Revista Internacional de Ingeniería de Estructuras

Vol. 21, 4, 375-387 (2016)

APLICACIÓN DE LAS TÉCNICAS H/V, FK Y SPAC PARA LA CLASIFICACIÓN DE SUELOS POR MEDIO DE LA RED ACELEROGRÁFICA DEL LIS, UNIVERSIDAD DE COSTA RICA

Victor Schmidt Díaz
Earthquake Engineering Laboratory
University of Costa Rica
Montes de Oca, San Pedro, San José
Correo Electrónico: victor.schmidt1@gmail.com

ABSTRACT

All earthquake monitoring networks require extensive additional information about the soil conditions in which ground motions are recorded. In the case of a strong motion network, identify the soil type using techniques systematically applied is essential to validate the recorded records.

In the Earthquake Engineering Laboratory (LIS) at the University of Costa Rica, some techniques were implemented based on the measurement of surface waves that allowed the characterization of soils under the accelerographic stations.

These techniques are: H/V (spectral ratio of the horizontal component from the vertical), FK (frequency-wavenumber) and SPAC (spatial autocorrelation). In the latter two cases, from dispersion and autocorrelation curves, an inverse algorithm is applied to generate models to obtain velocity profiles VS vs. depth. With these techniques it was possible to obtain critical parameters such as the fundamental period (T0) and Vs30 for more than 30 sites.

In general, the LIS's strong motion network instruments are generally located on alluvial valleys, ash or lacustrine deposits. Therefore, there is a predominance of soft soil sites which is defined as S3 according to the Costa Rican Seismic Code 2010 (CSCR-2010), which is characterized according to Vs30 between 180 m / s and 350 m / s.

We also found that more than half of the sites could be characterized as S 2 type, which corresponded to values of Vs30 between 350 m / s to 760 m / s. Only in a very few places soft soils (Vs30 <180 m / s) and the engineering rock (Vs30> 760 m / s) PREDOMINATED, corresponding to S4 and S1, respectively according to CSCR-2010 soil classification. S1, S2, S3and S4 correspond approximately to (A+B), C, D and E soil types respectively, based on NEHRP classification (FEMA-450, 2003).

Keywords: soil classification; ambient vibration; H/V, SPAC and FK methods; natural period; Vs30.

Recibido: Junio de 2016
Aceptado: Agosto de 2016

RESUMEN

Todas las redes de monitoreo de terremotos, requieren de una extensa información adicional acerca de las condiciones del suelo en las cuales se registran los movimientos de la tierra. En el caso de una red de movimiento fuerte, identificar el tipo de suelo utilizando las técnicas aplicadas de forma sistemática es esencial para validar los registros grabados.

En el Laboratorio de Ingeniería Sísmica (LIS), de la Universidad de Costa Rica, algunas técnicas que se implementan se basan en la medición de las ondas de superficie que permiten la caracterización de los suelos bajo el uso de las estaciones acelerográficas.

Estas técnicas son: H/V (relación espectral de la componente horizontal con la vertical), FK (frecuencia-número de ondas) y SPAC (autocorrelación espacial). En los últimos dos casos, de la dispersión y curvas de autocorrelación, se aplica un algoritmo inverso el cual permite generar modelos para obtener perfiles de la velocidad VS vs. profundidad. Con estas técnicas fue posible obtener los parámetros críticos tales como el periodo fundamental (T_0) y Vs30 en más de 30 sitios.

En general, los instrumentos de la red de movimientos fuertes del LIS, generalmente se encuentran localizados en valle aluviales, con contenidos de ceniza o depósitos lacustres. Por lo tanto, hay un predominio de los sitios con suelos de tipo blando los cuales se definen como S3 de acuerdo con el Código Sísmico de Costa Rica (CRSC-2010), los cuales se caracterizan con valores de Vs30 entre 180 m/s y 350 m/s.

