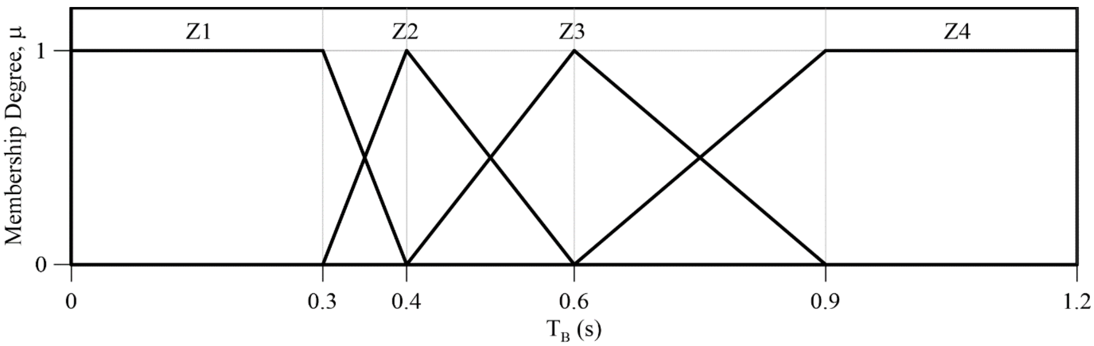


Fig. 6. Membership functions of shear wave velocity (V_s)



(a)



(b)

Fig. 7. Membership functions of spectrum characteristic periods, (a) T_A and (b) T_B

3.2. FIS and rule base

The logical connection between the input and output variables is possible by a rule base that consists of expert opinions in line with the code provisions. With four MFs assigned to each input variable, the fuzzy rule base (FRB) consists of 16 combinations for the logical system of each MF in input variables, as in Fig. 5 and 6. Each rule follows a general structure in the following form.

"**IF** topmost soil layer thickness **MF** **AND** soil group **MF** **THEN** T_A *or* T_B **MF**"

Between the IF and THEN of each statement, input MFs are combined using ANDing logical conjunction, while each fuzzy rule is combined by ORing logical conjunction. Table 6 presents the FRBs for the proposed FIS model. As explained above, each rule represents a logically valid relationship between input and output fuzzy MFs.

The "MIN" inference, which represents the logical combination of input sets to obtain output results in accordance with fuzzy set operations, is accomplished through the "ANDing" operator. Meanwhile, the aggregation process is conducted using the "MAX" operator corresponding to the "ORing" logical operation to combine the fuzzy output sets. Once the output is determined in terms of soil classes ("Z1", "Z2", "Z3", or "Z4"), a crisp value of the spectrum characteristic period can be derived to generate the response spectrum. For this purpose, the output is defuzzified using the "CENTROID" method, which takes into account the centroid of the consequent output fuzzy set leading to a crisp output value [34]. The three-dimensional appearances of the FIS rule base surface graphs are displayed in Fig. 8 for both seismic spectrum characteristic periods, T_A and T_B.

4. Case study

Twenty building locations in various districts of Istanbul City are selected as case studies to compare the response spectra generated by the crisp spectrum characteristic periods specified in the code with those produced by the proposed FIS model. Each case has unique soil properties and spectrum characteristics based on the input parameters, and some of the buildings have previously undergone seismic code-based assessments. Fig. 9 and 10 show the locations of these buildings on the hazard map of Istanbul with peak ground velocity (PGV) contour and photos of the buildings, including their identification numbers (IDs), respectively.

The input data for each building, obtained from site observations and expert opinions, include the thickness of the topmost soil layer (h_1) and shear wave velocity (V_s), from which T_A and T_B periods are calculated according to the TBEC 2007 [31] provisions as already described in Section 2. Building importance factors, I, and effective ground acceleration coefficients, A_0, are then applied to spectrum coefficients, $S(T)$, based on these crisp values to form the response spectra.

