Medición e interpretación de vibraciones producidas por el tráfico en Bogotá D.C.

Measurement and interpretation of vibrations produced by the traffic in Bogota D.C.

Hermes Vacca Gámez^{*1}, Jorge Alberto Rodríguez*, Daniel Ruiz Valencia*

* Pontificia Universidad Javeriana, Bogotá. COLOMBIA

Fecha de recepción: 27/ 12/ 2010
Fecha de aceptación: 02/ 03/ 2011
PAG. 61 - 80

Resumen

Debido al desarrollo de Bogotá (ciudad principal de Colombia) y a su incremento de población, se han construido en la última década sistemas de transporte. A pesar de que estos sistemas incrementan el bienestar de los ciudadanos, el tráfico vehicular podría generar problemas de vibraciones. Estas vibraciones afectarían negativamente a las personas y a las edificaciones cercanas. Estos efectos pueden ser importantes si se presentan altos niveles de amplitud de las vibraciones. Estas vibraciones, dependen, entre otros aspectos, de las características mecánicas de los suelos. Teniendo en cuenta los planes futuros de construcción de sistemas transporte en Bogotá, se registraron vibraciones de tráfico vehicular y ferroviario en 6 sitios de Bogotá. En estos lugares se identificaron suelos típicos del estudio de microzonificación sísmica. Se hicieron mediciones para registrar las vibraciones debidas al tren de la sabana, Transmilenio (buses articulados) y servicio público principalmente. Se determinaron curvas de atenuación en aceleración y velocidad. Se determinó que para las condiciones actuales las vibraciones pueden llegar a ser molestas para las personas pero no generan problemas a las estructuras. No obstante, estos valores deben tomarse como punto de referencia de mediciones futuras cuando se incremente el tráfico, el peso de los vehículos (metro) y las velocidades de circulación.

Palabras Clave: Vibraciones, tráfico, suelos blandos, acelerómetros

Abstract

Due to the development of Bogota (main city of Colombia) and to its increase of population, transport systems have been constructed in the last decade. Although these systems increase the well-being of the citizens, the traffic could generate vibrations problems. These vibrations could affect the people and the constructions near to highways. These effects can be important for high levels of vibrations. These vibrations, depend, among others aspects, of the mechanical characteristics of the soils. Considering the future plans of construction of transportation systems in Bogota, vibrations due to traffic and railroad in 6 sites of Bogota were registered. In this places were indentified typical soils of the seismic microzoning of Bogota. Measurements were made to register the vibrations due to the train of the savannah, Transmilenio (articulated buses) and public transport mainly. With this information curves of attenuation of acceleration and speed were determined. The actual vibrations levels are perceived by the people but they do not cause problems to the buildings. However, these vibration levels are the datum point of future measurements when increase the traffic, the weight and the speed of the vehicles.

Keywords: Traffic-induced ground vibrations, soft soils, accelerometers

1. Justification and backgrounds

Due to the increasing development of Bogota and, particularly due to its population increase, diverse transportation systems have been developed in parallel so as to meet inhabitant's needs.

According to governmental policies (Bogota City Hall, Provincial Government of Cudinamarca and Presidency of the Republic) and following the guidelines from Land Demarcation Plan of Bogota D.C.,

¹ Autor de correspondencia / Corresponding author:
E-mail: vacca@javeriana.edu.co

a Mobilization System was created, which includes a Transportation Sub-system elaborated around to the following massive transportation systems: suburban trains, subway and Transmilenio system. All of them under an institutional framework ruled and controlled by traffic authorities. Such plan would involve an increase of heavy vehicles to be incorporated by the government for the transportation of rural and urban population. These new vehicles (buses and subway system) could generate a negative impact at vibration level and would even affect nearby buildings as well as people. This situation could be worse considering the characteristics of Bogota's soft soils.

In spite of above situation, in literature detailed scientific studies are not abundant on soil responses at vibration level in Bogota. Even more there are no data available about source characterization and about soil surface response, although there is information about mechanical characteristics of transmitting waves soils. This knowledge gap is intended to be covered by the current study.

