METODOLOGÍA DE ZONIFICACIÓN DE RESPUESTA SÍSMICA DE DERECHOS DE VÍA DE SISTEMAS DE TRASPORTE POR DUCTOS DE HIDROCARBUROS

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Contenido

1. Introducción

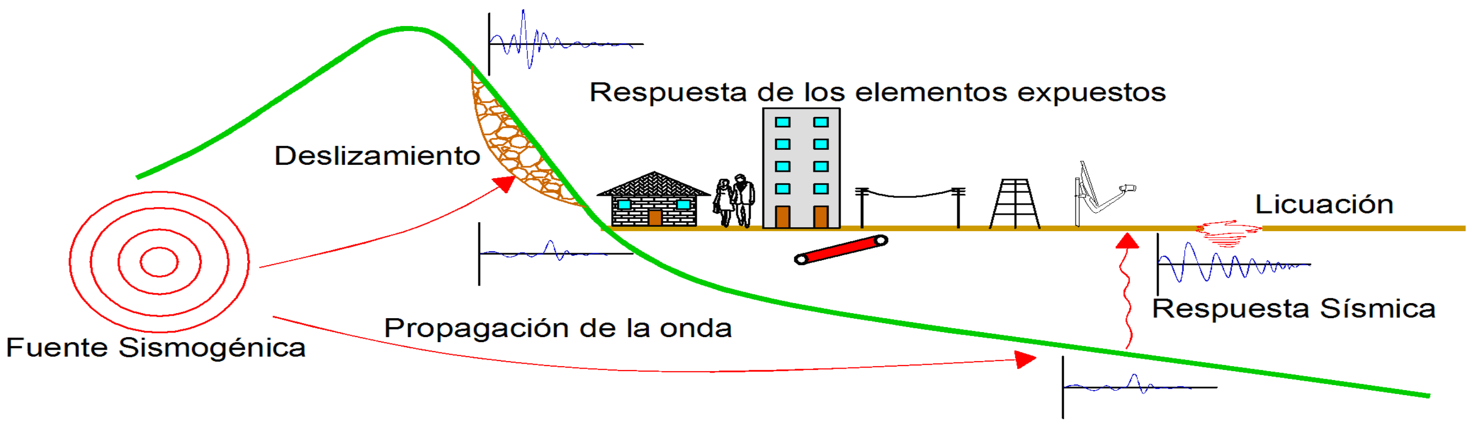
- Los estudios de Zonificación de Respuesta Sísmica o Microzonificación Sísmica definen la demanda sísmica para el diseño de estructuras y análisis geotécnicos, considerando la amenaza sísmica de la región en roca y los efectos del sitio por zonas de comportamiento dinámico homogéneo.

- Existen normas que definen parámetros sísmicos para el diseño sismorresistente de edificaciones, por ejemplo, en Colombia el Reglamento NSR-10 (MVDT, 2010) con aceleración horizontal (Aa) redondeada a cada 0,05g y efectos de sitio clasificados por perfiles geotécnicos de 30 m (A-F). En Perú, la Norma Técnica E.030 (Sencico, 2020) utiliza el coeficiente sísmico Z para dividir la peligrosidad sísmica en cuatro zonas (0.1g, 0.25g, 0.35g, 0.45g), clasificando también los efectos del sitio por los perfiles geotécnicos superiores de 30 m (S1-S4).

- La zonificación de respuesta sísmica de los derechos de vía del sistema de transporte de oleoductos y gasoductos se lleva a cabo para identificar las demandas sísmicas para los análisis de estabilidad de taludes en estas áreas. Este enfoque es necesario porque los parámetros sísmicos especificados en los estándares de diseño resistentes a terremotos se desarrollan principalmente para la construcción de edificios y perfiles de suelo típicos. Esto permite diseños de obras de estabilidad más seguros y económicos mediante el empleo de coeficientes sísmicos específicos del área de estudio.

1. Introducción

Enfoque conceptual del problema, escalas de análisis y efectos de sitio



ESCALA DE ANÁLISIS	RESULTADOS	ESTRATIGRAFICO	TOPOGRAFICOS	CUENCA
ESTUDIO DE RESPUESTA SISMICA LOCAL	Función de amplificación del perfil del sitio	Sí	Sí (2D)	Sí (2D o Ref)
ZONIFICACIÓN DE RESPUESTA SÍSMICA	Factores de amplificación promedios de los perfiles típicos de la zona	Sí	Sí	Sí
ESTUDIOS NACIONALES DE AMENAZA SÍSMICA	Factores de amplificación por estadística de perfiles sísmicos por Vs30	Sí	No	No

2. Zonificación de Respuesta Sísmica de Ciudades

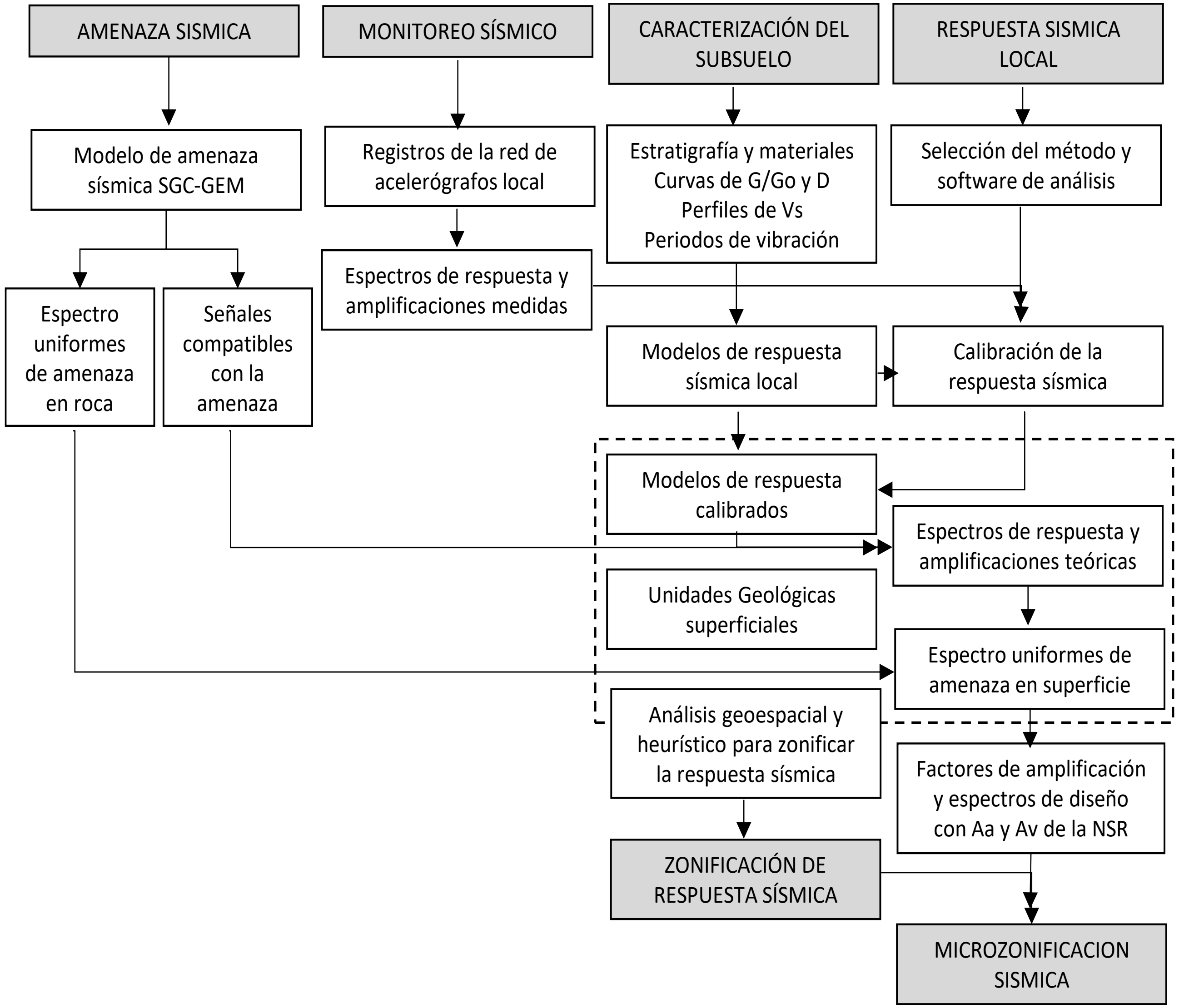


Diagrama metodológico de Zonificación de respuesta sísmica de ciudades. (Diaz-Parra et al. 2018)

2. Zonificación de Respuesta Sísmica de Ciudades

Zonificación de respuesta sísmica (ZRS)

Reagrupación por zonas minimizando variabilidad en cada variable

Zonificación de respuesta sísmica preliminar

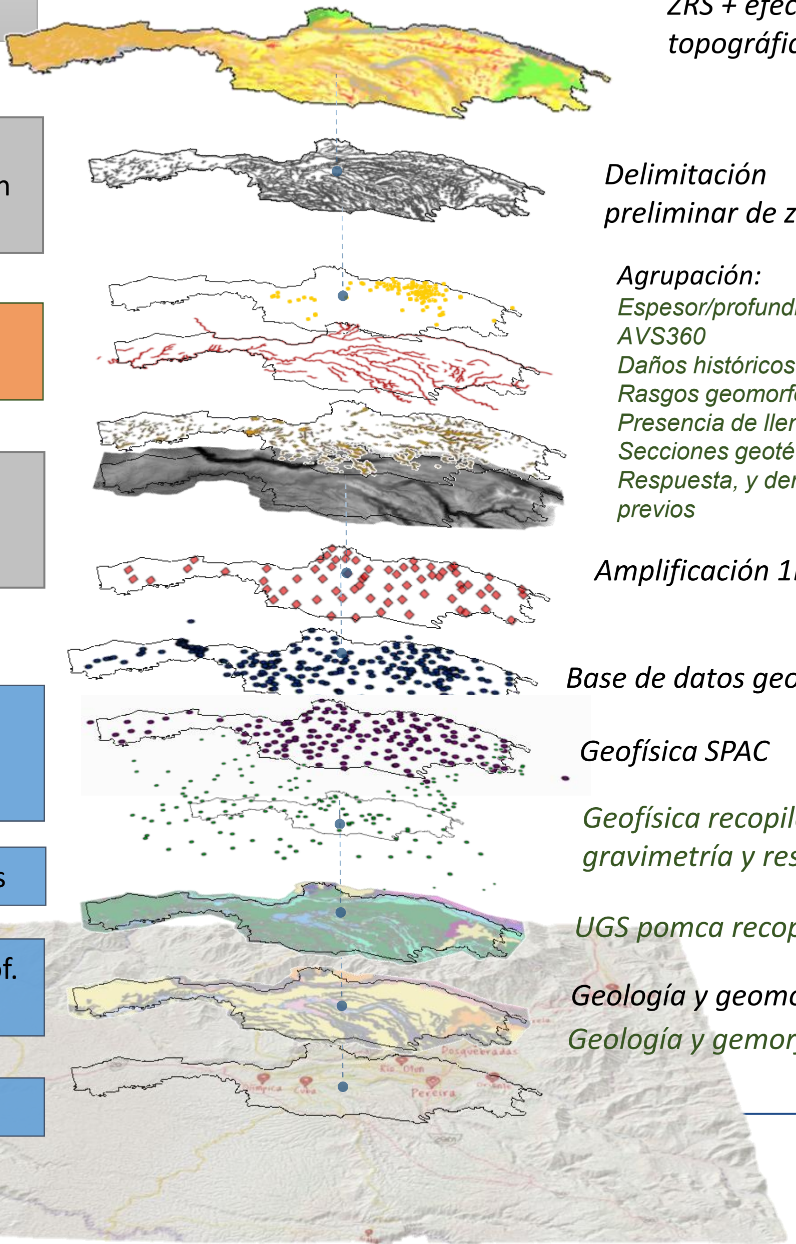
Agrupación por geomorfología y análisis heurístico - geoestadístico

