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Kayma Dalgası Hızı Oranının Yerel Saha Faktörleri Üzerindeki Etkisine İlişkin Analitik Çalışma

ANALYTICAL STUDY ON THE EFFECT OF SHEAR WAVE VELOCITY RATIO CHANGING ON LOCAL SITE FACTORS

Mohammad Mouaz HASSOUN[1], Deniz ÜLGEN[2], Ebru HARMANDAR[3]

ÖZET

Deprem sırasında hasar oranlarındaki artış, yapısal özelliklerin yanı sıra üzerine inşa edilen zeminin litolojik özellikleriyle doğrudan ilişkilidir. Kaya ve yumuşak zemin türündeki sahalar deprem sırasında farklı davranışlar sergilemekte olup, deprem etkileri özellikle zemin tabakalarında daha belirgin şekilde gözlemlenmektedir. Depreme ait sismolojik ve jeolojik parametreler; büyüklük, faylanma türü, faya olan uzaklık, yönlülük, yerel zemin koşulları ve spektral içerik açısından sınıflandırılabilir. Yerel zemin koşulları çeşitli faktörlere bağlı olarak belirlenir ve bunlar arasında en kritik olanlardan biri zeminin yapısal rijitliği ve yumuşaklığıdır. Bu özellik genellikle üst 30 metrelik zemin tabakasına ait kayma dalgası hızı (V_{S30}) esas alınarak tanımlanır. Bununla birlikte, kayma dalgası hızına dayalı zemin sınıflandırması, yönetmeliklerde belirlenen alt ve üst sınırlar çerçevesinde tanımlanan aralıklardan oluşmaktadır. Ancak, özellikle üst 10 metrelik zemin tabakasına ait duyarlılığın, bir deprem olayına karşı tahmin edilen davranışın değerlendirilmesinde ve yorumlanmasında önemli olduğu gözlemlenmektedir. Bu nedenle, bu çalışmada spektral davranıştaki değişimleri V_{S10m} / V_{S30} oranındaki değişimlere bağlı olarak yakalayabilmek amacıyla boyutsuz bir mühendislik oranı geliştirilmiştir. Bu oran, V_{S30} = 400 m/s olarak sınıflandırılan orta yumuşak ve yumuşak zemin koşulları için çeşitli senaryolar varsayımıyla oluşturulmuştur. Daha sonra, sekiz farklı zemin senaryoları oluşturulmuş ve bu zemin modellerine ait analizler, 16 deprem kayıdı kullanılarak doğrusal olmayan analiz yöntemleriyle gerçekleştirilmiştir. Tüm depremlere ait yer hareketi girdilerinin uygulanmasının ardından, kısa periyot ve 1 saniyelik periyotlar için yerel zemin faktörlerinin ortalamaları ($F_{sAverage}$ ve $F_{1Average}$) hesaplanmış ve değerlendirilmiştir. Daha sonra bu katsayılar, mühendislik tasarımı için Türkiye Bina Deprem Yönetmeliği (2018)'de belirtilen değerlerle karşılaştırılmıştır.

Anahtar Kelimeler: *Yerel Zemin Katsayıları, Kayma Dalgası Hızı, Sismik Tasarım Yönetmelikleri, Doğrusal Olmayan Zemin Tepki Analizi.*

[1]Ph.D. Student, Civil Engineering Department, Muğla Sıtkı Koçman Üniversitesi, 204801713@posta.mu.edu.tr (Sorumlu yazar).
[2]Prof. Dr., Civil Engineering Department Muğla Sıtkı Koçman Üniversitesi, denizulgen@mu.edu.tr.
[3]Assoc. Prof. Dr., Civil Engineering Department, Muğla Sıtkı Koçman Üniversitesi, ebruharmandar@mu.edu.tr.