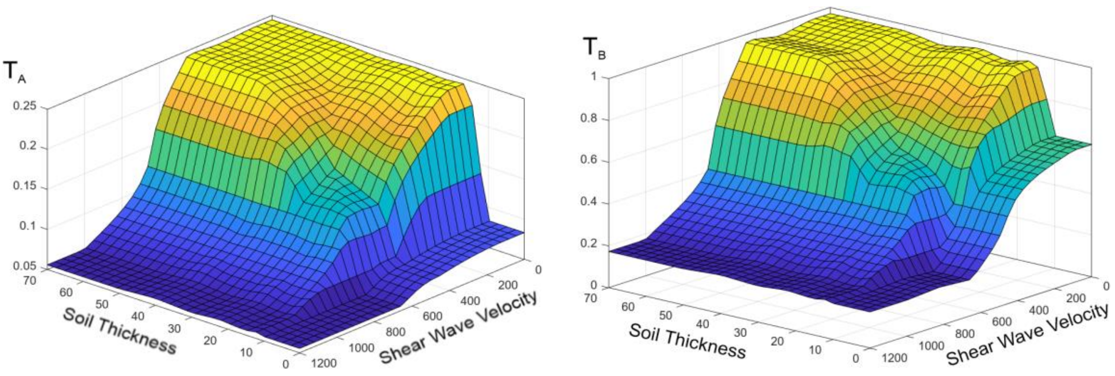
The FIS model is employed using the same h1 and VS values as inputs for each case to estimate the fuzzy T_A and T_B periods, $T_A'$and T_B, which are then used to calculate spectrum coefficients, $S(T)$, of the fuzzy response spectra. In the formation of fuzzy response spectra, the same I and A_0 values are applied to spectrum coefficients, and $S(T)$ is calculated by fuzzy spectrum characteristic periods considering various combinations of soil groups and profiles. Table 7, Fig. 11, 12 and 13 provide the results of these example cases, including the relative difference between the crisp and fuzzy spectrum characteristic period values.

Table 6. Rule base of spectrum characteristic periods, T_A and T_B

R1:	**IF** "Topmost_Soil_Layer_Thickness" is "**V.Low**" **AND** "Soil_Group" is "**A**" **THEN** "T_A" and "T_B" is "**Z1**"
R2:	**IF** "Topmost_Soil_Layer_Thickness" is "**V.Low**" **AND** "Soil_Group" is "**B**" **THEN** "T_A" and "T_B" is "**Z1**"
R3:	**IF** "Topmost_Soil_Layer_Thickness" is "**V.Low**" **AND** "Soil_Group" is "**C**" **THEN** "T_A" and "T_B" is "**Z2**"
R4:	**IF** "Topmost_Soil_Layer_Thickness" is "**V.Low**" **AND** "Soil_Group" is "**D**" **THEN** "T_A" and "T_B" is "**Z3**"

Table 6. Continued

R5:	IF "Topmost_Soil_Layer_Thickness" is "**Low**" AND "Soil_Group" is "**A**" THEN "T_A" and "T_B" is "**Z1**"
R6:	IF "Topmost_Soil_Layer_Thickness" is "**Low**" AND "Soil_Group" is "**B**" THEN "T_A" and "T_B" is "**Z2**"
R7:	IF "Topmost_Soil_Layer_Thickness" is "**Low**" AND "Soil_Group" is "**C**" THEN "T_A" and "T_B" is "**Z2**"
R8:	IF "Topmost_Soil_Layer_Thickness" is "**Low**" AND "Soil_Group" is "**D**" THEN "T_A" and "T_B" is "**Z4**"
R9:	IF "Topmost_Soil_Layer_Thickness" is "**Medium**" AND "Soil_Group" is "**A**" THEN "T_A" and "T_B" is "**Z1**"
R10:	IF "Topmost_Soil_Layer_Thickness" is "**Medium**" AND "Soil_Group" is "**B**" THEN "T_A" and "T_B" is "**Z2**"
R11:	IF "Topmost_Soil_Layer_Thickness" is "**Medium**" AND "Soil_Group" is "**C**" THEN "T_A" and "T_B" is "**Z3**"
R12:	IF "Topmost_Soil_Layer_Thickness" is "**Medium**" AND "Soil_Group" is "**D**" THEN "T_A" and "T_B" is "**Z4**"
R13:	IF "Topmost_Soil_Layer_Thickness" is "**High**" AND "Soil_Group" is "**A**" THEN "T_A" and "T_B" is "**Z1**"
R14:	IF "Topmost_Soil_Layer_Thickness" is "**High**" AND "Soil_Group" is "**B**" THEN "T_A" and "T_B" is "**Z2**"
R15:	IF "Topmost_Soil_Layer_Thickness" is "**High**" AND "Soil_Group" is "**C**" THEN "T_A" and "T_B" is "**Z4**"
R16:	IF "Topmost_Soil_Layer_Thickness" is "**High**" AND "Soil_Group" is "**D**" THEN "T_A" and "T_B" is "**Z4**"



(a) (b)

Fig. 8. Fuzzy logic controller surface graphs of the rule base for (a) T_A and (b) T_B