Respuesta sísmica y amplificación espectral teórica y modelada

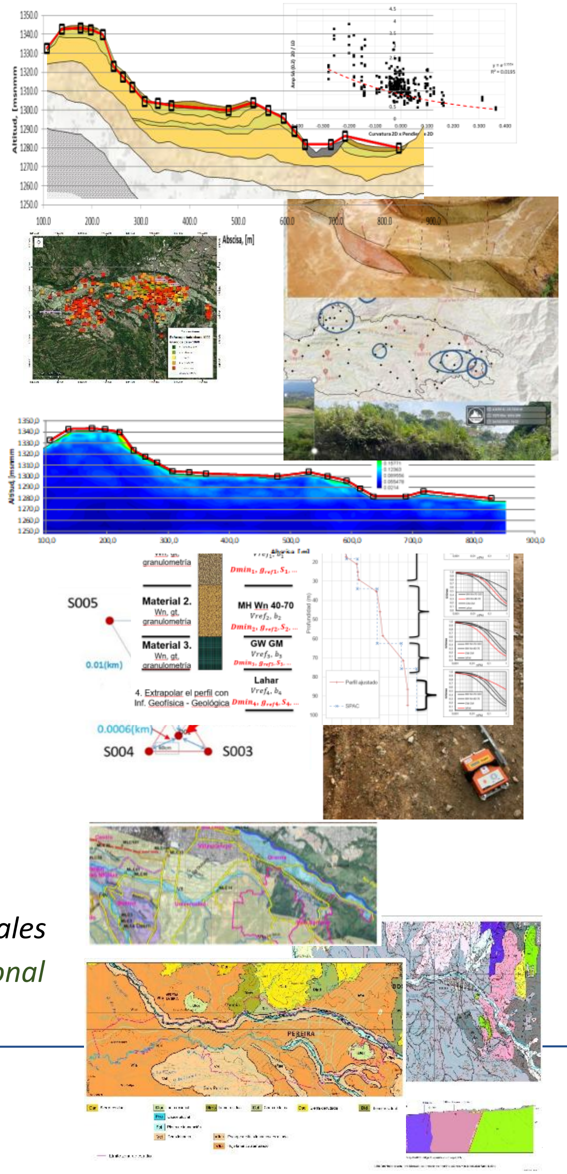
Perfiles geotécnicos típicos

Modelo geofísico Ts, Vs, prof. roca

Geología y geomorfología



ZRS Pereira (Diaz-Parra et al. 2021)

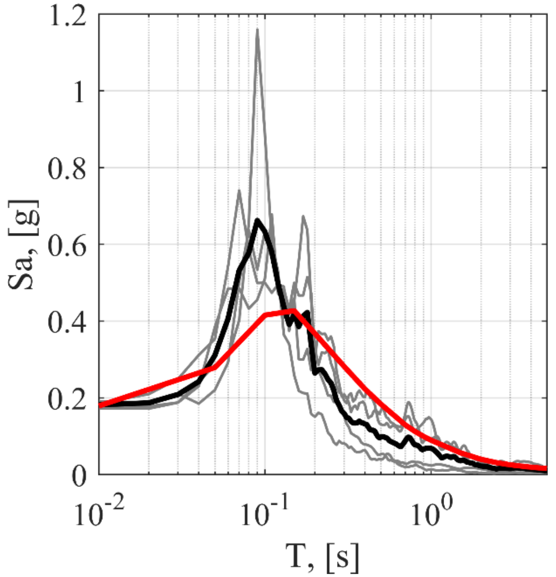


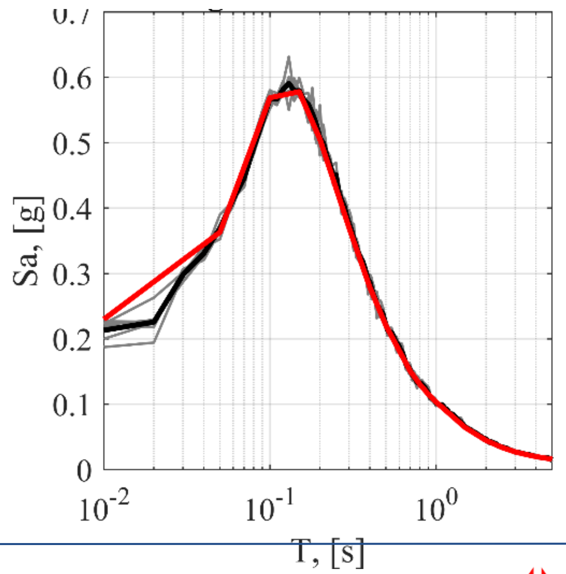
2. Zonificación de Respuesta Sísmica de Ciudades

- *Señales de modelación*

Teniendo en cuenta que el objetivo de la modelación de la respuesta de sitio es obtener las amplificaciones del terreno para varias intensidades, se recomienda:

- ✓ Consistentes con la desagregación de la amenaza sísmica en roca del Modelo Nacional de Amenaza Sísmica para Colombia del SGC.
- ✓ De estaciones sin efectos locales, con Vs mayor a 760 m/s.
- ✓ Al menos tres señales por nivel de intensidad (4 o 5 niveles de intensidad).
- ✓ Escalamiento frecuencial al espectro objetivo (Ferreira et al. 2020)





2. Zonificación de Respuesta Sísmica de Ciudades

- *Perfil estratigráfico y materiales típicos*

1. Información geotécnica (Perforaciones BDG)

2. Identificar materiales típico

3. Asignar Vs por tipo de material

5. Asignar curvas dinámicas por material

Material 1.
Wn, gt, granulometría

MH Wn 70-100
$Vref_1, b_1$
$\boldsymbol{Dmin_1, g_{ref1}, S_1, \ldots}$

Material 2.
Wn, gt, granulometría

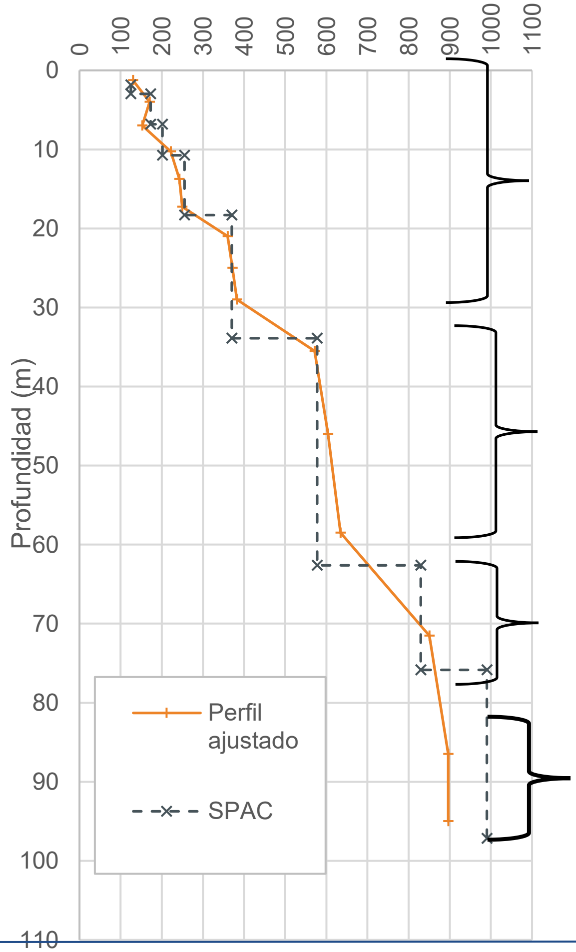
MH Wn 40-70
$Vref_2, b_2$
$\boldsymbol{Dmin_2, g_{ref2}, S_2, \ldots}$

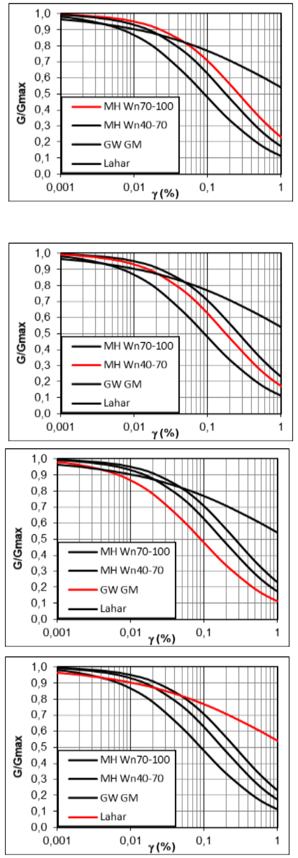
Material 3.
Wn, gt, granulometría

GW GM
$Vref_3, b_3$
$\boldsymbol{Dmin_3, g_{ref3}, S_3, \ldots}$

4. Extrapolar el perfil con Inf. Geofísica - Geológica

Lahar
$Vref_4, b_4$
$\boldsymbol{Dmin_4, g_{ref4}, S_4, \ldots}$

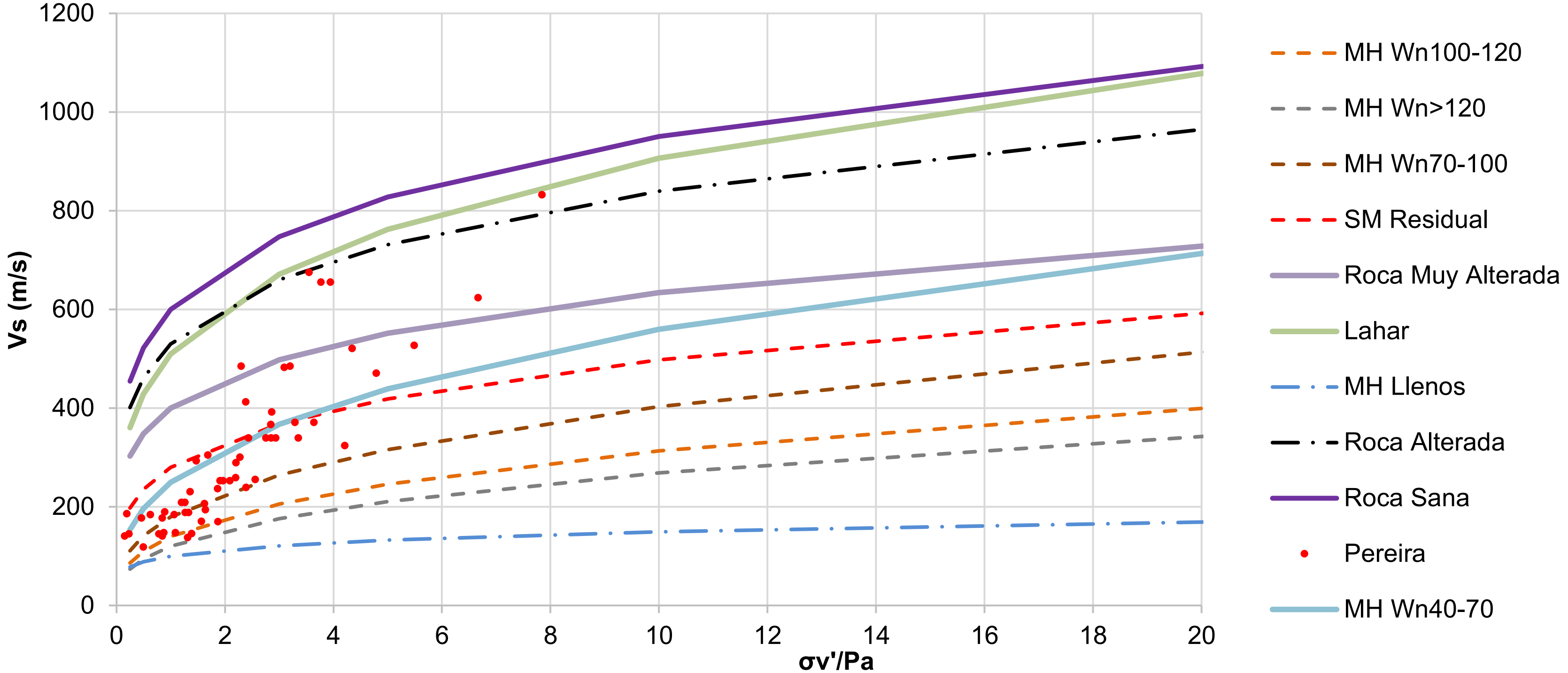




2. Zonificación de Respuesta Sísmica de Ciudades

- *Perfil de velocidad cortante*

$$Vs_i = V_{ref} \cdot \left(\frac{\sigma'_0}{Pa} \right)^b$$



2. Zonificación de Respuesta Sísmica de Ciudades

- *Curvas dinámicas*

Modelo de Comportamiento Dinámico de Arcillas Blandas

Dynamic Model Behavior of Soft Clay

Díaz-Parra Fernando, MSc[1], Alarcón-Guzmán Adolfo, PhD[2]