ABSTRACT

The increase in damage rates during earthquakes is directly related to the lithological characteristics of the ground built on, in addition to the structural characteristics of the building. Rock and soil sites display different behaviors during earthquakes, with the effects of earthquakes observed more in soil deposits. The seismological and geological parameters of an earthquake event shakings can be classified in terms of magnitude, faulting type, fault distance, directivity, site condition, and spectral content. Site condition is decided by several factors, one of the most critical factors is soil potential structural stiffness and softness. Which is usually decided basing on the relevant shear wave velocity for the top 30 m of soil. However, the shear wave velocity-based soil classification is defined as range (interval) with down and up boundaries which are determined in accordance to the criteria of the classification engineering code. However, it is observed that the sensitivity for the top 10 m is of soil significant when evaluating and judging the estimated response to an earthquake event. Therefore, in this study a dimensionless engineering ratio is built as V_{S10m} / V_{S30} to capture the variations in spectral behavior with respect to the V_{S10m} / V_{S30} ratio changes. This ratio is built in favor of assuming many scenarios for soil deposits that are classified as moderately soft and soft (V_{S30} = 400 m/s). Then, eight soil scenarios were developed, and the corresponding analyses of the soil models were conducted using nonlinear analysis approaches based on 16 earthquake records as input motions. After modelling the soil profile and applying the input motion data of all the earthquakes, average local site factors for short and 1 second periods, denoted as $F_{sAverage}$ and $F_{1Average}$, respectively are calculated and evaluated. These factors are then compared with the recommended values specified in the Turkish Building Earthquake Code (2018) for engineering design.

Keywords: *Local Site Factors, Shear Wave Velocity, Seismic Designing Codes, Nonlinear Site Response Analysis.*

1. INTRODUCTION

The seismic response of soil is intrinsically influenced by local site conditions and geological context. When accounting for the governing engineering factors of such a system -including faulting mechanism, earthquake magnitude, epicentral distance, and shear wave velocity- site amplification effects should be rigorously considered and not overlooked (Lee et al., 2012; Hwang et al., 1996). Despite this, contemporary building and design codes continue to adopt relatively generalized and broad-ranging values for local soil properties and parameters (Dobry et al., 2000). Local site coefficients specified in engineering design codes such as Turkish Building Earthquake Code (TBEC-2018) and American Society for Civil Engineers (ASCE 7) are typically derived from empirical relationships and tabulated values. These approaches, however, do not explicitly incorporate the governing soil and site-specific factors that may contribute to potential amplification or de-amplification effects. In addition, key parameters for soil classification, such as V_{S30}, are typically defined in terms of ranges and numerical intervals based on their measure or calculated values, without adequately considering the potential presence of subsurface layers or the interaction effects at layer interfaces. Furthermore, limited research has addressed the influence of the upper 10 meters within the top 30 meter soil profile on the behavior of response spectra. Even within a single soil class characterized by a fixed V_{S30} value, there exists an infinite number of possible soil layering configurations that can yield the same value (Güler, 2024).

The classification and definition of soil types in engineering design codes are based on various measured or computed parameters that serve as indicators of soil behavior. Nevertheless, inherent uncertainties persist, as soil is a natural material rather than a manufactured or standardized human made product. In this context, the introduction and evaluation of additional parameters may provide a more comprehensive understanding and help address existing gaps.

Shear wave velocity has consistently been recognized as a reliable indicator for identifying soil categories and classifications (Dikmen, 2009). The primary objective of this study is to contribute to the advancement of both engineering regulations and the scientific literature by incorporating additional descriptive parameters for soil characterization. The expected outcomes are anticipated to offer tangible benefits in terms of both economic efficiency and structural safety.

2. MODELLING AND ANALYSIS

In order to evaluate how variations in local site factors can impact seismic response over different time periods, especially focusing on the vertical stratification of the soil profile. The average shear wave velocity for the upper 30 meters (V_{S30}) is a standard metric, expresses the time-averaged shear wave velocity for a wave travel from depth of 30 meters to the ground surface. It is calculated according to TBEC-2018 by the following equation:

$$(V_S)_{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{h_i}{V_{S,i}}\right)} \quad (1)$$

This research explores the theoretical implications of profile variability. To achieve this, multiple layering configurations were modelled to produce the same (V_{S30}) value, allowing for a comparative analysis of how different depth-dependent velocity distributions influence site behavior despite having an identical shear wave value.