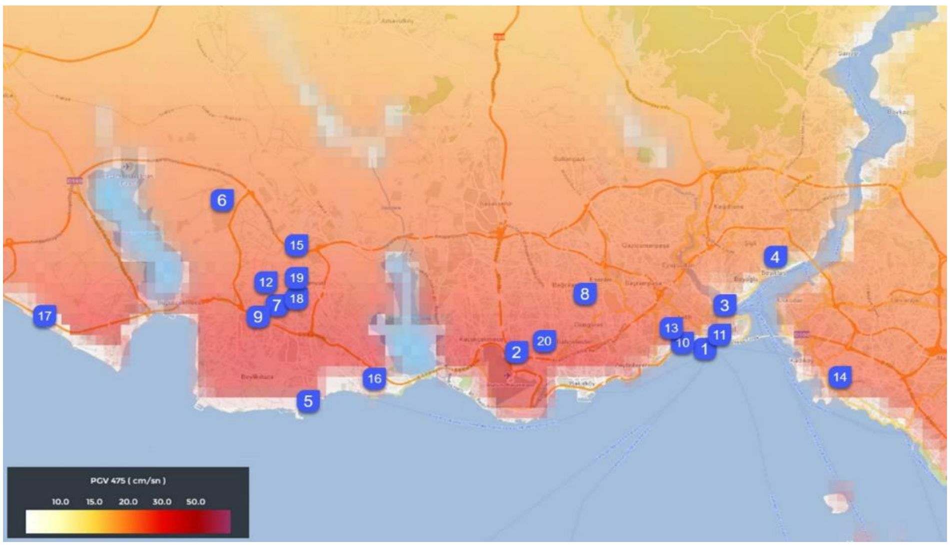


Fig. 9. Example building locations with ID numbers

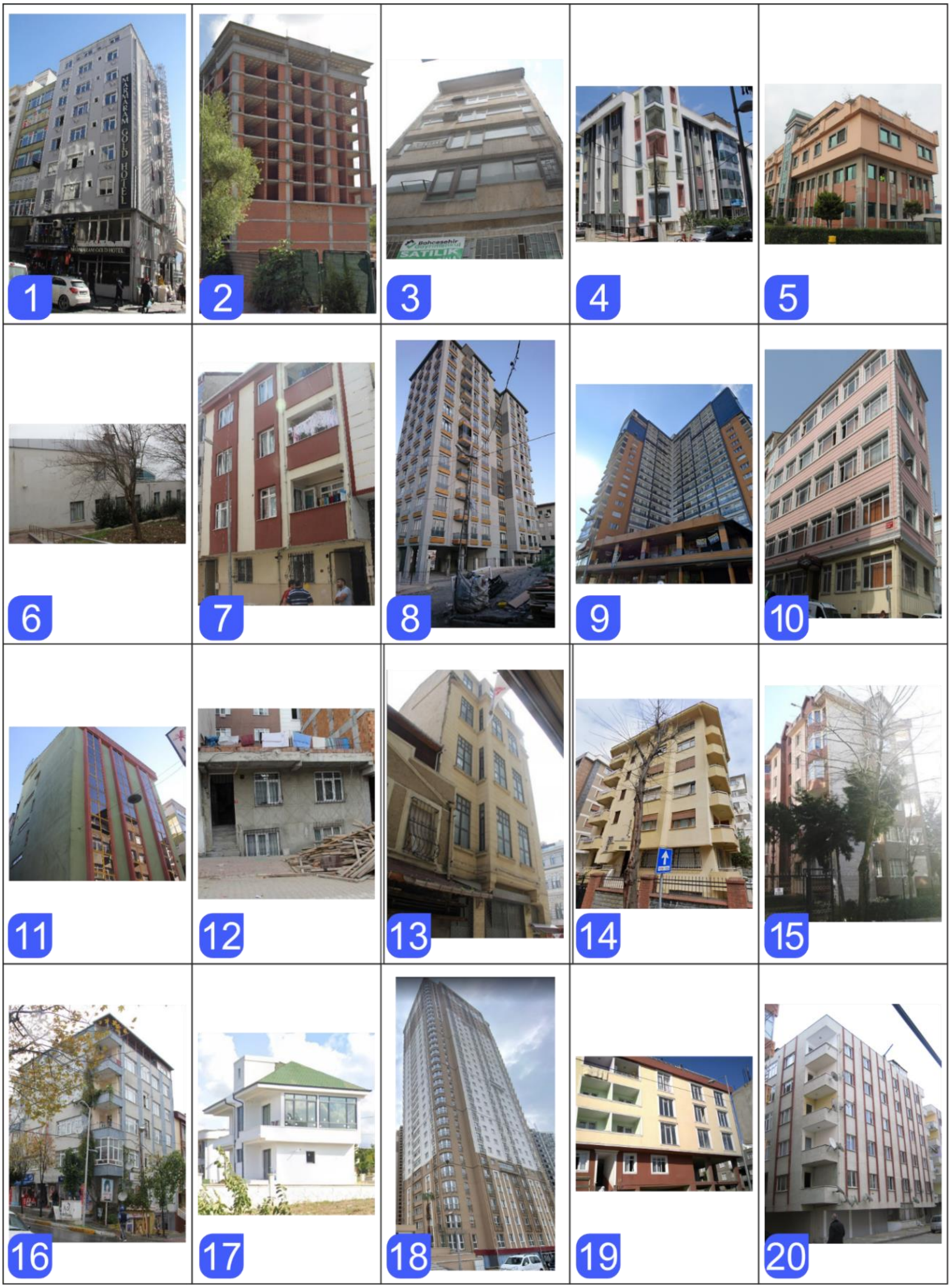


Fig. 10. Example building photos with ID numbers

Table 7. Results of the example building locations

Building No	$*h_1$ (m)	$*V_s$ (m/s)	Soil Group	I	$A0$	TBEC 2007		Fuzzy Model		Difference (%)	
						T_A	T_B	T_A'	T_B'	$T_A \rightarrow T_A'$	$T_B \rightarrow T_B'$
1	23	300	C	1.0	0.40	0.15	0.60	0.2007	0.7500	34%	25%
2	10	410	C	1.0	0.40	0.15	0.40	0.1374	0.4897	-8%	22%
3	22	150	D	1.0	0.30	0.20	0.90	0.2268	0.8754	13%	-3%
4	50	281	C	1.4	0.30	0.20	0.90	0.2414	0.9399	21%	4%
5	55	230	C	1.0	0.40	0.20	0.90	0.2421	0.9473	21%	5%
6	13	250	D	1.4	0.30	0.15	0.60	0.2104	0.7976	40%	33%