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[2] *Profesor Asociado Universidad Nacional de Colombia*

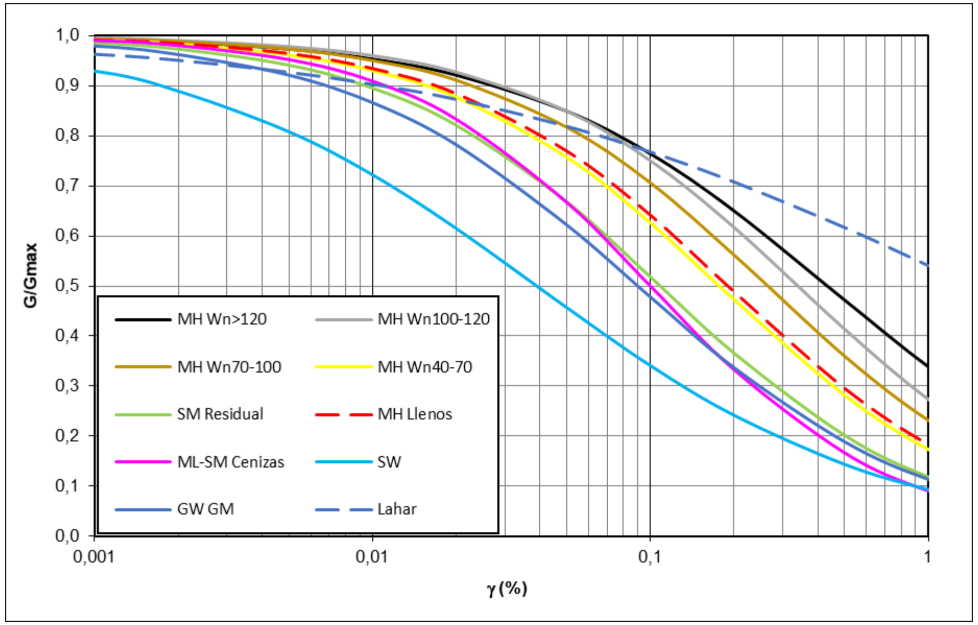
GRUPO	FACTOR	PARÁMETRO	EFECTO EN EL MÓDULO	EFECTO EN EL AMORTIGUAMIENTO
Asociados al tipo de suelo	Edad geológica	Tiempo	Aumenta	Disminuye
	Estructura	Empaquetamiento	Aumenta	Disminuye
	Cementación	Cohesión real	Aumenta	Disminuye
	Propiedades índice	Índice Plasticidad	Aumenta	Disminuye
	Propiedades físicas	Relación de vacíos	Disminuye	Disminuye
	Tamaño de partícula	Tamaño de partícula	Aumenta	Aumenta
	Estado de esfuerzos	Esfuerzo efectivo promedio	Aumenta	Disminuye
	Historia de esfuerzos	Relación de sobreconsolidación	Aumenta	Disminuye
	Compresibilidad	Índice de compresión y recompresión	Disminuye	Aumenta
	Resistencia	Resistencia No Drenada	Aumenta	Disminuye
Asociado al estado de esfuerzos	Confinamiento	Esfuerzo de confinamiento	Aumenta	Disminuye
Asociados a las cargas aplicadas	Esfuerzo cortante	Relación de esfuerzo cortante	Disminuye	Aumenta
	Repeticiones de carga	Número de ciclos	Aumenta en arenas y Disminuye en arcillas	Disminuye en arenas y aumenta en arcillas
	Velocidad de aplicación de la carga	Frecuencia de los ciclos	No afecta en arenas y aumenta en arcillas	No afecta en arenas y disminuye en arcillas

Tabla 1. Factores, parámetros y efectos que controlan el comportamiento dinámico de suelos

2. Zonificación de Respuesta Sísmica de Ciudades

- *Curvas dinámicas*

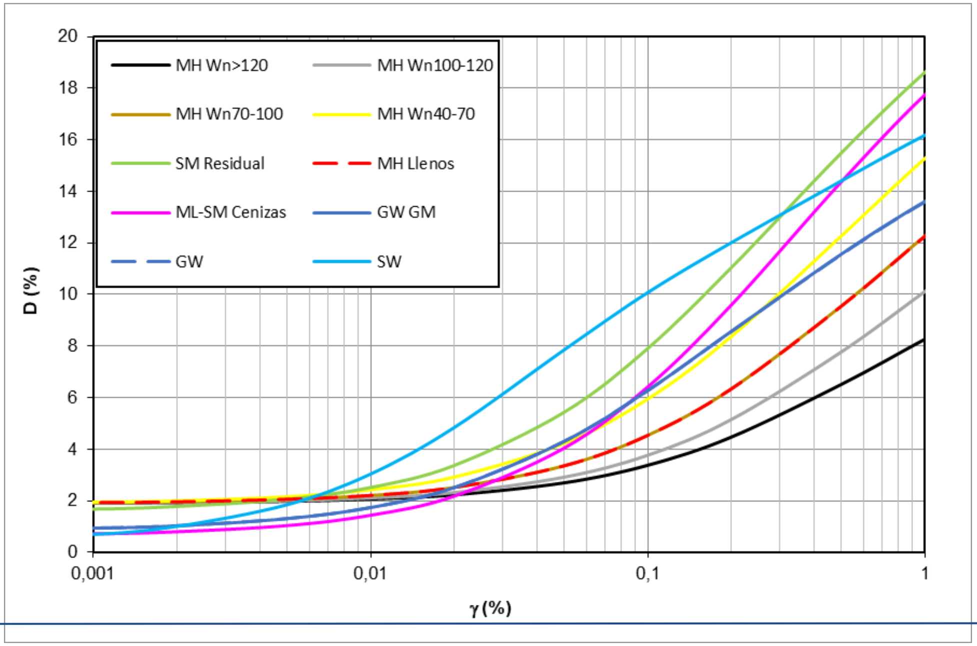
Parametrización de los materiales típicos al modelo hiperbólico extendido MKZ



$$\tau = \frac{G_o\gamma}{1+\beta\left(\frac{G_o}{\tau_{\max}}\gamma\right)^s} = \frac{G_o\gamma}{1+\beta\left(\frac{\gamma}{\gamma_r}\right)^s}$$

$$\gamma_r = a\left(\frac{\sigma'}{\sigma_{ref}}\right)^b$$

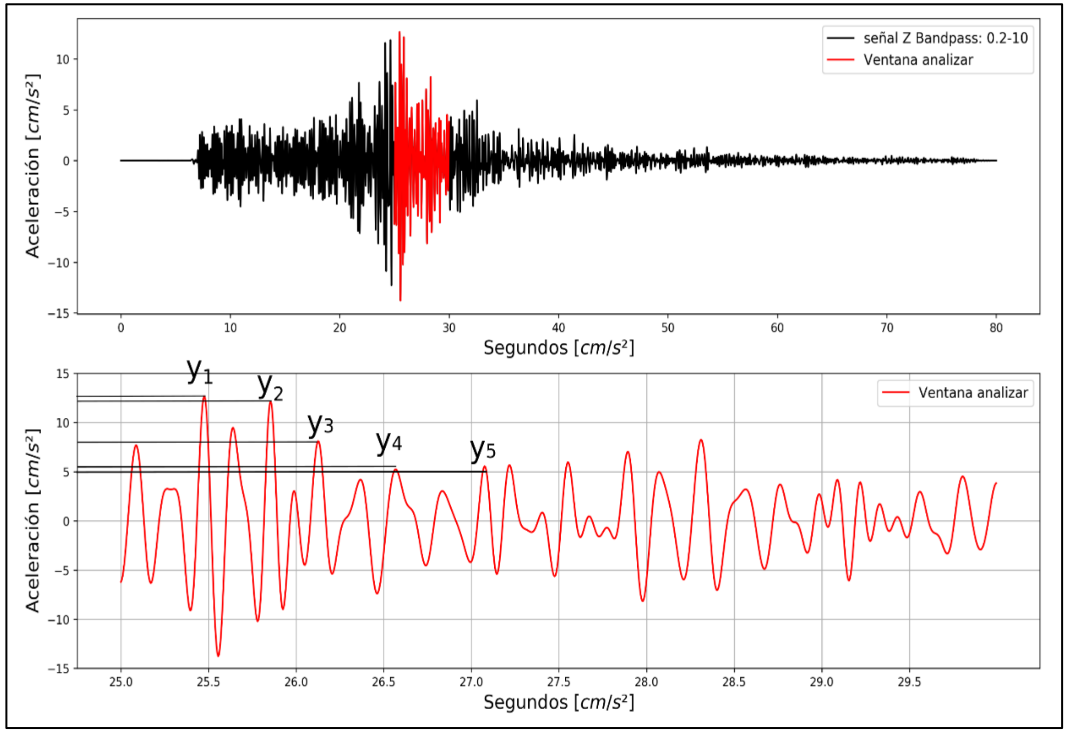
$$D = D_{min} + P1\left(\frac{G}{G_0}\right)^{P2} \cdot D_{masing}$$



Presión de confinamiento = 101 kPa

2. Zonificación de Respuesta Sísmica de Ciudades

- *Amortiguamiento mínimo o viscoso*



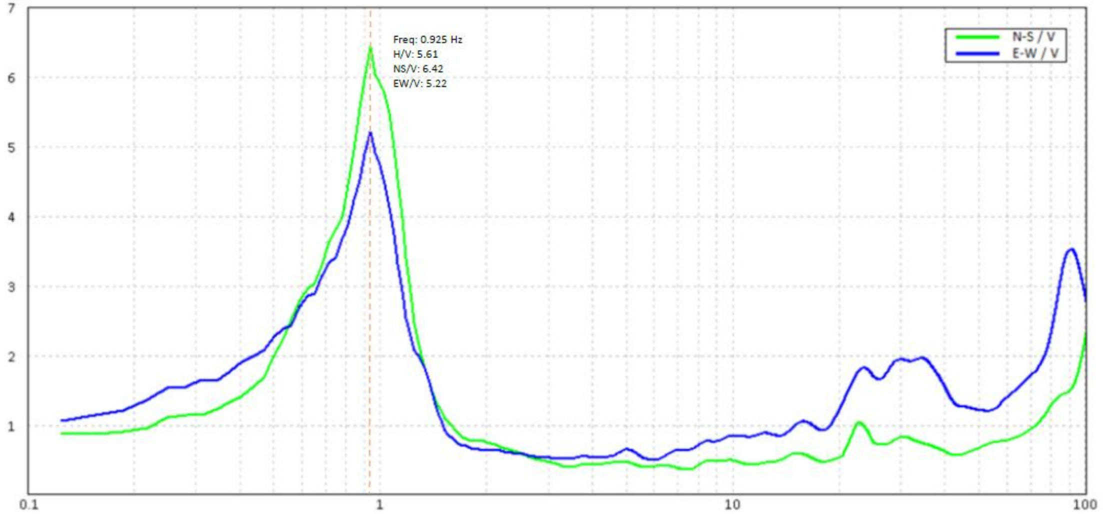
$$\xi = \frac{1}{2\pi}\Delta, donde\ \Delta = \frac{1}{N-1}\log\frac{y_1}{y_n}$$