También, se encontró que más de la mitad de los sitios podrían caracterizarse como de tipo S2, que corresponden a valores de Vs30 entre 350m/s y hasta 760 m/s. Sólo en muy pocos lugares se encontraron suelos blandos (Vs30 < 180 m/s) y roca ingenieril (Vs30 > 760 m/s) PREDOMINARON, correspondiente a S4 y S1, respectivamente, de acuerdo con la clasificación del suelo CSCR-2010. S1, S2, S3 y S4, corresponden aproximadamente a los tipos de suelo (A+B), C, D y E, respectivamente basándose en la clasificación NEHRP (FEMA-450, 2003).

Palabras Claves: clasificación de suelos; vibración ambiental; métodos H/V, SPAC y FK; periodo natural; Vs30.

1 INTRODUCTION

The Earthquake Engineering Laboratory (LIS) at the University of Costa Rica has acquired more than 100 new accelerometers since 2010. They are connected TO the Internet AND transmit information in real time, making it possible to generate a large amount of useful data for professionals from different fields (engineers, geologists, geotechnical, urban planners and emergency-care) a few minutes after the event has occurred. This information is available for both local and foreign researchers.

Various researchers around the world agree that it is essential to know exactly the type of existing soil in places where earthquakes are recorded, due to the dependence of very important parameters required for the seismic design of structures to soil type, such as the peak acceleration, the pseudo acceleration, velocity, and displacement and design spectra.

The application of three techniques based on measurement of surface waves called H/V, FK and SPAC is presented. They are briefly described in the methodology proposed. These techniques are not invasive or destructive of the environment where they applied, they are also quick and easy to apply and have a relatively low cost. For those reasons they are very suitable for the characterization of sites corresponding to accelerographic networks.

The main advantage of working with surface waves is that THEY ARE PRESENT most of the time and everywhere. This way that measurement can be performed at any time, with relatively simple procedures.

2 METHODOLOGY

The equipment used for the implementation of the H/V, FK and SPAC techniques consists of 8 sensors Lennartz 20 seconds (LE-3D / 20s) and an integrated model SMA Reftek digitizer.

To achieve a homogeneous classification of sites, in each selected station they were applied the following methods:

2.1 H/V TECHNIQUE

This involves the determination of the Fourier spectra of the horizontal (H) and vertical (V) components of ambient vibration records, obtained with a velocimeter or a triaxial accelerometer for a time window of 30 minutes per site. Next, H/V spectral ratio is calculated, which is considered by its author [5] an approximate transfer function of soil layers on the bedrock. When counted on two horizontal (E-W and N-S) components, H is usually regarded as the average of the spectra in the horizontal plane. The peak observed in the spectral ratio corresponds to the fundamental period of vibration of the site (T_0).

Once T_0 is obtained, it is possible to classify the site from correlations established according to the following table:

Table 1 Correspondence between site classes, T_0 and velocity ranges Vs [8].

Site Classes	**Site natural period** T_0 **(s)**	**Shear wave average velocities (m/s)**	**Equivalent NEHRP**
S I (rock/stiff soil)	$T_0 < 0,2$	Vs30 > 600	A+B
S II (hard soil)	$0,2 = T_0 < 0,4$	300 < Vs30 = 600	C
S III (medium soil)	$0,4 = T_0 < 0,6$	200 < Vs30 = 300	D
S IV (soft soil)	$T_0 = 0,6$	Vs30 = 200	E

If each spectral ratio has a very flat shape and values of H / V close to unity, it is considered that the site corresponds to rock.

Windows of 30 minutes were selected, which were divided by the calculation algorithm in lengths according to different criteria. In this particular case, we worked with lengths such that f_0 ($f_0 = 1 / T_0$) number within each window is greater than 30.

The fundamental frequency of site (f_0) or the characteristic site period ($T_0 = 1 / f_0$) [4] is read as the frequency associated to the maximum peak corresponding to the average of the H / V ratios.

2.2 Techniques based on arrays of sensors for the implementation of the FK (Frequency-wave number) and SPAC methodologies (Spatial Autocorrelation)

The first method assumes that ambient vibrations are composed of surface waves and subsurface structure is composed of horizontal layers. In unidimensional and heterogeneous media, surface waves are dispersive and show the apparent velocity differences according to frequency. Love modes (SH) and Rayleigh (P-SV) waves coexist in the horizontal components, while the vertical ones are affected only by Rayleigh surface waves [8].