2.1. Soil Profile Scenarios and Modelling

Soil profile scenarios were modelled and configured within the DEEPSOIL software platform. These models adhere to established soil layering criteria and numerical modeling standards consistent with current design codes. To determine site-specific responses, earthquake ground motion records were selected based on rigorous engineering standards. Furthermore, the study utilizes literature-validated methods for calculating local site factors and follows traditional processing protocols for the filtering and baseline correction of seismic records. To investigate spectral behavior, eight numerical scenarios were developed based on the dimensionless V_{S10m} / V_{S30} ratio. These scenarios represent several soil deposits with a fixed shear wave velocity of V_{S30} = 400 m/s. While keeping V_{S20m} at 300 m/s to retain the magnitude of V_{S30}, the individual values V_{S10m} and V_{S30m} were varied within the range 300 – 1200 m/s to capture a broad spectrum of velocity distributions. Subsequently, site response analyses were performed in DEEPSOIL using earthquake ground motion records selected in strict accordance with Turkish Building Earthquake Code (TBEC-2018). As shown in the following table, the suggested values for V_{S10m}, V_{S20}m, and V_{S30m} are:

Table 1. Suggested values of V_{S10m}, V_{S20m}, and V_{S30m} within the same V_{S30} = 400 m/s.

Soil Type	V_{S30} = 400 (m/s)							
Case No	1	2	3	4	5	6	7	8
V_{S10m} / V_{S30}	0,75	0,90	1,05	1,20	1,35	1,50	1,65	1,80
V_{S10m} (m/s)	300	360	420	480	540	600	660	720
V_{S20m} (m/s)	300	300	300	300	300	300	300	300
V_{S30m} (m/s)	1200	720	560	480	432	400	377	360
V_{S30} (m/s)	400	400	400	400	400	400	400	400

The V_{S10m} / V_{S30} ratio range was selected to be 0.75–1.80 which is bounded by the physical applicability of the layered profiles. With V_{S30} = 400 m/s and the 10 m thickness middle layer kept at 300 m/s, fulfilling Eq. (1) requires the top 10 m and bottom 10 m layer shear wave velocities are coupled, and both must exceed 240 m/s. Furthermore, the lower limit of the ratio range 0.75 occurs when the top layer equal to the middle layer (V_{S10m} = 300 m/s) over a 1200 m/s base layer. Thereafter, lower ratios would require base shear wave velocities above 1500 m/s (V_{S10m} / V_{S30} < 0.71) which is beyond the ZB range of TBEC-2018. Within these limits, the adopted range gives a gradual variation of the individual layer velocities (top layer 300–720 m/s) and the constant rate of 0.15 (60 m/s in V_{S10m}) provides eight evenly spaced cases. All of the eight distinct soil profile cases were modelled in DEEPSOIL to examine the gradual variations in site-specific response spectra. This approach allowed for a systematic evaluation of seismic response by modifying the characteristics of the most critical layers (boundary layers): the top surface layer and the bottom layer where the input ground motion enters the soil profile.

2.2. Input Ground Motion and Nonlinear Analysis

16 different earthquake event input motion records all are chosen to be normal fault mechanism, moderate (4.6 – 6.1) and high moment magnitude (6.2 – 7.8), and near field categorized earthquake taken from the Pacific Earthquake Engineering Research Center (PEER) database from different earthquakes in different locations.

Table 2. Earthquake ground input motion records obtained from PEER.

Earthquake Event	Predominant period (s)	Time interval (s)	Arias Intensity (m/s)
RSN292_ITALY_A-STU000	0,38	0,0024	1,184
RSN292_ITALY_A-STU270	0,2	0,0024	1,395
RSN1141_DINAR_DIN090	0,3	0,005	2,031
RSN1141_DINAR_DIN180	0,34	0,005	1,642
RSN284_ITALY_A-AUL000	0,1	0,0029	0,054
RSN284_ITALY_A-AUL270	0,26	0,0029	0,064
RSN300_ITALY_B-CTR000	1,2	0,0024	0,453
RSN300_ITALY_B-CTR270	0,58	0,0024	0,529
RSN108_OROVILLE_B-OR1000	0,12	0,005	0,005
RSN108_OROVILLE_B-OR1270	0,08	0,005	0,005
RSN117_OROVILLE_D-OAP180	0,1	0,005	0,009
RSN117_OROVILLE_D-OAP270	0,12	0,005	0,0146
RSN112_OROVILLE_D-EBH000	0,08	0,005	0,063
RSN112_OROVILLE_D-EBH090	0,08	0,005	0,0432
RSN114_OROVILLE_D-OR5090	0,0758	0,005	0,017
RSN114_OROVILLE_D-OR5180	0,14	0,005	0,0196

These earthquake ground motion records are applied to the eight soil profile scenario, the outcrop spectral accelerations at the top layers and input spectral accelerations are found via the nonlinear numerical analysis results tables of DEEPSOIL. Thereafter, the individual local site factors at short period and at 1 second period Fs and F_1 are calculated throughout dividing the outcrop spectral acceleration of top surface layer by the engineering bedrock input spectral acceleration for each earthquake ground motion record.