On the other hand, for vibration records the maximum amplitude signal (acceleration, speed and displacement), signal significant duration and its dominant frequency must be taken into account. The mechanical characteristics of transmission means, internal waves and surface waves must also be taken into account. Therefore, as presentation, some traffic-induced ground vibrations studies, as well as a brief description about soft soils characteristics in Colombia capital city, will be introduced.

Traffic-induced ground vibrations

Traffic-induced ground vibrations might damage nearby buildings and generate annoyances to human beings. Such effects might be significant in function of vibrations amplitude level which depend, among other aspects, on the characteristics of soils. The consequences of traffic-induced ground vibrations due to heavy vehicles and trains can be classified mainly into two aspects:

- Damage to constructions or small structures, low height-rigid buildings founded on soft soils near heavy load traffic roads.

- Annoyance to human population: taking into account that human being is only able to assimilate a vibration portion by means of audition, sensorial and visual senses emphasizing that sensorial sense is associated to a dangerous situation.

Among few studies carried out in Bogota city (Sarria, 2006), it was found that structures founded on soft soils may be negatively affected due to heavy traffic-induced ground vibrations at distances lower than 100 meters.

According to (Sarria, 2004), vehicles traffic generates surface waves reaching relatively short distances and, in occasions, they shake constructions bordering a given road. The impact produced by vehicles will depend on their weight and displacement speed. Impact load generates surface waves at different frequencies. Local site conditions composed by pavement and soil particularly influence the impact.

If impact takes place on a soft soil pavement, it will be possible that low frequency R waves tend to appear, while if it takes place on stable ground, dominance will be of higher frequency waves. In the first case, penetration is deeper affecting potential measurements to reduce vehicles-generated-shaking on nearby buildings.

On the other hand (Francois, 2007) modeled the passing of a two-axis vehicle near a structure or two-story-single-family house.

According to this study two situations could take place: For a building founded on soft soil (which does not have structural strain), the global structural response is dominated by rigid body kinematics; if the soil is rigid in relation to the structure, walls will become strained in a quasi static way by following the soil motion.

Another study carried out in the United States (Haoa, 2001), due to the increasing construction of higher and higher housing and buildings built at lower distances from roads as vibration source, the need of investigating about traffic-induced ground vibrations became a must. In this research traffic-induced ground vibrations were measured at four locations by identifying soils characteristics, site conditions and distance from road center. Five reinforced concrete structures were analyzed and then compared to several standard specifications on allowed vibration levels.

The research shows three main concerns faced to traffic-induced ground vibrations affecting nearby buildings:

- Structures may suffer structural affectation.
- Affectation over such buildings inhabitants.
- Affectation over the normal operation work of vibration sensitive equipment.

In a similar scenario as the one described above, (Watts a, 2000) proposed a vibration measurement method to determine the influence from different kinds of vehicles on buildings surrounding the studied road by taking into account their suspension system and wheels axis. This research mainly controlled two variables: type of vehicle and vehicle velocity. In Figure 1 some values are indicated for particle peak velocity and variation against vehicle velocity for different kinds of soils.

Figura 1. Velocidad PPV (ordenadas) contra Velocidad del vehículo articulado km/h (abscisas). (G.R. Watts a, 2000)

Figure 1. PPV Velocity (ordinates) against articulated vehicle Velocity km/hr (abscises). (G.R. Watts a, 2000)

Among relevant conclusions, the influence of velocity on increasing traffic-induced-ground vibrations was found, which may eventually damage nearby structures. Therefore, it is important to determine distances and allowed loads in order to avoid damages on future new buildings.

Limits Definition in order to avoid damages

Generally, criteria defining vibration threshold for structural damage will depend, not only on traffic-induced ground vibration, but also on structural load, material characteristics, dynamic characteristics, amplitude excitation and sensitive frequency. Standardization authorities around the world have defined guidelines about soils allowed vibration levels affecting buildings (Regulations ISO 2631, ISO 6897 and DIN 4150). Available regulations and literature have traditionally worked with acceleration criteria and particles velocity to define limit values to avoid damages to structural systems. Several codes and researchers provide allowed limits for structural vibration in terms of particle peak velocity (PPV).