The FK method assumes that plane waves PASS TRHROUGH the array which is located on the surface. Considering a wave with frequency f with known propagation direction and velocity (or the number of equivalent wave kx and ky along the horizontal axes X and Y). Then arrival times are calculated for each sensor according to each location and the phases of the records are changed according to delay times. The response of the array is calculated by adding the signals transformed to the frequency domain. If the waves travel with specific velocity and direction, all contributions will accumulate constructively, resulting an array of high output. The location of this maximum from the kx and ky plane (also known as beam power), provides an estimate of the velocity and the azimuth of the waves traveling through the array.

The SPAC method represents another possibility to analyze the recorded signals, which assumes the random source distribution of the noise waves, both in time and space. For a dispersive wave, it has been shown that the autocorrelation ratios are a function of the phase velocities and the aperture of the array. This method then uses the random distribution of the sources to correlate the autocorrelation ratios with phase velocities.

For the implementation of the FK and SPAC techniques, there were placed in most cases 8 sensors on a horizontal surface, usually in soccer fields that are open and horizontal spaces that prevail in both rural and urban areas of Costa Rica.

One sensor is placed at a central point of the array and seven at the circle perimeter as appropriate azimuthal coverage that should be achieved. Because it should also properly register the wavefronts in radial terms, measurements were conducted considering two diameters per site: shorter diameter to define the surface layers (high frequency at the dispersion curve) and the larger diameter defining deeper layers (low frequencies).

The maximum available cable length is 50 m which determines the maximum diameter of the array which is 100 m. However, the usual limitations of existing open spaces where these techniques were applied match to these apertures. Each sensor was located in specific sites using measuring tape. Sensors were also protected against wind, and other undesirable disturbances, by using plastic boxes.

After obtaining the velocity profile, the Vs30 parameter which is a kind of average wave velocities corresponding to the first 30 m measured from the surface, was estimated. Its mathematical expression is (1):

$$Vs30 = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \qquad (1)$$

Where di is the thickness in meters of each layer of soil profile up to 30 m deep, Vsi the shear wave velocity of each layer i in m / s and N the number of layers to reach 30 m. An important advantage of Vs30 is that many of the soils in the world have been classified using this parameter which facilitates its use and comparison worldwide.

It is possible to obtain soil classification for each station according to the correspondence shown in Table 2, which are proposed by the NEHRP codes used as a worldwide reference [1] and Costa Rican Seismic Code CSCR 2010 [2]. It is noted that in the case of CSCR-2010 there is no classification of "hard rock" as it is very unlikely to find at the surface in this country.

Table 2 Soil classification based on the NEHRP [1] and CSCR 2010 [2] codes.

NEHRP			CSCR-2010		
Soil type	**Soil description**	**Vs30 range (m/s)**	**Soil type**	**Soil description**	**Vs30 range (m/s)**
A	Hard rock	Vs30 > 1500			
B	Rock	760 < Vs30 ≤ 1500	S1	Rock or rigid soil or dense	≥ 760
C	Very dense soil to soft rock	360 < Vs30 ≤ 760	S2	Moderately dense to dense or moderately rigid to rigid	350 to 760
D	Hard soil to middle	180 ≤ Vs30 ≤ 360	S3	6 to 12 m of clay with soft to moderately rigid consistency	180 to 350
E	Soft soil	Vs30 < 180	S4	More than 12 m of soft clay	≤ 180

After obtaining T_0 with H / V method and the Vs30 parameter, a table in which all the criteria used in this study is presented and soil type for each site is defined. Thus it is possible to obtain a homogeneous and consistent classification.

3 RESULTS

Figures 1, 2 and 3 show the results obtained in some representative sites of this study. At the upper left of each figure the spectral ratio H / V is shown, the dispersion curves obtained with the FK and SPAC techniques are also shown at the upper right of the same figures and the models of Vs vs. depth obtained by those two methods are located at the bottom of the figures (lower left corresponds to FK and lower right to SPAC).