Later on, the arithmetic means for these individual local site factors are calculated to judge how averagely these factors behave under different conditions of soil layering scenarios.

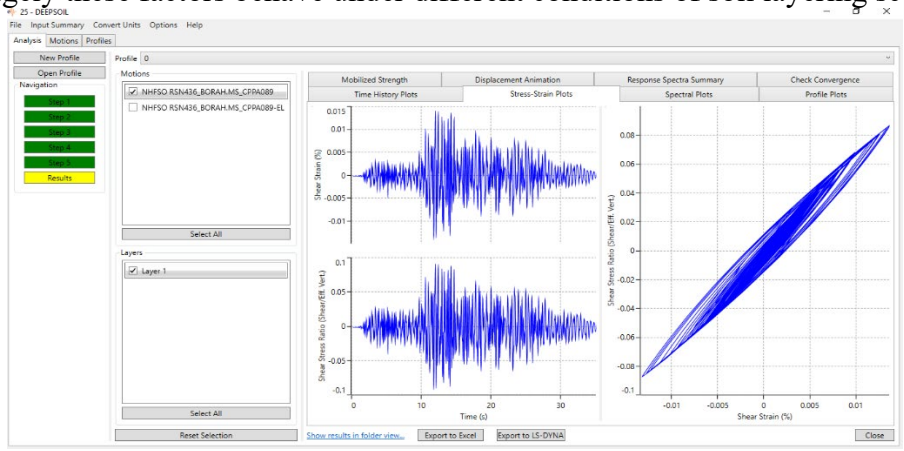

Figure 1. Nonlinear Graphical analysis results Stress-Strain plots (DEEPSOIL).

3. RESULTS

The numerical nonlinear series of analyses applied to the aforementioned multi layering soil profile scenarios had shown that the individual short period individual values (F_S) ranged from 0.63 to 2.05, while one-second period individual values (F_1) presented a numerical smaller range of 1.07 – 1.84, indicating that the short period local site factor was more sensitive for soil layering sequence changes regarding the investigated earthquake ground motion records and the relevant soil profiles.

Table 3. Individual and average values of short period local site factor Fs and $F_{SAVERAGE}$.

EARTHQUAKE EVENT & Vs10/Vs30	Fs							
	0,75	0,9	1,05	1,2	1,35	1,5	1,65	1,8
RSN292_ITALY_A-STU000	1,08	0,95	0,88	0,88	0,84	0,83	0,76	0,74
RSN292_ITALY_A-STU270	0,77	0,66	0,63	0,65	0,67	0,68	0,68	0,66
RSN1141_DINAR_DIN090	0,95	0,84	0,78	0,76	0,71	0,71	0,66	0,69
RSN1141_DINAR_DIN180	1,16	1,04	0,95	0,90	0,84	0,83	0,78	0,75
RSN284_ITALY_A-AUL000	1,85	1,63	1,45	1,40	1,39	1,38	1,29	1,20
RSN284_ITALY_A-AUL270	1,86	1,67	1,50	1,42	1,28	1,19	1,07	1,00
RSN300_ITALY_B-CTR000	1,19	1,06	0,95	0,89	0,81	0,81	0,80	0,80
RSN300_ITALY_B-CTR270	1,26	1,11	1,10	1,12	1,10	1,09	1,03	0,98
RSN108_OROVILLE_B-OR1000	2,00	1,87	1,77	1,70	1,59	1,49	1,41	1,32
RSN108_OROVILLE_B-OR1270	2,05	1,84	1,61	1,47	1,36	1,30	1,25	1,18
RSN117_OROVILLE_D-OAP180	1,52	1,28	1,09	1,00	0,93	0,84	0,82	0,81
RSN117_OROVILLE_D-OAP270	1,55	1,45	1,42	1,40	1,33	1,25	1,15	1,04
RSN112_OROVILLE_D-EBH000	1,82	1,57	1,38	1,30	1,33	1,31	1,23	1,15
RSN112_OROVILLE_D-EBH090	1,62	1,45	1,27	1,16	1,01	0,95	0,87	0,80
RSN114_OROVILLE_D-OR5090	1,63	1,70	1,62	1,52	1,37	1,25	1,11	1,06
RSN114_OROVILLE_D-OR5180	1,57	1,38	1,20	1,14	1,05	0,97	0,94	0,89
$F_{SAVERAGE}$	**1,49**	**1,34**	**1,23**	**1,17**	**1,10**	**1,06**	**0,99**	**0,94**