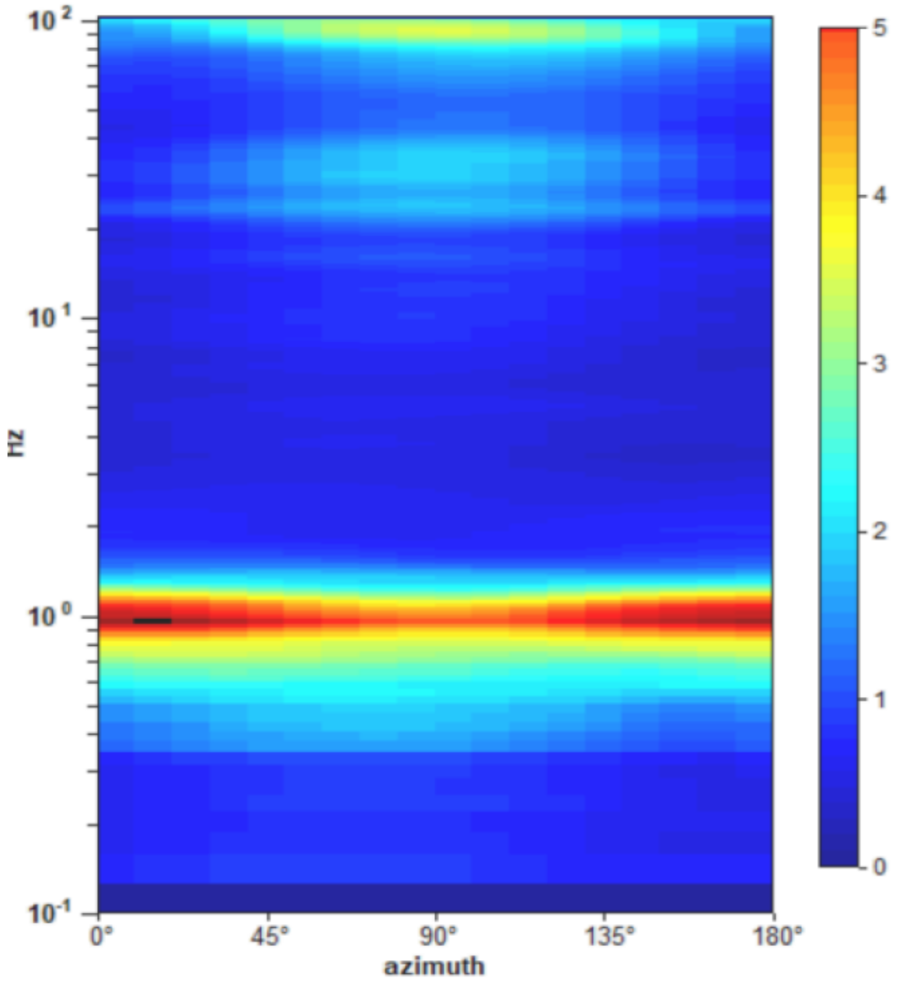
2. Zonificación de Respuesta Sísmica de Ciudades

- *Periodo de vibración*

✓ Tener en cuenta que los periodos del suelo (Ts) medidos por microtrepidaciones representa el modo de vibración de las capas de suelos firmes y blandos, el periodo del suelo medido es similar al periodo calculado del perfil de velocidad desde superficie hasta una velocidad cortante del orden de 360 m/s.

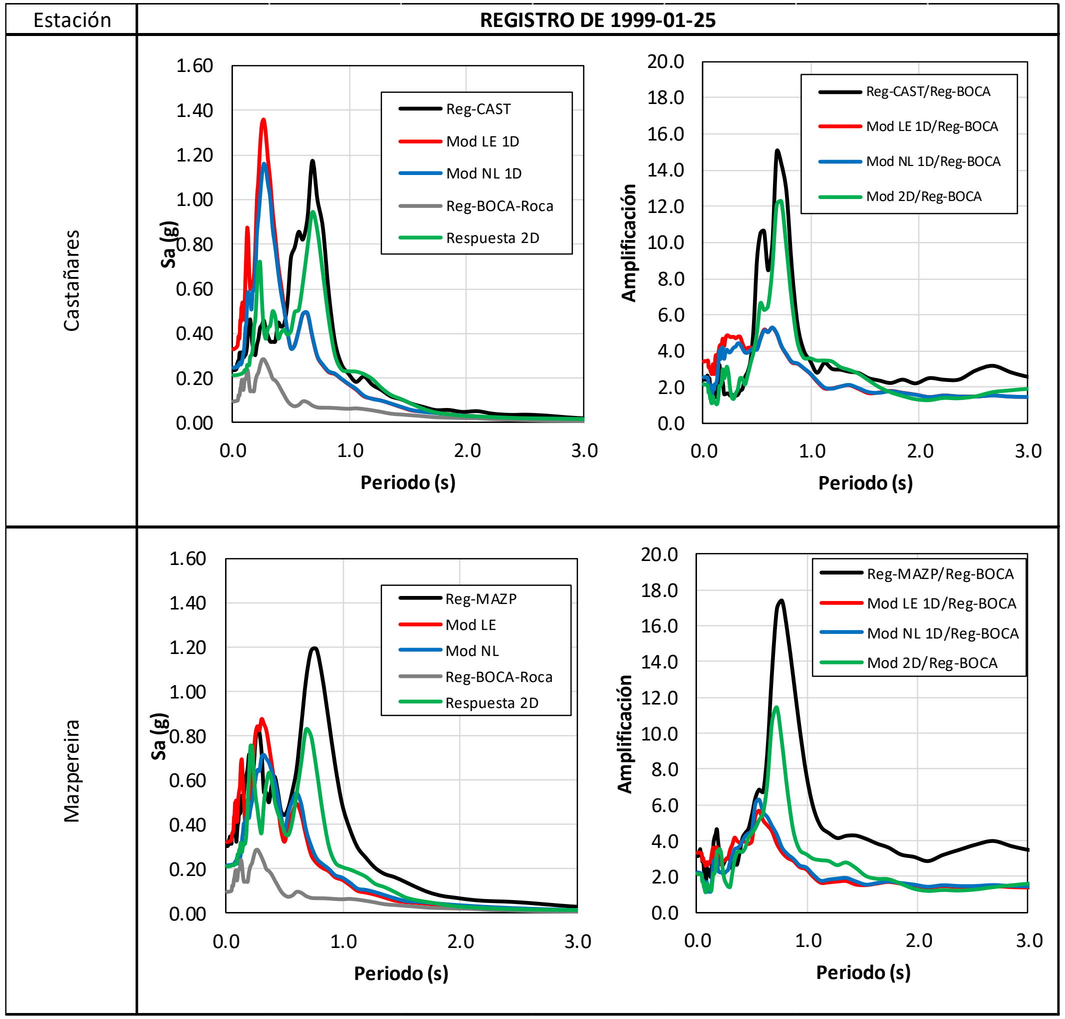
✓ Por su parte los periodos fundamentales (Tf) de los modelos de respuesta se calcula para todo el perfil (hasta Vs mayor a 760 m/s).





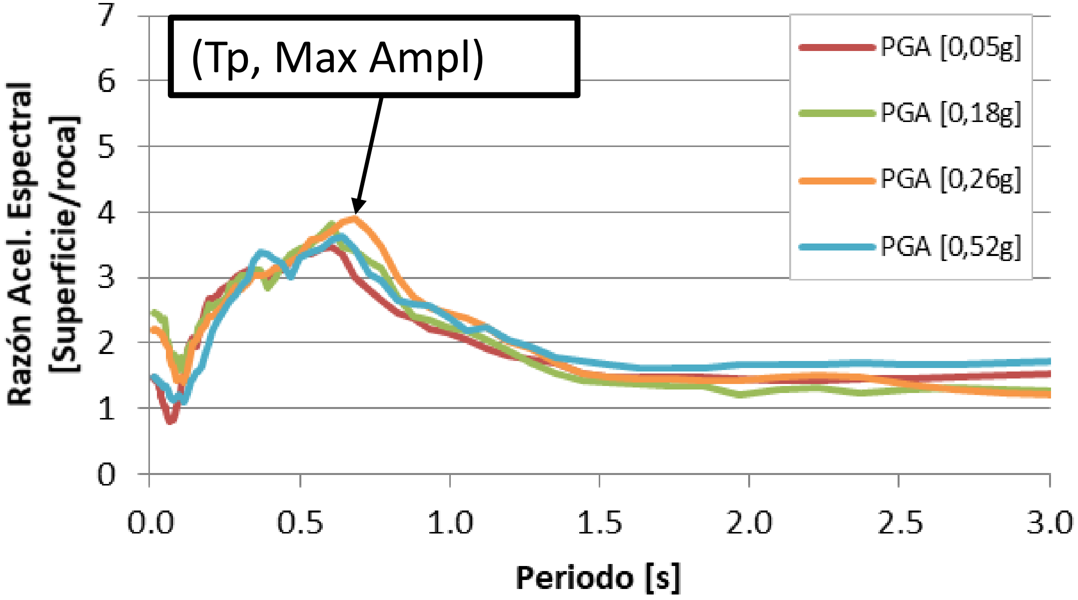
2. Zonificación de Respuesta Sísmica de Ciudades

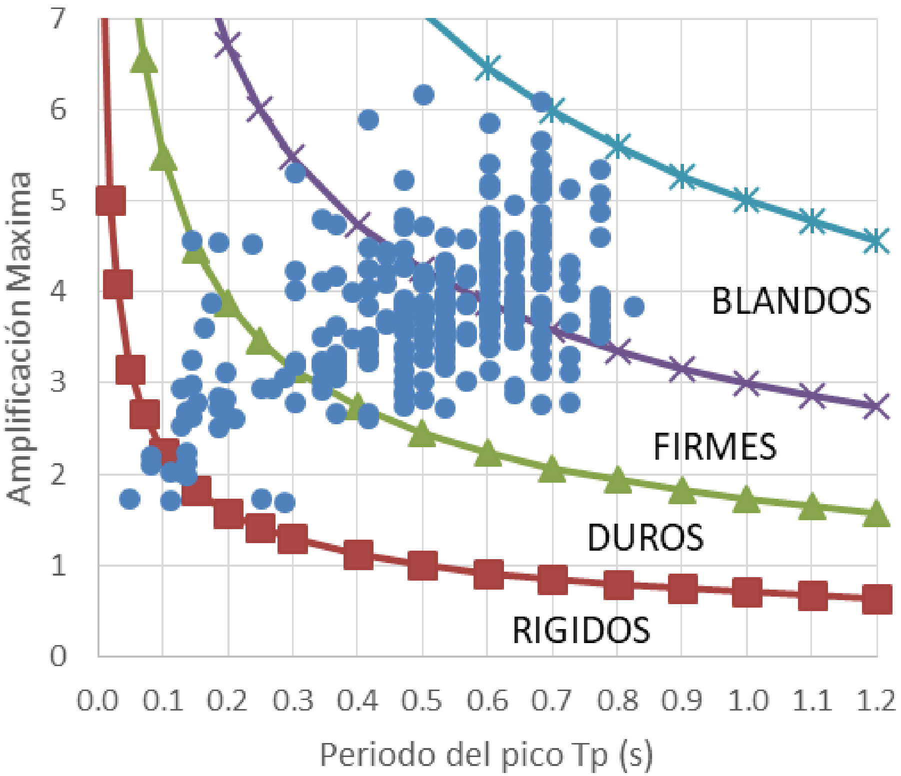
- *Validación – calibración de la respuesta con registros acelerográficos*