For the site called “Alajuela Plaza Acosta” (Fig. 1), the spectral ratio H / V clearly define a single peak around 1.42 Hz for what it is considered to be the presence of a very strong contrast between layers. Trends of dispersion curves obtained with the FK and SPAC are quite similar, even though SPAC provides more information at low frequencies and FK is clearer at high frequencies.

Using both methods, IT IS POSSIBLE TO SEE THAT the best models obtained are similar: two layers and the basement, showing the highest contrast between the second layer and the basement at 40 to 45 m measured from the surface.

On a softball field called “La Sabana” (Fig. 2), it is clear and well-defined the peak shown by H / V at 2 Hz, which shows an evident contrast at 40 m approx. The dispersion curve obtained by SPAC is not clear, so it is not presented. However, the generated FK is clear at high frequencies, generating a model of two layers and a basement. The first layer (Vs around 200 m/s) and the first contrast are very well defined, then a second Vs around 400 m/s and the associated contrast show more dispersion and finally the basement.

In the site called “Colegio St. Jude” located at Santa Ana (Fig. 3), the ratio H / V shows a very flat shape up to 10 Hz approximately, for what the medium seems to be homogeneous and rigid. This is confirmed by the dispersion curve obtained with FK. The curve shows virtually no dispersion so the waves do not exhibit the phenomenon of apparent velocity variation with respect to frequency. This prevents the use of FK and SPAC methods obtain Vs models with depth for this specific site.

Being approximately constant Vs on this site, the Vs30 is estimated as the inverse of the almost constant slowness: 1/0,0065 = 1,538 m / s. One important limitation in this site is the reduced available space to place the instruments which prevents the recording of wavefronts traveling through deeper soil layers.

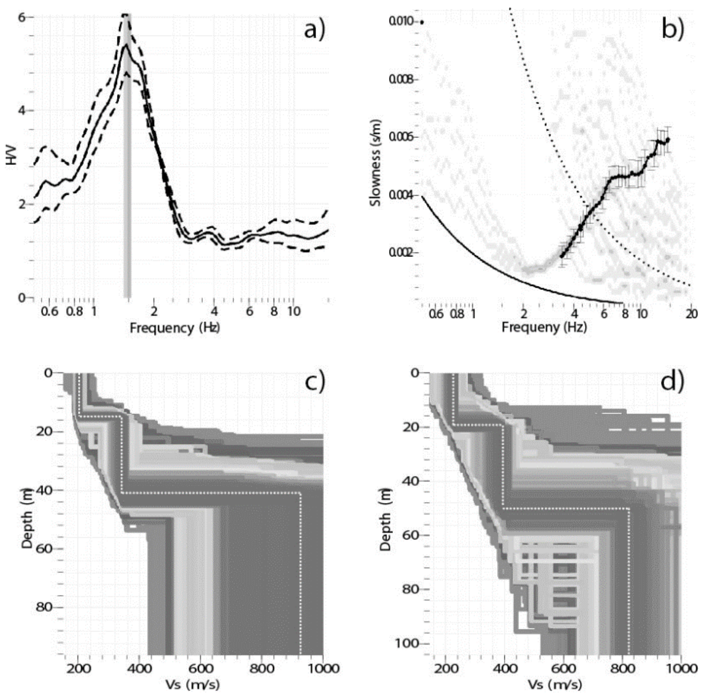

Figure 1 Site called “Alajuela Plaza Acosta” close to station AALA. a) H/V spectral ratio. b) FK and SPAC dispersion curves. c) Vs. vs. depth models obtained from de

inversion of FK dispersion curve. d) Vs. vs. depth models obtained from de inversion of SPAC dispersion curve [6].