7	18	230	D	1.0	0.30	0.15	0.60	0.2166	0.8306	44%	38%
8	21	480	B	1.0	0.30	0.15	0.40	0.1468	0.5614	-2%	40%
9	16	410	C	1.0	0.40	0.15	0.60	0.1629	0.5833	9%	-3%
10	18	320	C	1.0	0.40	0.15	0.60	0.1958	0.7351	31%	23%
11	13	175	D	1.0	0.40	0.20	0.90	0.2181	0.8307	9%	-8%
12	8	180	D	1.0	0.30	0.15	0.60	0.1588	0.6089	6%	1%
13	5	150	D	1.0	0.40	0.15	0.60	0.1617	0.6180	8%	3%
14	17	340	C	1.0	0.40	0.15	0.60	0.1904	0.7114	27%	19%
15	19	320	C	1.0	0.30	0.15	0.60	0.1954	0.7324	30%	22%
16	21	220	C	1.0	0.40	0.15	0.60	0.2154	0.8212	44%	37%
17	19	750	A	1.0	0.30	0.10	0.30	0.0953	0.3232	-5%	8%
18	5	930	A	1.0	0.30	0.10	0.30	0.0569	0.1778	-43%	-41%
19	10	160	D	1.0	0.30	0.15	0.60	0.1607	0.6150	7%	3%
20	17	590	B	1.0	0.40	0.15	0.40	0.1387	0.5020	-8%	26%