2. Zonificación de Respuesta Sísmica de Ciudades

- *Análisis de resultados*





Carta de clasificación de efectos de sitio (Díaz-Parra et al. 2020)

3. Metodología de Zonificación de Respuesta Sísmica de DDV

Marco lógico de actividades para zonificar la respuesta sísmica. (Ingeciencia, 2024)

- Organización de la Cartografía Base y temática
- Adopción de Amenaza Sísmica en roca (PGA y EAU)
- Señales para la modelación de la respuesta sísmica

→

- Exploración geofísica
- Base de Datos Geofísica y Geotécnica Georreferenciada
- Caracterización Geológica, Geotécnica y Geofísica

→

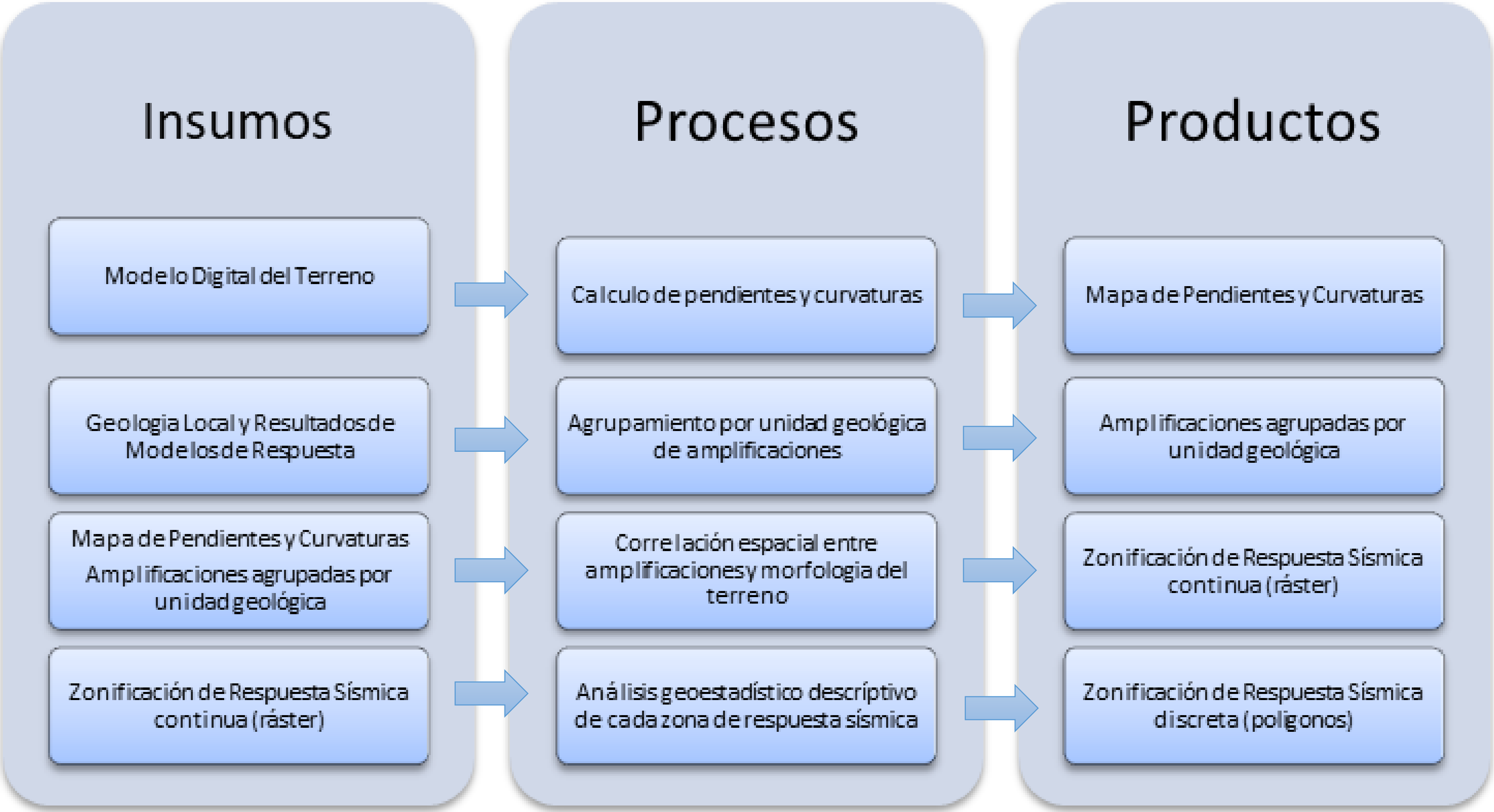
- Definición de Materiales y Perfiles Típicos
- Caracterización dinámica de los materiales típicos
- Modelación de la respuesta sísmica de perfiles típicos

→

- Análisis de resultados de la respuesta sísmica
- Definición de la Zonificación de Respuesta Sísmica
- Definición de Funciones y Factores de amplificación

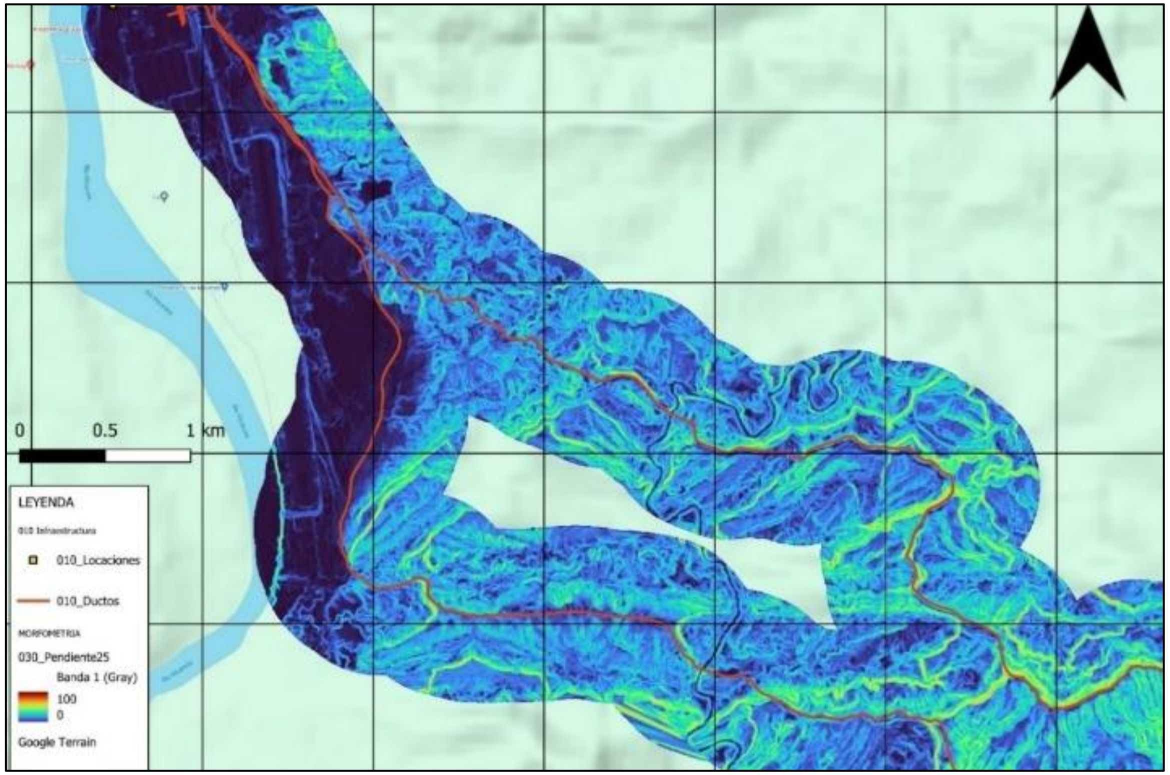
3. Metodología de Zonificación de Respuesta Sísmica de DDV

Metodología de zonificación de respuesta sísmica. (Ingeciencia, 2024)