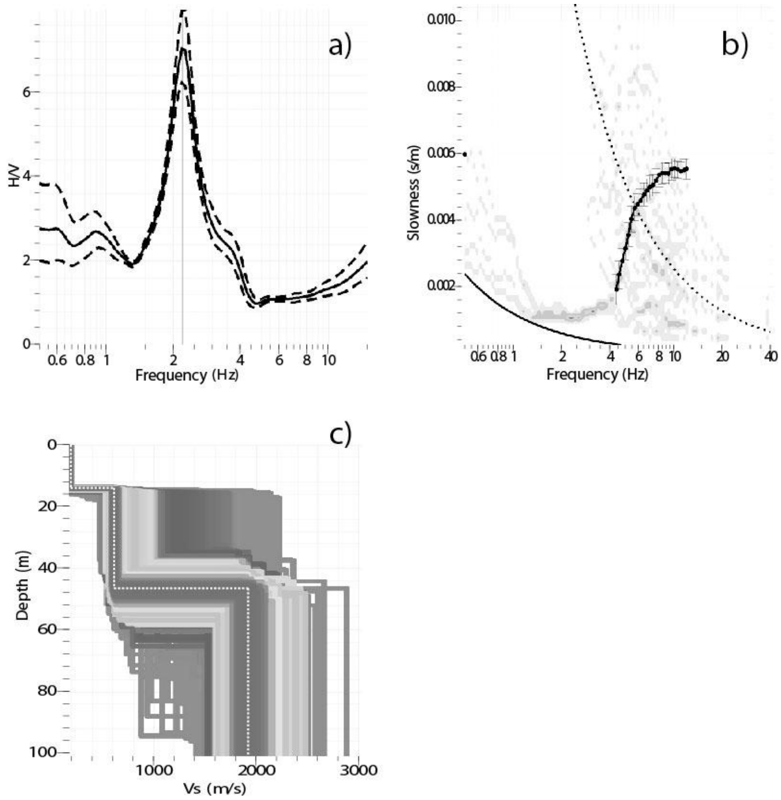

Figure 2 Site called “La Sabana”. a) H/V spectral ratio. b) FK and SPAC dispersion curves. c) Vs. vs. depth models obtained from de inversion of FK dispersion curve [6].

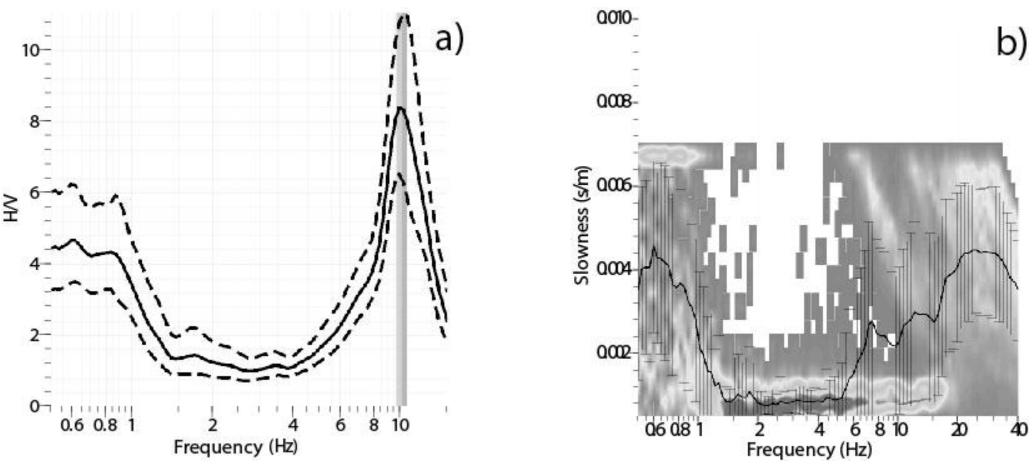

Figure 3 Near SJUD station. a) H/V spectral ratio. b) FK dispersion curve [6].

For the final classification of the sites, two criteria were applied: the Seismic Code of Costa Rica [1,2] which uses only Vs30 as classification parameter and the one proposed by [8] which is based on both Vs30 and the natural period of the site (T_0).

Table 3 shows the values Vs30 for the 31 sites considered in this study that compares to this parameter with the ranges defined by the CSCR-10 according to table 2.

They were able to identify 19 sites (61% of total) with soil S3, which corresponds to a Vs30 between 180 m / s and 350 m / s. In this case, the average Vs30 calculated based on all S3 sites is very similar to the average of the range mentioned, that is 265 m / s.