* Input values used in the fuzzy model

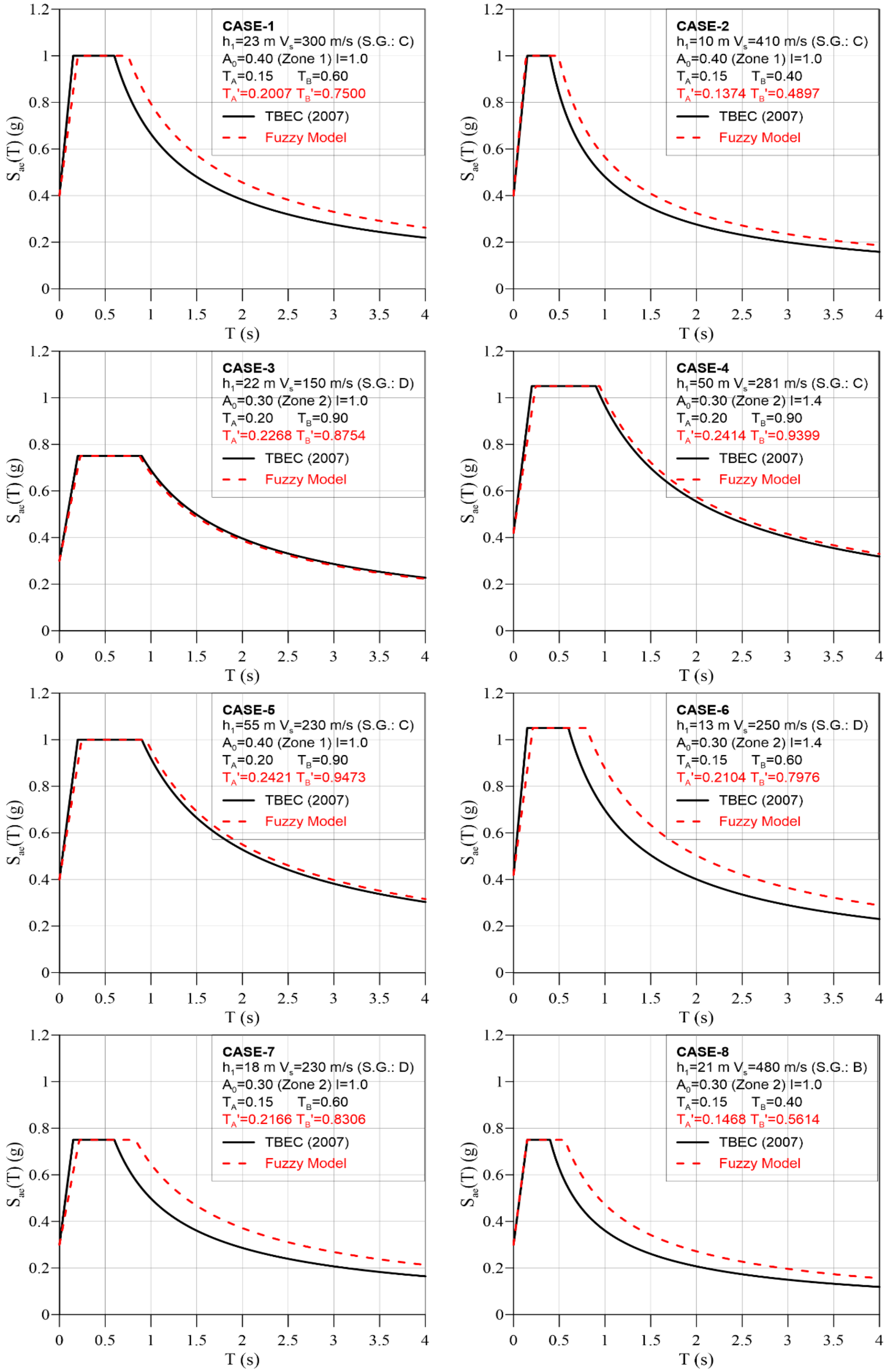


Fig. 11. TBEC 2007 [31] vs fuzzy response spectra; case 1~8

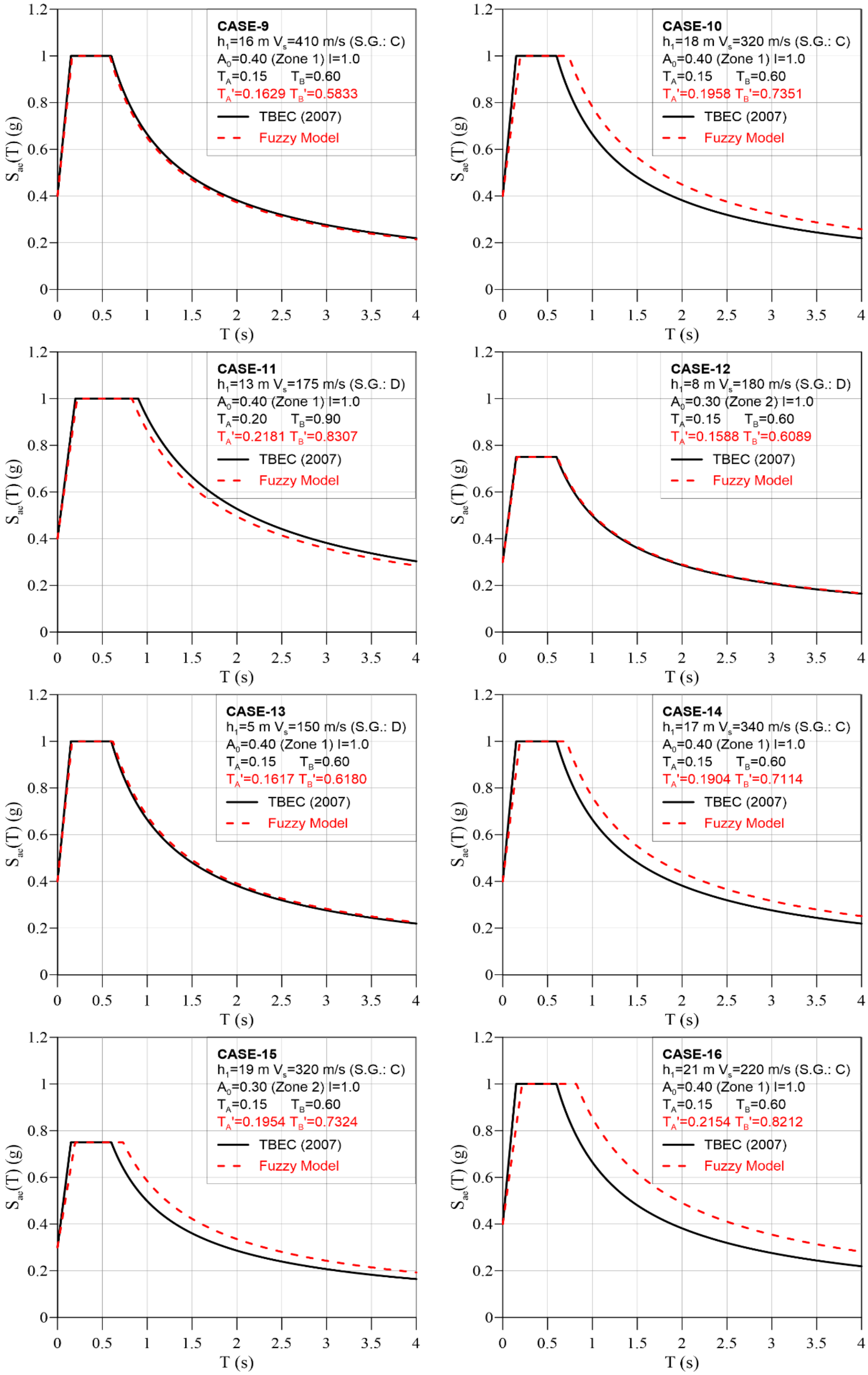


Fig. 12. TBEC 2007 [31] vs fuzzy response spectra; case 9~16

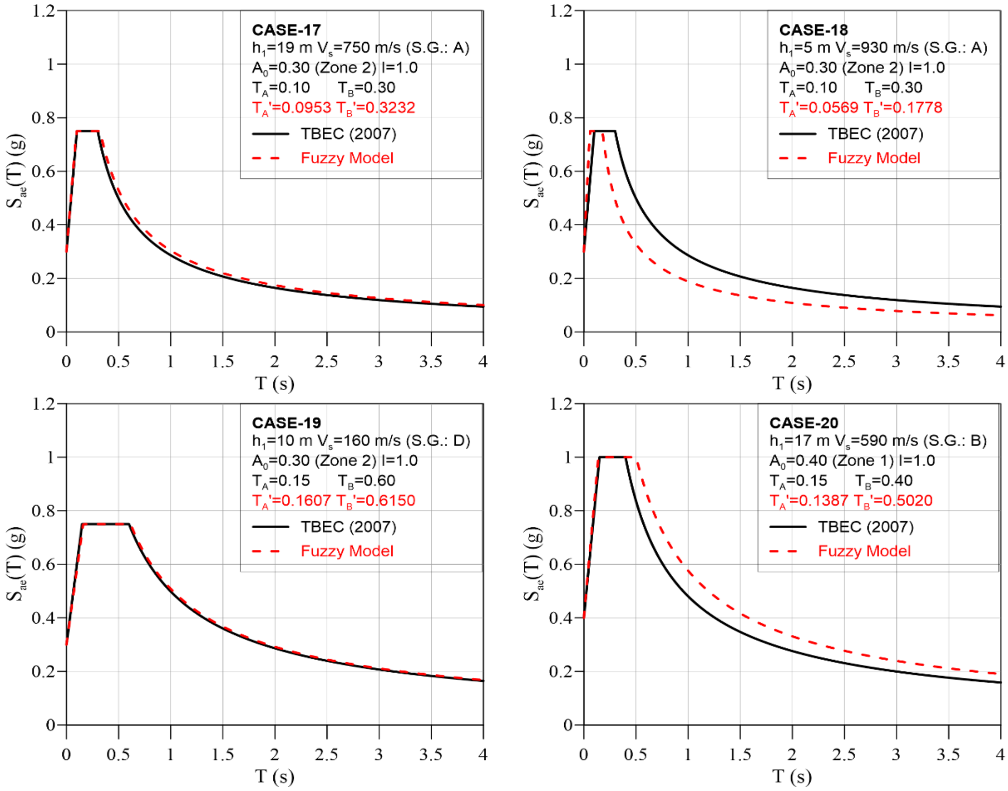


Fig. 13. TBEC 2007 [31] vs fuzzy response spectra; case 17~20

As stated by Oğuz [35], the acceleration spectrum intensity indicates the damage potential in case of a strong ground motion. The area under the response spectrum with a specified period range shows the intensity of that region. Travasarou et al. [36] showed a strong correlation between the displacement demand that emerged from an earthquake and acceleration spectrum intensities, which in all example cases are calculated to compare the damage potential of the building locations (Table 8). Fig. 14 shows the areas (spectrum intensities) under several regions on an example acceleration spectrum graph. PGA stands for the peak ground acceleration, and A_T corresponds to the total area of the spectrum, namely the acceleration spectrum intensity. A_1, A_2, and A_3 stand for the area of the increasing acceleration, constant acceleration and constant velocity regions, respectively.

5. Discussion