4. Caso de aplicación

Mapas procesados de pendientes y curvaturas del terreno

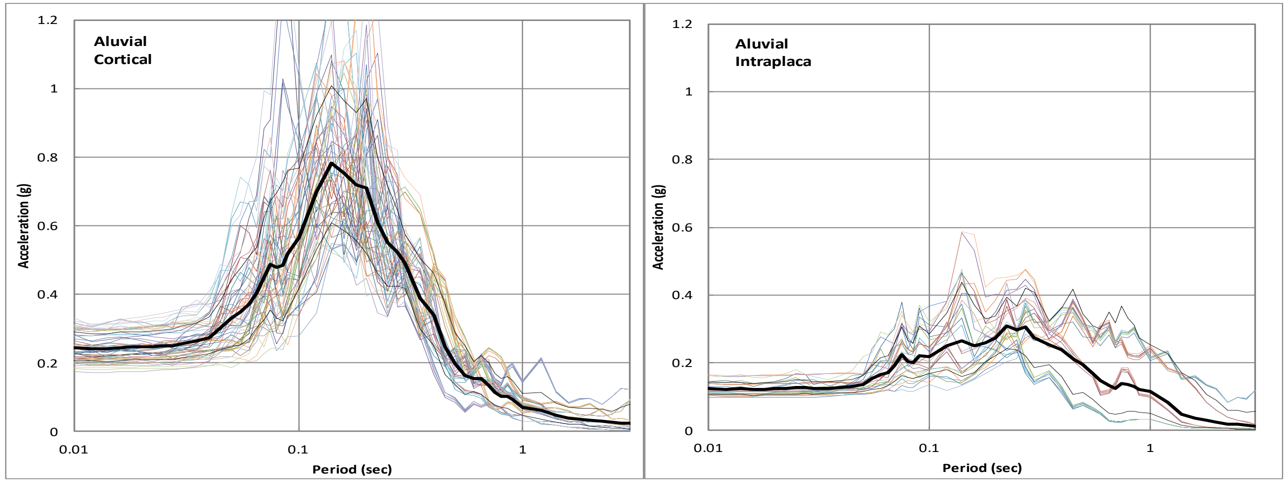


Modelo de pendiente

Modelo de curvaturas

4. Caso de aplicación

Amplificaciones agrupadas por unidad geológica



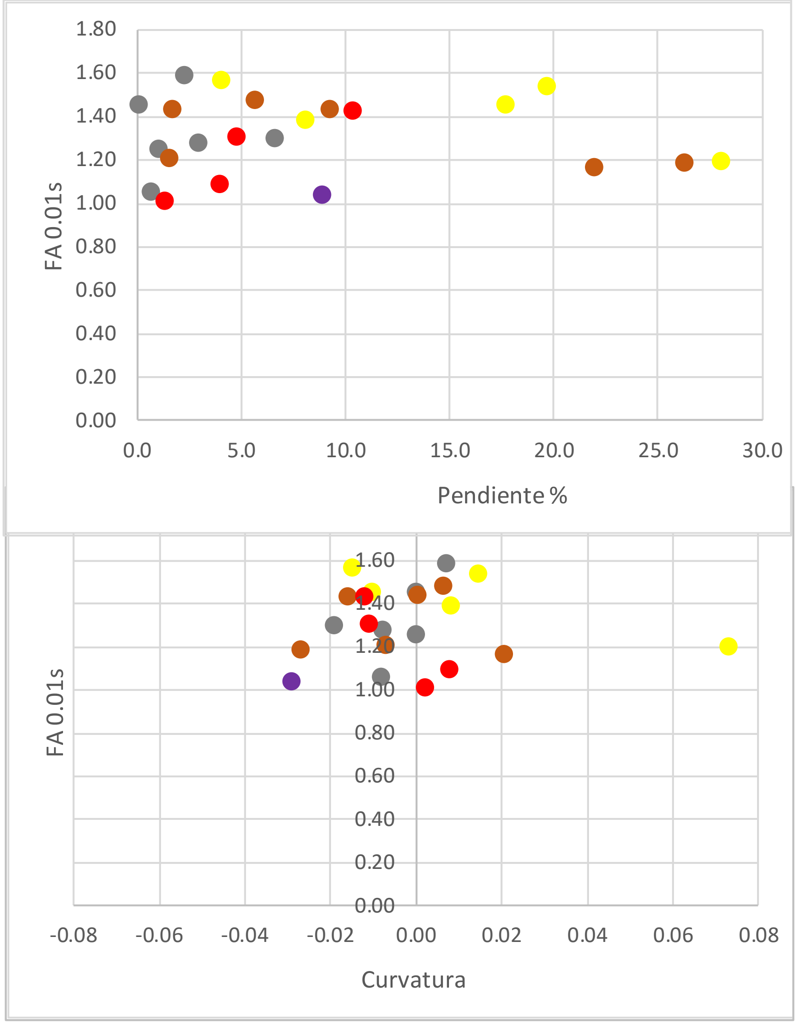
Espectros de respuesta en superficie configuración 1 para sismos corticales y de intraplaca

Agrupación de resultados	Configuración 1 FA (0.01s) Cortical	Configuración 2 FA (0.01s) Cortical	Configuración 3 FA (0.01s) Cortical	Promedio de las tres configuraciones de FA (0.01s)
Depósitos Aluviales	1.31	1.32	1.32	1.32
Formación Neógeno	1.37	1.29	1.43	1.36
Formación Precámbrico	1.21	1.17	1.32	1.24
Formación Precámbrico2	1.33	1.32	1.21	1.29
Formación Precámbrico 3	1.14	1.07	1.04	1.08

Factores de amplificación de PGA promedios por unidad geológica

4. Caso de aplicación

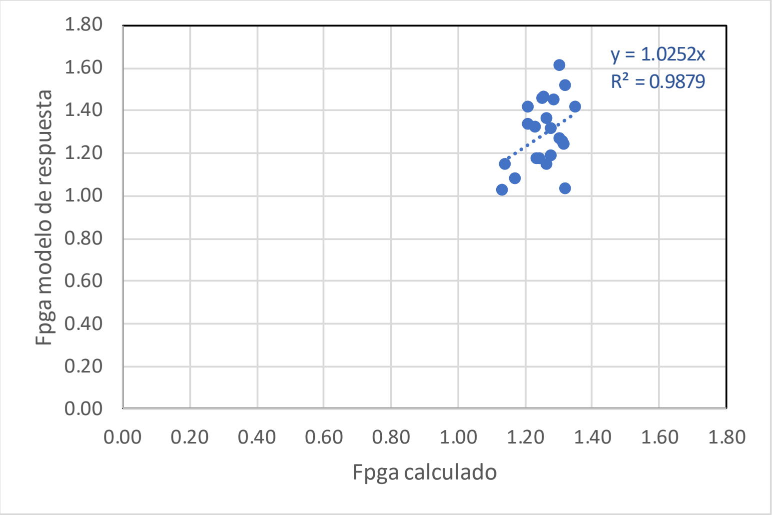
Correlación espacial entre amplificaciones y morfología del terreno



Relaciones entre la amplificación con la pendiente y curvatura

$$F_{PGA} = C1 + C2 * Curvatura + C3 * Pendiente$$

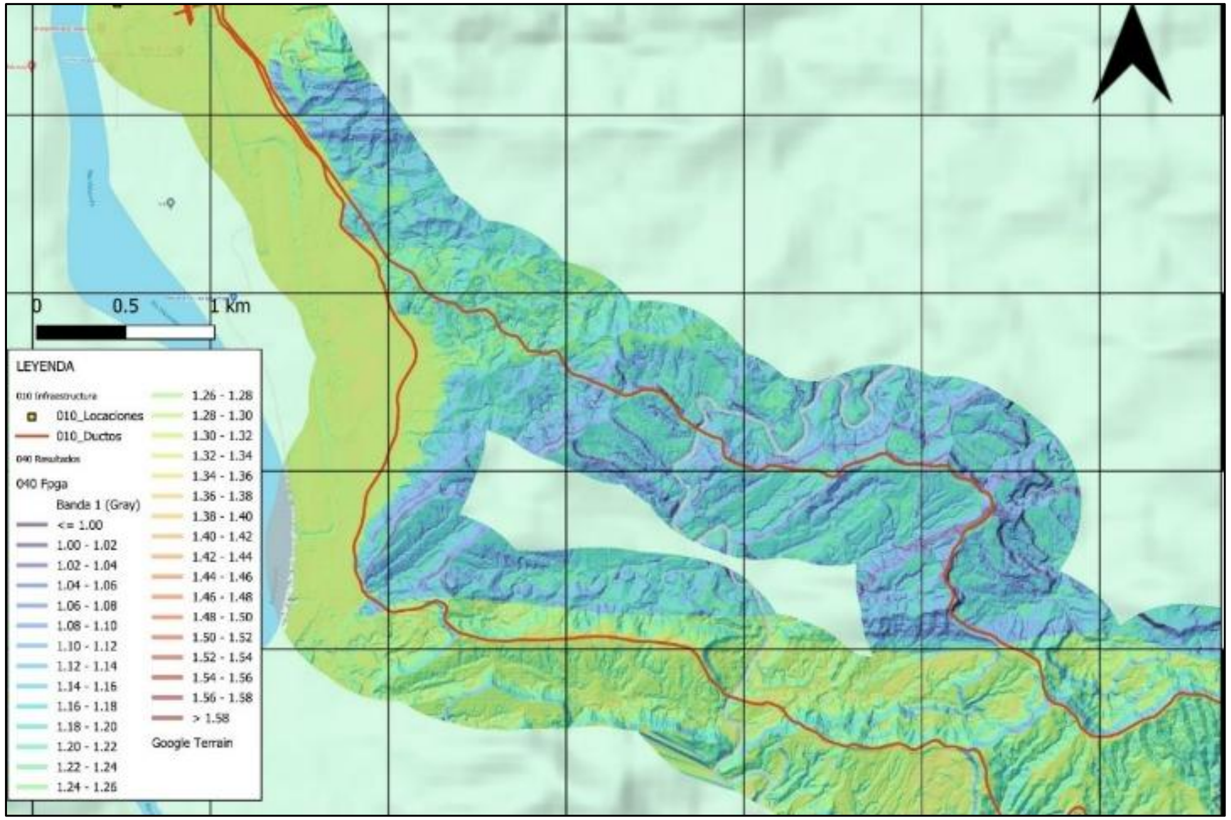
ZRS	C1	C2	C3
Depósitos Aluviales	1.32	-0.656	-0.0045
Formación Neógeno	1.36		
Formación Precámbrico	1.24		
Formación Precámbrico 2	1.29		
Formación Precámbrico 3	1.20		



Comparación de resultados de Fpga calculado con la correlación y los modelados

4. Caso de aplicación

Zonificación de Respuesta sísmica continua ráster



Mapa de variación espacial de Fpga

Mapa de variación espacial de PGAsup

4. Caso de aplicación

Zonificación de Respuesta sísmica discreta (polígonos)

ID	ZRS	PGAroca	Fpga	PGAsup	Kst
1	Aluviales	0.193	1.298	**0.251**	0.168
2	Neógeno	0.193	1.266	**0.244**	0.164
3	Precámbrico	0.193	1.147	**0.221**	0.148
4	Precámbrico 2	0.193	1.209	**0.233**	0.156
5	Precámbrico 3	0.190	1.126	**0.214**	0.143
6	Cretácico	0.190	1.093	**0.208**	0.139

Parámetros según E030: PGAroca=0.25, S_2=1.2 a S_3=1.4, **PGAsup entre 0.3 a 0.35**

5. Conclusiones

- ✓ Las condiciones de amenaza sísmica se pueden evaluar, incluidos los efectos del sitio en el derecho de vía, adaptando metodologías originalmente concebidas para ciudades para su aplicación en sistemas de transporte de hidrocarburos.
- ✓ La metodología desarrollada y aplicada permitió realizar la zonificación de respuesta sísmica del derecho de vía de los sistemas de transporte de hidrocarburos, enfocada en los parámetros sísmicos del diseño geotécnico de estabilidad de taludes.
- ✓ Los resultados son insumo para zonificar la amenaza por movimientos en masa, el análisis de riesgo sísmico y el sistema de alerta temprana de deslizamientos por sismo.
- ✓ Para efectos de diseño y construcción de obras de estabilidad en el derecho de vía, se generó una zonificación de respuesta sísmica por cada unidad geológica, donde se definen los coeficientes sísmicos de cada zona a partir de la geoestadística de los valores Fpga y PGAsup.
- ✓ En el caso de aplicación se logró definir el coeficiente sísmico de diseño de taludes utilizando información directa y más precisa, obteniendo un valor aproximadamente 20% inferior al recomendado por las normas nacionales.
- ✓ Se recomienda realizar los análisis de estabilidad de taludes por desempeño sísmico, control de desplazamiento en vez de Factor de Seguridad.

¡Gracias!

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SEISMIC RESPONSE ZONING METHODOLOGY FOR OIL AND GAS PIPELINE TRANSPORT SYSTEMS

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ABSTRACT

The paper presents the proposed methodology implemented to seismic response zoning of the right-of-way of oil and gas pipeline transport system. The proposal is based on the microzoning methodology for cities of the Colombian Geological Service by Diaz-Parra et al. (2018), adapted to the available inputs, the scale of analysis and focusing the results for geotechnical analyses of slope stability.

The proposed methodology was applied in the study of 170 km of ROW, to illustrate how the methodology is applied, the information considered, the analyses carried out and the results obtained are summarized in a general way. The methodology highlights the approach to spatialize the amplification results, where a spatial relationship between the morphology of the terrain and the amplification was identified.

Seismic response zoning is used in seismic slope design, mass movements hazard zoning, seismic risk analysis of the ROW and early warning system for landslides due to earthquakes.

Keywords: Seismic Response Zoning, Microzonation, seismic design parameter, Seismic slope stability

NOMENCLATURE

DTM: Digital Terrain Model.
Fa: Acceleration Amplification Factor
Fpga: Peak Ground Acceleration Amplification Factor.
Fv: Velocity Amplification Factor
GEM: Global Earthquake Model
GIS: Geographic Information System.
IGP: Instituto Geofísico de Perú
MMHZ: Mass Movement Hazard Zoning.
MSHM: National Seismic Hazard Model of Colombia
NSR-10: Norma Sismo Resistente 2010 (In Spanish)
PGA: Peak Ground Acceleration.
ROW: Right of Way.
SENCICO: Servicio Nacional de Capacitación para la Industria de la Construcción
SF: Safety Factor
SGC: Colombian Geological Service
SRZ: Seismic Response Zoning.
UHS: Uniform Hazard Spectra

1. INTRODUCTION

The Oil and Gas pipeline transportation systems are extensive networks with right-of-way that are exposed to various geohazard such as mass movements, earthquakes, floods, scour and torrential floods, among others. To carry out a comprehensive management of the risks associated with these geohazard, particularly geotechnical, Understanding the geohazard conditions affecting rights of way is important for effective management and assessment.