Furthermore, 11 of 31 sites (36%) are classified as S2, which corresponds to a velocity range between 350 m / s and 760 m / s, according to the CSCR-10. In this case, the average Vs30 considering all S2 sites is less than the average range for this category, which is 555 m / s. Only one of the studied sites showed a spectral ratio H / V flat across the whole frequency range and no dispersion was observed in the curve. This site was SJUD.

The site that shows the lower Vs30 is PPQR, with a value of 214 m / s. The geological description of this site corresponds to "continental and transition coastal marine sediments Quaternary" according to the Geological Map of Costa Rica [3].

Regarding the classification criteria given by [8] (see table 1) that ranges of Vs30 to define each category differ from those presented by the CSCR-10. Based on this classification and according to the table 1, 9.7% of sites are classified as S I, 41.9% as S II and 48.4% S III and there are no sites classified as S IV (soft soil).

Similar to the classification criteria proposed by the CSCR-10, most sites are classified as S II and S III, but in this case there is less of type S III and less of S II.

Regarding the criteria proposed by [8] but for the natural period of the site (T0) according to table 1 the classification significantly changes: 32% as SI, 10% as S II, 26 % as S III and 32% as S IV.

These differences could be explained because T0 is possible to identify from the H / V technique as long as there are significant contrasts of Vs between layers. In several of the studied cases this condition is not obvious, because the shape of the H / V ratio turned out to be fairly flat and with little amplification. When this happens, the soil is classified as rock even when it is not.

However, if the corresponding percentages to SI and S II soils are added (rock and hard soil respectively) a total percentage of 42% is obtained. In a similar way, if the percentages for S III and S IV (medium soft ground respectively) are also added the percentage obtained is 58%.

These percentages (42% and 58%) are quite similar to those obtained by applying the CSCR-10, in the sense that the higher percentage corresponds to medium plus soft soil and the lower percentage corresponds to rock plus hard soil. According to CSCR-10 these percentages are 39% and 61% respectively.

All applied classification criteria match that S 3 (according to CSCR-10) and S III (according to [8]) predominates in the studied sites.

Table 3 Soil classification according to CSCR-2010 [2]

STATION	**PLACE**	**VS30 ESTIMATED**	**SOIL ACCORDING Vs30**
AALA	PLAZA ACOSTA ALAJUELA	263,0	S3
AFBR	FABIO BAUDRIT	283,5	S3
AGRE	TACARES	277,0	S3
AORT	CRUZ ROJA, OROTINA	584,6	S2
APMR	CRUZ ROJA, PALMARES	285,0	S3
ASCS	BIBLIOTECA CIUDAD QUESADA	265,7	S3
ASRM	SAN RAMÓN, SEDE OCCIDENTE	274,0	S3
CCRT	BIBLIOTECA MUNICIPAL DE CARTAGO	432,1	S2
CORS	COLEGIO TÉCNICO PROESIONAL DE OROSI	687,3	S2
CPAR	SEDE UCR, PARAÍSO	269,0	S3
CTBA	SEDE UCR, TURRIALBA	385,0	S2
CTEC	INSTITUTO TECNOLÓGICO DE CARTAGO	377,0	S2
GNAN	MUNICIPALIDAD DE NANDAYURE	721,7	S2
HCPD	SAN MIGUEL, SANTO DOMINGO	278,5	S3
LGPI	SEDE UCR, GUÁPILES	586,7	S2
LSQR	INS, SIQUIRRES	442,1	S2
NSTN	INGENIERIA ELECTRICA UCR	340,0	S3
NSTN	ECOLOGICO UCR	283,0	S3
NSTN	PLAZA IGLESIAS CARTAGO	244,0	S3
PCOB	COLEGIO DE CÓBANO	407,5	S2
PJAC	CRUZ ROJA, JACÓ	324,0	S3
POSA	MUNICIPALIDAD DE PUERTO CORTÉS	258,0	S3
PPQR	CRUZ ROJA, PAQUERA	214,0	S3
PQUE	BOMBEROS, QUEPOS	354,0	S2
SCOH	EBAIS, CIUDAD COLÓN	265,0	S3
SGTS	ESCUELA DE GUATUSO	268,0	S3
SHTH	CLÍNICA HATILLO	379,6	S2
SIAC	CRUZ ROJA, SAN IGNACIO DE ACOSTA	263,0	S3
SJUD	COLEGIO ST. JUDE	FLAT (NO DISPERSION)	S1
SLPF	SEDE RODRIGO FACIO, UCR	347,0	S3
SSBN	ICODER, LA SABANA	302,0	S3