Application of the FIS model to the different code response spectra showed that there is a tendency for a change in spectrum shape as well as in spectrum intensity. The spectra obtained with the FIS model provide distinctive results in the building locations. In some cases, they are found to be conservative or nearly the same as the traditional code spectra. In others, they provide lower spectral accelerations.

Based on the results of cases 17 and 18, a significant correlation exists between the increase in the Vs and the decrease in the spectral acceleration values. For case 18, the FIS model spectrum provides much lower spectral acceleration values than the code spectrum in the constant acceleration (A_2) and constant velocity (A_3) regions. This result is invalid for the increasing acceleration region (A_1) because the FIS model spectrum tends to provide higher spectral acceleration values. It shows that the FIS model spectrum can provide more conservative values and higher structural safety for short-period structures in stiff soils, as expected from any structural design code.

Table 7. Acceleration spectrum intensity comparisons

Building No	Acceleration Spectrum Intensity (g.s.)								Differences (%)			
	TBEC-2007				Fuzzy Model							
	A_1	A_2	A_3	A_T	A_1'	A_2'	A_3'	A_T'	$A_1 \rightarrow A_1'$	$A_2 \rightarrow A_2'$	$A_3 \rightarrow A_3'$	$A_T \rightarrow A_T'$
1	0.11	0.45	1.38	1.94	0.14	0.55	1.49	2.18	**33%**	**22%**	**8%**	**12%**