The Seismic Response Zoning or Seismic Microzoning studies define the seismic demand for the design of structures considering the seismic hazard of the region and the site effects in the study area. These studies follow national earthquake resistance regulations.

Because the corridors through which the right of way of the oil and gas pipeline transport systems are in rural areas and have variable geological and geotechnical conditions, they have seismic hazard conditions and particular local effects throughout their extension.

Therefore, the objective of the paper is to present the methodology developed and applied to seismic response zoning of the ROW of oil and gas pipeline transport systems, focusing on the seismic parameters of slope stability geotechnical design.

There are standards that define seismic parameters for the earthquake-resistant design of buildings, for example, in Colombia, the NSR-10 Regulation (MVDT, 2010) sets building seismic design coefficients, with horizontal acceleration (Aa) rounded to every 0.05g and site effects classified by 30 m geotechnical profiles (A-F). In Peru, Technical Standard E.030 (Sencico, 2020) uses seismic coefficient Z to divide seismic hazard into four zones (0.1g, 0.25g, 0.35g, 0.45g), also classifying site effects by the upper 30 m geotechnical profiles (S1-S4).

National seismic resistance regulations include seismic parameters primarily intended for structural design. The seismic hazard coefficients in rock are provided as large-scale, rounded, and zoned values. Local effects are described for general profiles, based on the characteristics of the upper 30 meters of soil. For stability analyses of rights-of-way slopes, national regulatory parameters often do not apply and are generally considered conservative because of the rounding effects of hazard coefficients and the amplification factors included in these regulations.

The Seismic Response Zoning of oil and gas pipeline transport system rights of way is conducted to identify seismic demands for slope stability analyses in these areas. This approach is necessary because the seismic parameters specified in earthquake-resistant design standards are developed primarily for building construction and typical soil profiles. This allows for safer and more economical stability works designs by employing seismic coefficients specific to the study area.

2. SEISMIC RESPONSE ZONING OF CITIES

The seismic activity assessment and monitoring group of the Colombian Geological Service (SGC) developed and implemented a methodology to seismic microzoning studies of Colombian cities (Diaz-Parra et al. 2018). The **Figure 1** presents a diagram of the methodology for cities (In Spanish), covering the following components: seismic hazard assessment, seismic monitoring, subsurface characterization, local seismic response, and seismic response zoning.

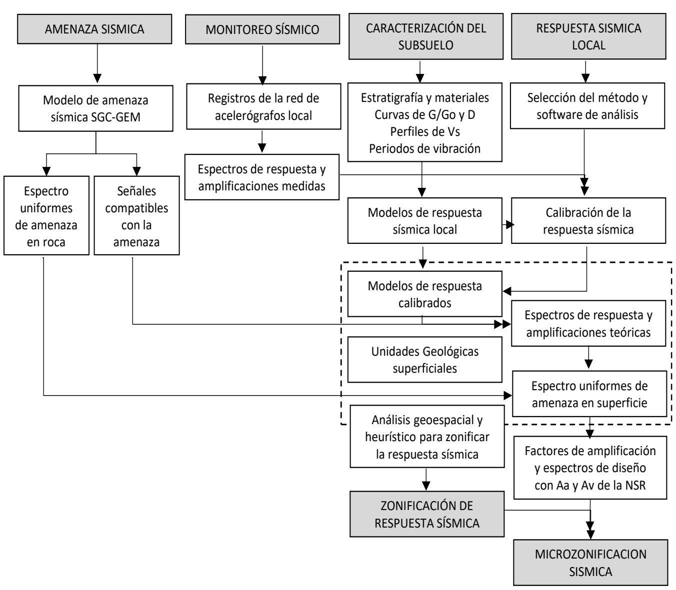

Figure 1. Methodological diagram of cities seismic response zoning. (Díaz-Parra et al. 2018 original in Spanish).

This methodology considers for the analysis of the seismic hazard it is proposed to use the National Seismic Hazard Model MSHM for Colombia, prepared by the SGC (Arcila et al. 2020), which compiles the available information regarding the geology of the country, characteristics of the events that occurred, a homogeneous catalog of earthquakes, as well as the analysis under methodologies of the state of art of seismogenic sources, of its seismicity and models of strong ground motion.

At the same time, it is proposed to consolidate the results in a homogeneous seismic response zoning map, where each zone has its own amplification functions for various levels of intensity. This way of consolidating the results facilitates the evaluation of seismic action on the surface, since it allows the evaluation of the site response for different intensities of the movement. For regulatory purposes, microzoning (which can be the same seismic response zones) are defined with the respective amplification factors, Fa and Fv, according to Regulation NSR-10.

This methodology, designed for urban areas and building design, includes components that may not be available in rural areas through which the right-of-way of oil and gas pipeline transport systems. For this reason, it is used as a reference framework for the development of the methodological proposal summarized below.

3. RIGHT-OF-WAY SEISMIC RESPONSE ZONING METHODOLOGY

Considering the particular characteristics of the right of way of oil and gas pipeline transport systems, such as the variability of geological, geotechnical, morphological conditions of the corridors that are hundreds of kilometers, the variability is high and changes the conditions of regional seismic hazard at the level of the seismic basement. It is proposed in the **Figure 2** the logical framework of activities to seismic response zoning of rights of way of oil and gas pipeline transport systems, which includes the following stages.

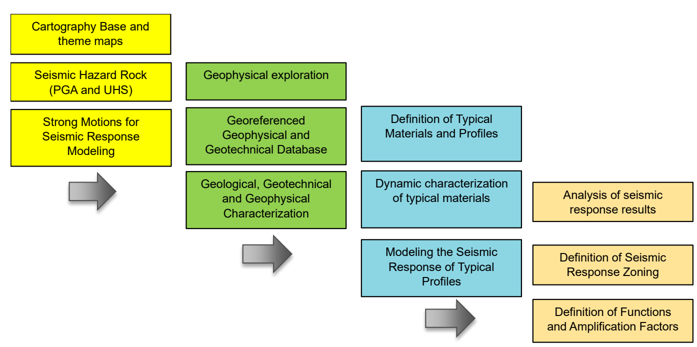

Figure 2. Logical framework of activities to zone the seismic response.

- Base and thematic cartography of inputs at a scale of 1:10,000 and characterization of the seismic hazard in rock.
- Geological, geophysical and geotechnical characterization of terrain.
- Dynamic characterization of typical materials, definition of models and modeling of the seismic response of typical profiles.

- Seismic Response Zoning with amplification functions and amplification factors for typical profile.

To obtain the seismic response zoning, the spatial analysis methodology is proposed that consolidates the results of the previous stages as presented in the **Figure 3**.

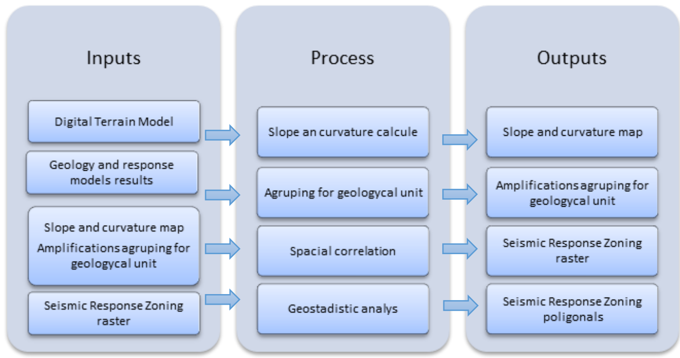

Figure 3. Seismic response zoning methodology.

The methodology highlights the way to spatialize the amplification results, where a spatial relationship was found between the morphology of terrain and the amplification, in order to generate a continuous seismic response zoning (raster), which presents the spatial distribution of the seismic coefficients of PGA amplification factor (Fpga) that quantifies the effect of the amplification or deamplification of the acceleration in rock, due to the passage of the wave forms through the surface stratigraphy of terrain, to obtain the peak surface ground acceleration (PGAsup) as the product of the seismic amplification coefficient (Fpga) times the acceleration in rock (PGArock). The continuously spatialized results are an input to mass movements hazard zoning, seismic risk analysis and early warning system for landslides triggered by earthquakes.

For the purposes of design and construction of stability works in the right of way, a seismic response zoning is generated by grouping by each geological unit (by zones), where the seismic coefficients of each zone are defined from the geostatistics of the Fpga and PGAsup values.

4. APPLICATION CASE

The proposed methodology was implemented in a case study involving 170 km of rights of way in Peru. To demonstrate its application, this summary provides an overview of the information considered, analyses performed, and results achieved. Due to confidentiality requirements, only general characteristics essential for understanding the methodology are presented.

BASIC AND THEMATIC CARTOGRAPHY

Information coverage of the infrastructure comprising the pipelines with their progressives, access to right-of-way, locations, heliports, and the 500 m buffer (1000 m wide) analysis corridor were collected, organized, and georeferenced.

Based on the Lidar information, the process was carried out to obtain the digital terrain model DTM with pixel resolution of 2.5 m by 2.5 m that was used for the seismic response zoning analyses.

Using the DTM, GIS was employed to generate digital models of terrain slopes (**Figure 4**) and curvature (**Figure 5**).

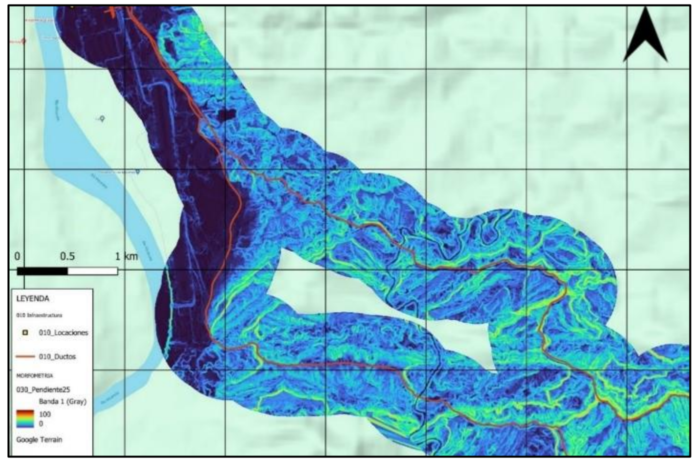

Figure 4. Slope model.

Figure 5. Curvatures model.

Characterization of seismic hazard in rock

A seismic hazard model is essential for determining uniform hazard spectra at various exceedance probabilities, as well as identifying the ruptures that contribute most significantly to a study area based on parameters such as magnitude, distance, and seismic sources. This data supports the selection of ground motion records that are compatible with the specific hazard characteristics of the area, enabling accurate modelling of seismic response in subsequent analyses.

For the application case, the seismic hazard for rock profile type S_1 whit Vs_{30} = 500 m/s was characterized based on the studies led by the National Geophysical Institute of Peru (IGP in Spanish) and the National Training Service for the Construction Industry (Sencico In Spanish), choosing to use the results of the Sencico study (2016) available for public access on the official website http://ppsh.sencico.gob.pe/.

The adopted PGA for rock with a 475-year return period is approximately 0.18 to 0.20g (Sencinco, 2016), while the value of the seismic zone Z is 0.25g according to the E.030 Standard of 2018. Note that the data in the reference hazard model are those of the study area and are not rounded as in the standard.

Subsequently, the disaggregation analyses of the seismic hazard are carried out for the study area to know the magnitude and distance scenarios that contribute to the hazard, records of crustal events with magnitudes between 6.2 and 6.8 at hypocentral distances between 30 and 40 km and at depths less than 30 km; Likewise, intraplate events with magnitudes between 6.5 and 7.0 for hypocentral distances between 140 and 160 km and depths between 100 and 150 km. the final proceed was search the world databases of PEER for seismic records of rock condition.