Table 4 Soil classification according Zhao [6]

STATION	PLACE	VS30 ESTIMATED	SOIL ACCORDING Vs30	PERIOD H/V AMBIENT VIBRATIONS	SOIL ACCORDING H/V
AALA	PLAZA ACOSTA ALAJUELA	263,0	S III	0,71	S IV
AFBR	FABIO BAUDRIT	283,5	S III	0,48	S III
AGRE	TACARES	277,0	S III	0,77	S IV
AORT	CRUZ ROJA, OROTINA	584,6	S II	0,12	S I
APMR	CRUZ ROJA, PALMARES	285,0	S III	2,00	S IV
ASCS	BIBLIOTECA CIUDAD QUESADA	265,7	S III	1,00	S IV
ASRM	SAN RAMÓN, SEDE OCCIDENTE	274,0	S III	1,05	S IV
CCRT	BIBLIOTECA MUNICIPAL DE CARTAGO	432,1	S II	1,11	S IV
CORS	COLEGIO TÉCNICO PROESIONAL DE OROSI	687,3	S I	0,11	S I
CPAR	SEDE UCR, PARAÍSO	269,0	S III	1,00	S IV
CTBA	SEDE UCR, TURRIALBA	385,0	S II	FLAT	S I
CTEC	INSTITUTO TECNOLÓGICO DE CARTAGO	377,0	S II	1,21	S IV
GNAN	MUNICIPALIDAD DE NANDAYURE	721,7	S I	0,09	S I
HCPD	SAN MIGUEL, SANTO DOMINGO	278,5	S III	0,50	S III
LGPI	SEDE UCR, GUÁPILES	586,7	S II	0,11	S I
LSQR	INS, SIQUIRRES	442,1	S II	FLAT	S I
NSTN	INGENIERIA ELECTRICA UCR	340,0	S II	0,34	S II
NSTN	ECOLOGICO UCR	283,0	S III	0,48	S III
NSTN	PLAZA IGLESIAS CARTAGO	244,0	S III	1,00	S IV
PCOB	COLEGIO DE CÓBANO	407,5	S II	0,16	S I
PJAC	CRUZ ROJA, JACÓ	324,0	S II	1,01	S IV
POSA	MUNICIPALIDAD DE PUERTO CORTÉS	258,0	S III	FLAT	S I
PPQR	CRUZ ROJA, PAQUERA	214,0	S III	0,43	S III
PQUE	BOMBEROS, QUEPOS	354,0	S II	0,19	S I
SCOH	EBAIS, CIUDAD COLÓN	265,0	S III	0,60	S III
SGTS	ESCUELA DE GUATUSO	268,0	S III	0,45	S III
SHTH	CLÍNICA HATILLO	379,6	S II	0,37	S II
SIAC	CRUZ ROJA, SAN IGNACIO DE ACOSTA	263,0	S III	0,47	S III
SJUD	COLEGIO ST. JUDE	FLAT (NO DISPERSION)	S I	0,10	S I
SLPF	SEDE RODRIGO FACIO, UCR	347,0	S II	0,28	S II
SSBN	ICODER, LA SABANA	302,0	S II	0,47	S III

4 CONCLUSIONS

H/V, FK and SPAC techniques were applied to determine T0 (characteristic site period) and Vs30. Those parameters were obtained to classify 31 sites where accelerometers of the LIS (Laboratorio de Ingeniería Sísmica) strong motion network are located.