2	0.11	0.25	1.17	1.52	0.10	0.35	1.28	1.73	**-6%**	**40%**	**9%**	**13%**
3	0.11	0.53	1.17	1.80	0.12	0.49	1.16	1.77	**16%**	**-7%**	**-1%**	**-2%**
4	0.15	0.73	1.64	2.52	0.18	0.73	1.66	2.57	**20%**	**0%**	**1%**	**2%**
5	0.14	0.70	1.56	2.40	0.17	0.71	1.58	2.46	**20%**	**1%**	**1%**	**2%**
6	0.11	0.47	1.45	2.04	0.15	0.62	1.59	2.36	**40%**	**31%**	**9%**	**16%**
7	0.08	0.34	1.04	1.45	0.12	0.46	1.15	1.72	**48%**	**36%**	**11%**	**19%**
8	0.08	0.19	0.88	1.14	0.08	0.31	1.01	1.40	**1%**	**64%**	**16%**	**22%**
9	0.11	0.45	1.38	1.94	0.11	0.42	1.37	1.90	**6%**	**-7%**	**-1%**	**-2%**
10	0.11	0.45	1.38	1.94	0.14	0.54	1.48	2.16	**34%**	**20%**	**7%**	**11%**
11	0.14	0.70	1.56	2.40	0.15	0.61	1.53	2.30	**10%**	**-13%**	**-2%**	**-4%**
12	0.08	0.34	1.04	1.45	0.08	0.34	1.04	1.46	**7%**	**0%**	**0%**	**1%**
13	0.11	0.45	1.38	1.94	0.11	0.46	1.40	1.97	**6%**	**2%**	**1%**	**2%**
14	0.11	0.45	1.38	1.94	0.13	0.52	1.47	2.12	**27%**	**16%**	**6%**	**9%**
15	0.08	0.34	1.04	1.45	0.11	0.40	1.11	1.62	**35%**	**18%**	**7%**	**11%**
16	0.11	0.45	1.38	1.94	0.16	0.60	1.53	2.29	**48%**	**33%**	**11%**	**18%**
17	0.05	0.15	0.76	0.97	0.05	0.17	0.79	1.01	**2%**	**10%**	**4%**	**5%**
18	0.05	0.15	0.76	0.97	0.03	0.09	0.57	0.70	**-39%**	**-40%**	**-25%**	**-28%**
19	0.08	0.34	1.04	1.45	0.08	0.34	1.04	1.47	**6%**	**2%**	**1%**	**1%**
20	0.11	0.25	1.17	1.52	0.10	0.36	1.29	1.75	**-6%**	**44%**	**11%**	**15%**