Table 4. Local site factor F_S at short period (TBEC-2018).

Local Ground Class	Local Ground Impact Coefficient F_S For Short Period Region					
	$S_S \leq 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.0$	$S_S = 1.25$	$S_S \geq 1.50$
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.9	0.9	0.9	0.9	0.9	0.9
ZC	**1.3**	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**
ZD	1.6	1.4	1.2	1.1	1.0	1.0
ZE	2.4	1.7	1.3	1.1	0.9	0.8
ZF	Site-specific soil behavior analysis will be performed					

When checking and comparing the short period local site factors F_S achieved at different V_{S10m} / V_{S30} values levels. It is observed that for all the suggested V_{S10m} / V_{S30} the attained average values $F_{SAVERAGE}$ belong to the numerical range (0.94 – 1.49) which is wider than the level of F_S values listed (1.2 – 1.3) for soil type (ZC) in the Turkish Building Earthquake Code TBEC 2018 (Table 4). This differentiation highlights the influence of the vertical shear-wave velocity distribution on short-period site response, which is not explicitly represented by VS30 solely. Furthermore, as the ratio V_{S10m} / V_{S30} increases from 0.75 to 1.80 while keeping the shear wave velocity for the top 30 m V_{S30} constant at 400 m/s, the results show that the average short-period site factor is steadily decreasing and being influenced by the soil layering sequence.

Table 5. Individual and average values of 1 second period local site factor F_1 and $F_{1AVERAGE}$.

EARTHQUAKE EVENT & Vs10/Vs30	F1							
	0,75	0,9	1,05	1,2	1,35	1,5	1,65	1,8
RSN292_ITALY_A-STU000	1,47	1,46	1,48	1,51	1,54	1,56	1,57	1,57
RSN292_ITALY_A-STU270	1,26	1,27	1,29	1,30	1,32	1,33	1,38	1,42
RSN1141_DINAR_DIN090	1,28	1,28	1,34	1,38	1,44	1,48	1,57	1,63
RSN1141_DINAR_DIN180	1,27	1,30	1,36	1,39	1,43	1,45	1,51	1,56
RSN284_ITALY_A-AUL000	1,18	1,18	1,20	1,21	1,21	1,23	1,25	1,29
RSN284_ITALY_A-AUL270	1,07	1,102	1,15	1,18	1,20	1,22	1,23	1,25
RSN300_ITALY_B-CTR000	1,27	1,27	1,30	1,32	1,36	1,39	1,45	1,50
RSN300_ITALY_B-CTR270	1,29	1,32	1,37	1,40	1,43	1,44	1,51	1,58
RSN108_OROVILLE_B-OR1000	1,12	1,14	1,16	1,18	1,21	1,23	1,24	1,24
RSN108_OROVILLE_B-OR1270	1,14	1,15	1,17	1,18	1,20	1,22	1,23	1,24
RSN117_OROVILLE_D-OAP180	1,42	1,40	1,45	1,52	1,59	1,64	1,61	1,56
RSN117_OROVILLE_D-OAP270	1,42	1,42	1,43	1,44	1,46	1,47	1,48	1,50
RSN112_OROVILLE_D-EBH000	1,56	1,55	1,63	1,71	1,80	1,84	1,84	1,83
RSN112_OROVILLE_D-EBH090	1,33	1,38	1,46	1,49	1,48	1,49	1,46	1,42
RSN114_OROVILLE_D-OR5090	1,28	1,29	1,28	1,27	1,25	1,24	1,27	1,31
RSN114_OROVILLE_D-OR5180	1,31	1,28	1,3	1,34	1,36	1,41	1,45	1,48
$F_{1AVERAGE}$	**1,30**	**1,30**	**1,34**	**1,37**	**1,40**	**1,42**	**1,44**	**1,47**