Records of 30 minutes of ambient vibration were recorded in each site using 8 sensors and one digitizer. T_0 was calculated as the inverse of f_0 which corresponds to the frequency with the highest amplification observed at H / V spectral ratios.

The models of Vs vs. depth were obtained from inversion of dispersion and auto correlation curves generated by FK and SPAC techniques.

Sites classification was made using criteria established by CSCR-10 [2] and Zhao [8]. Last one WAS based on soil classification given by NEHRP [1].

Three results of 31 studied sites were described in more detail. In two of them called “Alajuela Plaza Acosta” and “La Sabana”, the H / V spectral ratios show only one peak very well defined. Also, the dispersion curves obtained for these sites using both FK and SPAC methods are quite similar.

For the station called “SJUD”, both H / V spectral ratios and the dispersion curve obtained using FK method show very flat shapes and no amplification identified in a wide range of frequencies. This indicates the predominance of rock at the site or, the presence of a homogeneous soil without significant differences of Vs an then, consequently without dispersion.

When classifying 31 studied sites according to Vs30 ranges presented in CSCR-10 [2], it is observed that 61% of sites are classified as S3, and 36% as S2. The foregoing is an important result since CSCR-2010 proposed that in the absence of soil studies, it is possible the use of S 3 soil type for design purposes. However, in many urban areas S2 soil predominates which may result in an over-designing of structures.

Only one site was classified as S1 due to both H/V and dispersion curve are almost flat in the whole frequency range considered.

According to Zhao [8], based on Vs30 the sites are classified as follows: 9.7% as S I (rock/stiff soil), 41.9% as S II (hard soil), 48.4% as S III (medium soil) and none sites are classified as SIV (soft soil).

If the characteristic period (T_0) classification criteria proposed by Zhao [8] is considered, the percentages significantly change: 32% as SI, 10% as S II, 26% as S III and 32% as S IV.

The differences observed using both Vs30 and T_0 according to Zhao [8] could be related to the fact that some sites show H / V spectral ratio very flat and with amplification around 1.0. This involves a few or none Vs changes between layers and T_0 (or f_0) is not possible to identify. For that reason, those sites are classified as S1 according to soil characteristic period. However, a dispersion curve is obtained for those sites and Vs30 parameter is possible to estimate.

Still, all soil classification criteria considered in this study agree that the predominant soil is S3 according to CSCR-10 [2] and S III according to Zhao [8], being S3 and S III similar according to Vs30 ranges.

REFERENCES

[1] BSSC (Building Seismic Society Council (2003): The 2003 NEHRP Recommended Provisions for New Buildings and Other Structures, Part 1 (Provisions) and Part II (Commentary). *FEMA 368/369*, Washington D. C.

[2] CFIA Colegio Federado de Ingenieros y de Arquitectos de Costa Rica (2010): *Código Sísmico de Costa Rica 2002*. Editorial Tecnológica de Costa Rica, 4ta ed. Cartago, Costa Rica.

[3] Denyer P, Alvarado G (2007): *Mapa Geológico de Costa Rica.* Librería Francesa. Costa Rica.

[4] Kramer S L (1996): *Geotechnical earthquake engineering*. *Prentice-Hall,* New Jersey.

[5] Nakamura Y (1989): A method of dynamic characteristics estimation of subsurface using microtremor on the ground surface, *Railways Technical Research Institute.* 30:1, 9. Tokyo.

[6] Schmidt V (2014). Clasificación de suelos de 15 estaciones acelerográficas mediante el uso de métodos basados en vibraciones ambientales y del parámetro Vs30. Revista Geológica de América Central, 51:33-67.

[7] Wathelet M (2007): *Array recordings of ambient vibrations: surface-wave inversions*.Thesis Ph. D Université de Liège, Belgium.

[8] Zhao J, Asano A, Fukoshima Y, Irikura K, John X, Ogawa H, Ohno Y, Oouchi T, Somerville PG, Takahashi T, Zhang J (2006): An empirical site-classification method for strong-motion in Japan using H/V response spectral ratio.- *Bull. Sesism. Soc. Am.* Vol.96(3): 914-925.