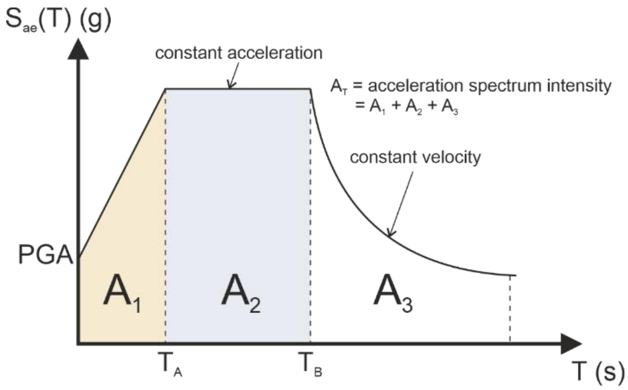


Fig. 14. Acceleration spectrum intensity calculations

On the other hand, for the medium stiffness soils (cases 2, 8 and 20), a widening is evident in the A_2 region, which affects T_B and A_2 intensity differences. In case 8, the T_B value increased from 0.4 sec to 0.56 sec with a 40% ratio, and the A_2 intensity increased from 0.19 gs to 0.31 gs with a 64% ratio. The shape and intensity of the A_3 region are also affected towards more conservative values with an average intensity difference of 12%. However, the change in the shape and intensity of the A1 region is not apparent but provides almost the same spectral shapes in that region. Ultimately, the total intensity ranges from 14% to 24% for cases 2, 8 and 20.

The relatively low stiffness soils with V_S values between 220 m/s and 340 m/s exhibit similar behaviour to those of cases 2, 8 and 20. The constant acceleration region is extended along with an offset caused by the increase of both T_A and T_B values. For example, in case 7, the T_B value increased from 0.6 sec to 0.83 sec with 0.23 sec. (38%) difference. The change in T_A values is relatively low (0.07 sec), but the difference (44%) is considered significant. In these cases, the traditional code spectra provide more conservative results in the A_1 region regarding spectral acceleration values. On the other hand, this outcome is not valid for the acceleration spectrum intensity values. Due to the lengthening of the T_A period, an increase in the A_1 intensities is observed in the FIS model spectra that reach a ratio of 48%.

FIS model spectra provide quite similar results with the traditional code spectra as an interesting outcome for the soft soils both in shape and spectrum intensities.

6. Conclusion

The fuzzy logic inference system (FIS) model is an effective tool for handling linguistic uncertainties based on fuzzy sets. It has been extensively utilized in many fields to address problems including imprecision, vagueness, incompleteness and alike in data. Contrary to crisp seismic code classification, the proposed FIS model response spectra methodology accounts for imperfections in soil group selection and topmost soil layer thickness. The study employs the seismic parameters of the Türkiye Building Earthquake Code (TBEC 2007) [31] provisions on twenty building examples with different soil profiles, shear wave velocities and topmost soil layer thicknesses data. The comparison of the fuzzy and crisp output seismic parameters shows a significant difference in the response spectra's shape and acceleration spectrum intensity values except for the soft soils where similar results were obtained.

In specific building locations characterized by diverse soil profiles, the response spectra obtained from the FIS model tend to provide higher spectral acceleration values than traditional response spectra. This observation implies that the design acceleration values prescribed by the code may not offer sufficient structural safety when considering the uncertainties present in those locations. Conversely, in some other areas, the response spectra generated by the FIS model yield comparable or lower values than the traditional approach. This suggests that the traditional response spectra might result in potentially excessive design forces for structures that adhere to the code requirements. Consequently, the utilization of the fuzzy version of the response spectrum has the potential to offer a design solution that is potentially safer or more cost-effective in various scenarios, taking into account the vagueness of the soil profile.

For buildings on stiff soils, the FIS model response spectra tend to provide lower spectral acceleration values, resulting in a conservative approach for short-period structures. FIS model response spectra provide a more conservative approach both in the constant acceleration and the velocity regions with medium stiffness soils. The differences between the total spectrum intensities were found to vary from 1% up to 28%, and the differences between the characteristic period values were found to be 1%~44% in various cases.

Fuzzy logic-based inferencing model usage helps to generate response spectra with a more realistic representation of the uncertainties present in the problem, which leads to more robust and reliable designs. Furthermore, a similar approach can be used to study the seismic parameters of other design codes. However, more comprehensive research is necessary to fully understand this approach's potential and limitations.

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Data availability statement

No new data were created or analyzed in this study.

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