On the other hand, regarding site response at long periods; from the above table and its listed averaged values of one-second period $F_{1AVERAGE}$, it is observed that the average values rising up from 1.30 gradually to levels of 1.47 for soil layering case 8 whereas

V_{S10m} / V_{S30} = 1.8 this increase in $F_{1AVERAGE}$ -somehow- describes the distinct behavior of soil profiles in such cases and under similar layering conditions.

Table 6. Local site factor F_1 at 1 second period (TBEC-2018).

Local Ground Class	Local Ground Impact Coefficient F_1 For 1 Second Period Region					
	$S_1 \leq 0.10$	$S_1 = 0.20$	$S_1 = 0.30$	$S_1 = 0.40$	$S_1 = 0.50$	$S_1 \geq 0.60$
ZA	0.8	0.8	0.8	0.8	0.8	0.8
ZB	0.8	0.8	0.8	0.8	0.8	0.8
ZC	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.4**
ZD	2.4	2.2	2.0	1.9	1.8	1.7
ZE	4.2	3.3	2.8	2.4	2.2	2.0
ZF	Site-specific soil behavior analysis will be performed					

Regarding the calculated average local site factor $F_{1AVERAGE}$ values, the values were compared with the corresponding TBEC-2018 site coefficient for soil class ZC. Although all profiles had the same V_{S30} of 400 m/s, the variation in the $F_{1AVERAGE}$ values describes the influence of layering sequence, which is not explicitly represented by a classification based primarily on V_{S30}. This finding shows the importance of taking into consideration the potential variations in the soil layering sequence and their influence on amplification of site response, even for profiles characterized by the same soil type.

REFERENCES

ASCE. (2022), “Minimum Design Loads and Associated Criteria for Buildings and Other Structures (7-22)”.

Güler, S.A. (2024), “Assessment of Local Site Coefficients Proposed in TBEC-2018”, Master’s Thesis, Muğla Sıtkı Koçman University, Graduate School of Natural and Applied Sciences, Muğla, Türkiye.

Dikmen, Ü. (2009), “Statistical Correlations of Shear Wave Velocity and Penetration Resistance for Soils”, Journal of Geophysics Engineering, Vol 6(1), 61-72.

Dobry, R., Borcherdt, R.D., Crouse, C.B., Idriss, I.M., Joyner, W.B., Martin, G.R., et al. (2000), “New Site Coefficients and Site Classification System Used in Recent Building Seismic Code Provisions”, Earthquake Spectra, Vol 16(1), 41-67.

Hwang, H. ve Huo, J.-R. (1996), “Fragility of Memphis Buildings”, Proceedings of the 11th World Conference on Earthquake Engineering, 23-28.

Lee, C.-T., Hsieh, B.-S., Sung, C.-H. ve Lin, P.-S. (2012), “Regional Arias Intensity Attenuation Relationship for Taiwan Considering VS30”, Bulletin of the Seismological Society of America, Vol 102(1), 129-142.

PEER. (2023), “The PEER Ground Motion Database”, https://ngawest2.berkeley.edu/ (10 February 2026).

TBEC. (2018), “Turkish Building Earthquake Code”.

SYMBOLS LIST

Symbol	Statement
V_{S10m}	Shear wave velocity for the 0 - 10 m soil layer.
V_{S20m}	Shear wave velocity for the 10 - 20 m soil layer.
V_{S30m}	Shear wave velocity for the 20 - 30 m soil layer.
V_{S30}	Average shear wave velocity for the top 30 m thickness of soil profile.
ASCE	American Society for Civil Engineers.
TBEC	Turkish Building Earthquake Code.
F_S	Local site factor at period 0.2 (short period).
F_1	Local site factor at period 1.0 s (long period).
$F_{SAVERAGE}$	Average value of local site factor at period 0.2 (short period).
$F_{1AVERAGE}$	Average value local site factor at period 1.0 s (long period).