As a result of the signal selection for rock condition, 9 representative signals of cortical events and 4 representative signals of intraplate events are obtained. For the signals their response spectrum was calculated and validated that the average of the response spectra of the signals represents the uniform hazard spectrum of the study area.

Subsurface exploration

The optimal approach for cost and time efficiency in these field operations involves drilling boreholes within the principal geological units to depths reaching rocky or seismic basement levels (Vs > 500 m/s). Concurrently, it is advisable to conduct comprehensive geophysical surveys throughout the study area. This enables correlation of borehole data with wave velocity and vibration period measurements from geophysical investigations, facilitating spatial identification of variations across each analytical unit.

For this instance, all collected geophysical and geotechnical data were systematically organized and georeferenced into an exploration database, comprising 99 geophysical surveys and 63 geotechnical boreholes.

Subsoil characterization

The characterization of the subsoil in the first instance must consider all the available information of the area: soil studies, geological, geomorphological, geotechnical maps, etc., so that a baseline can be established for a preliminary model with secondary information that allows identifying the areas where additional geotechnical and geophysical exploration is required.

In the study, the local geological cartography is the basis for the analyses, so it must be at the scale of analysis and according to the resolution of the DTM, for this reason it was considerably improved in the contacts between the units of alluvial quaternary deposits with the rock formations, due to the different scales used and the methodology used by the IGP in the elaboration of the thematic maps.

The alluvial deposits in the study area are very similar to each other, presenting Vs30 between 400 m/s and 500 m/s, reaching the highest velocity from 500 m/s to between 18 m and 26 m. This corresponds to coarse, very compact and rigid alluvial deposits. Sedimentary formations in general are similar, presenting averages greater than 315 m/s to 428 m/s, thickness weathering profiles that correlate with the depth of Vs 500 m/s between 15 m and 33 m depth on average.

Local seismic response

To determine the degree of soil amplification (local subsurface dynamic response or site effects) it is necessary to know the stratigraphy and dynamic properties, such as the fundamental period of soil vibration, shear wave velocities profile, and modulus degradation and damping curves. Based on the above, it is possible to develop models to evaluate the response of a soil column to a given seismic wave, as summarized in the procedure of the **Figure 6**.

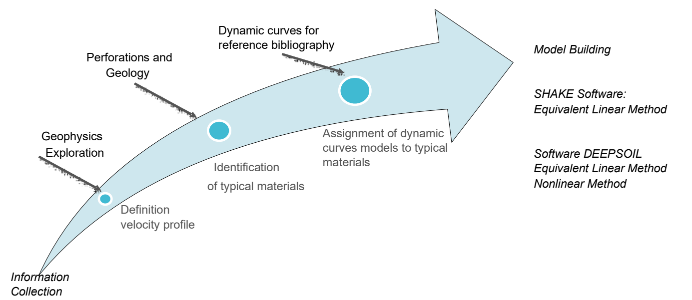

Figure 6. Procedure to develop one-dimensional response models.

In the study case, one-dimensional modeling was carried out in 22 sites covering the study area. The sites were selected by prioritizing the sites with the best geophysical information with Vs < 500 m/s and with geotechnical information, in order to reduce uncertainties in the construction of the modeled profiles.

The shear velocity profile is modeled up to layers of values greater than 500 m/s, where the seismic basement has been defined compatible with the seismic hazard reported by the Sencico (2020) study.

Based on the types of soils identified in the case study, as well as considering the limitations of unaltered sampling, the particularities of dynamic tests and the experience in the application and interpretation of these procedures, internationally accepted dynamic behavior models were selected. For fine soils, the models of Darendeli (2001) and Ishibashi (1993) were used, while for granular soils the models proposed by Menq (2003) and Seed (1970) were used.

In order to consider several models of dynamic curves, it was decided to perform the modeling with three configurations, the first with the Darendeli and Menq models to evaluate in equivalent linear SHAKE, the second with the Seed and Ishibashi models to evaluate in equivalent linear SHAKE and the third to model nonlinear in DEEPSOIL with the Darendeli and Menq models.

Amplification results for each model are grouped by geological unit for later zoning analysis.

Seismic Response Zoning

Seismic response zoning consists of defining areas of similar behavior when a seismic event happens. To do this, it is necessary to consider the variables that influence the seismic behavior of the subsoil, such as the type of soil or rock, stiffness, density, damping and thickness.

The way to spatialize the amplification results using a spatial relationship between the morphology of the terrain and the amplification is highlighted, obtaining a multiple correlation between a base value of amplification of each geological unit (C1), the variation by curvature (C2) and the variation by slope (C3).

$$Fpga = C1 + C2*Curvature + C3*Slope$$

Where the coefficient C1 was defined taking into account the average of the seismic response results modeled per geological unit, the coefficients C2 and C3 were calculated with the help of Excel tools (solver), looking for the least dispersion between the amplification results of the model sites and those calculated with the correlation. The **Figure 7** shows the validation of the correlation obtained by comparing the calculated Fpga with the correlation and the Fpga obtained from the response models.

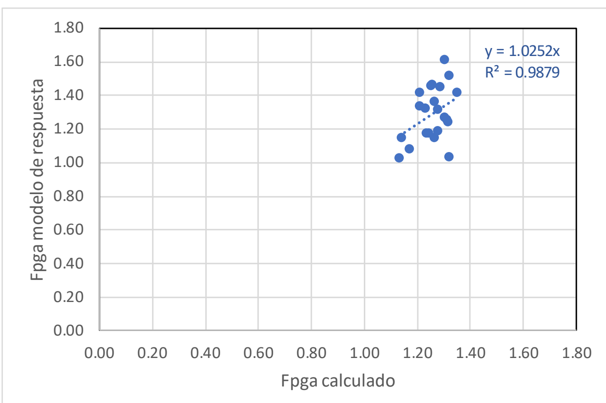

Figure 7. Fpga calculated Vs Fpga modeled.

The amplification specialization is calculated with the expression for the entire study area by performing GIS map algebra with geology, slope and curvature coverages. In this way, the continuous seismic response zoning (raster) was obtained, which presents the spatial distribution of the seismic coefficients of PGA amplification factor (Fpga) that quantifies the effect of the amplification or deamplification of the acceleration for rock, due to the passage of wave forms through the surface stratigraphy of the terrain (**Figure 8**).

The peak surface terrain acceleration (PGAsup) shown in **Figure 10** is calculated by multiplying the seismic amplification factor (Fpga) by the acceleration in rock (PGAroca).

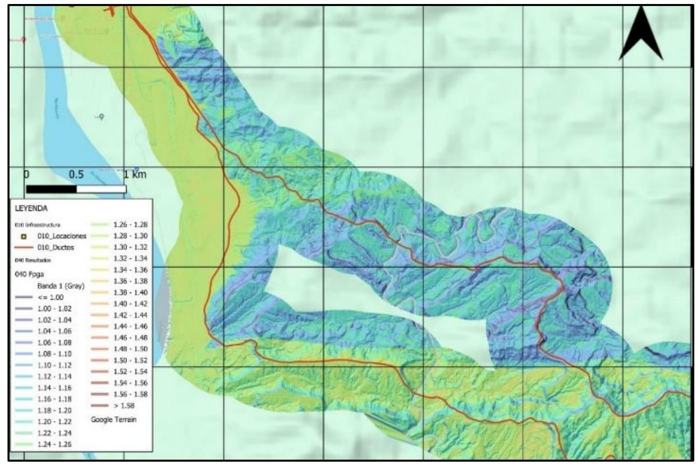

Figure 8. Fpga spatial variation map.

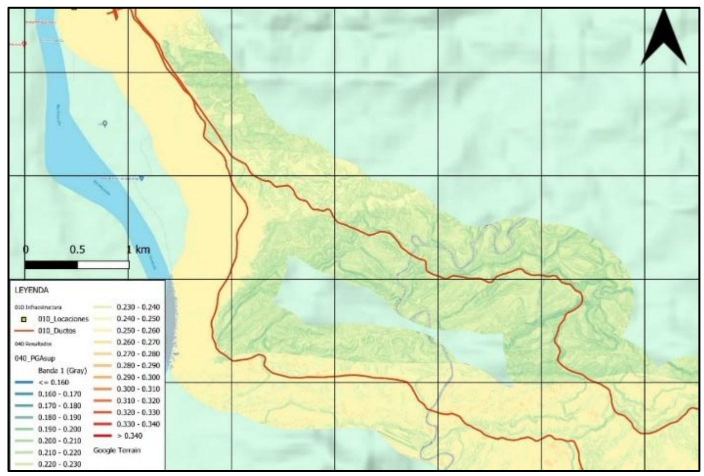

Figure 9. Spatial variation map of PGAsup.

5. CONCLUSIONS

Seismic hazard conditions can be evaluated, including site effects on right-of-way, by adapting methodologies originally conceived for cities for application in oil and gas pipeline transport systems.

The methodology developed and applied allowed to carry out the seismic response zoning of the right-of-way of the oil and gas pipeline transport systems, focused on the seismic parameters of geotechnical design of slope stability.

The continuously spatialized results are an input to mass movements hazard zone, seismic risk analysis and earthquake landslide early warning system.

On the other hand, for the purposes of design and construction of stability works in the right of way, a seismic response zoning was generated by each geological unit, where the seismic coefficients of each zone are defined from the geostatistics of the Fpga and PGAsup values.

In the application case it was possible to define the seismic coefficient of slope design using direct and more precise information, obtaining a value approximately 20% lower than that recommended by the national seismic resistance standards.

The results of the seismic response zoning studies are inputs for a geohazard monitoring and management system, which allows the identification of the probability of landslides due to rain and earthquakes that allows system operators to take preventive operational actions.

REFERENCES

Arcila, M. García, J., Montejo, J., Eraso, J., Valcarcel, J., Mora, M., Viganò, D., Pagani, M. y Díaz, F. (2020). Modelo Nacional de Amenaza Sísmica para Colombia. Bogotá: Servicio Geológico Colombiano y Fundación Global Earthquake Model. https://doi.org/10.32685/9789585279469

Darendelli, M. B. 2001. Development of a new family of normalized modulus reduction and material damping curves. Ph.D. Thesis. The University of Texas.

Diaz-Parra F. Mora M., Eraso J., Valcárcel J., Arcila M., Montejo J. (2018). Propuesta metodológica de microzonificación sísmica. XVI Congreso Colombiano de Geotécnica. Colombia.

Hashash, Y.M.A., Musgrove, M.I., Harmon, J.A., Ilhan, O., Xing, G., Numanoglu, O., Groholski, D.R., Phillips, C.A., and Park, D. (2020) “DEEPSOIL 7.0, User Manual”. Urbana, IL, Board of Trustees of University of Illinois at Urbana-Champaign.

Idriss, I.M. and Sun, J.I. (1992). “SHAKE91: A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits,” User’s Guide, University of California, Davis, California, 13 pp.

MAVDT (2010). Ley 400 de 1997 (Modificada por la Ley 1229 de 2008, el Decreto 019 de 2012 y la Ley 1796 de 2016), Decreto 926 del 19 de marzo de 2010 por medio del cual se adopta el Reglamento Colombiano de Construcción Sismo Resistente NSR-10, Ministerio de Vivienda Ciudad y Territorio, Bogotá, Colombia.

Menq, F.Y. (2003). “Dynamic properties of sandy and gravelly soils.” Ph.D. Dissertation, Dept. of Civil Eng., Univ. of Texas, Austin.

Sencico (2016). Actualización del programa de cómputo orientado a la determinación del peligro sísmico en el país.

Sencico (2020). Norma E.030 Diseño Sismo Resistente versión 2018. Edición digital Sencico.