Damage concept is relative since it may involve from micro-cracks generation to cracking's arousal, which may lead to some kind of building collapse. Additionally the presence of damages or not, micro-cracks and cracking is closely related with the quality of materials and constructive techniques. Although Colombia has a construction code, it may be difficult to standardize materials characteristics and constructive processes as far as unreliable construction housings are concerned. Therefore, a specific study of damages on a given building would demand detailed evaluations ranging from soil characterization and construction material employed up to the evaluation of working loads (vibrations due to traffic, cantilevers, dead loads, normal loads, winds, etc.).

However, if soil particles limit values established by international regulations (associated to traffic-induced ground vibrations) are exceeded; visible damages on building elements are likely to take place. Nevertheless, it shall be taken into account that they are only reference values. Accordingly, DIN 4150 regulation establishes peak vibration values (in mm/s) in function of frequency to avoid damages on different kinds of buildings (commercial, housing, buildings, industries). Such values are indicated in Table 1. The same are shown in reference (ITME, 1985), which limit values are summarized in Table 2.

Tabla 1. Valores Máximos de Velocidad de partícula (mm/s) para evitar daños (Norma DIN 4150)

Table 1. Particle peak velocity values (mm/s) to avoid damages (DIN 4150 Regulation)

Tipo de Edificación / Type of Building	Frecuencia / Frequency		
	< 10 Hz	10-50Hz	50-100 Hz
Estructuras delicadas, muy sensibles a la vibración / Weak buildings, highly sensitive to vibrations	3	3-8	8-10
Viviendas y Edificios / Housing and buildings	5	5-15	15-20
Comercial e Industrial / Commercial and Industrial	20	20-40	40-50

Tabla 2. Valores Máximos de Velocidad de partícula establecidos en la referencia (ITME, 1985)

Table 2. Particle peak velocity established by regulation (ITME, 1985)

Tipo de Edificación Type of Building	Velocidad máxima de partícula Particle peak velocity
Para edificaciones en muy mal estado de construcción o edificios en madera o mampostería For buildings under poor construction conditions, wooden or masonry buildings	12 mm/s
Edificios muy sensibles a las vibraciones Building highly sensitive to vibrations	0 a 10 Hz → 3 mm/s 10 a 50 Hz → 3 a 8 mm/s 50 a 100 Hz → 8 a 10 mm/s

On the other hand Australian standards (AS 2187.2) establish as limit for residential buildings a peak velocity of 10 mm/s. The same standardization establishes for commercial or industrial buildings, made of reinforced concrete or steel, a maximum limit of 25 mm/s; for hospitals, dams, historical monuments buildings a limit of 5 mm/s.

Similarly, British standards (BS 7385) establish a peak velocity of 50 mm/s for framed industrial structures and commercial buildings with frequency vibration higher than 4 Hz. The same regulation suggests a limit between 15 and 20 mm/s for non-reinforced buildings, residential housings with frequencies between 4Hz and 15 Hz.

For example the Swiss standard (SN 640) established 12 mm/s as allowed level for steel or reinforced concrete structure, 5mm/s for masonry buildings and, 3 mm/s for architectonic-interest buildings or weak structures.

It is relevant to point out that social-economic condition and regulations in each country are associated with limits established above, since a given residential housing built in Australia, United States or Europe - in general- will have a different mechanical behavior than one built in a developing country.

Above is supported under the consideration that in low social strata of a third world country, houses are built by means of self-help construction system without technical supervision of an engineer and, in the best of cases, they are built by a master craftsman. This aspect would lead to weaker buildings.

Characteristics of Bogota's soils

In accordance with (Rodriguez, 2005) and (Rodriguez and Velandia, 2008) Bogota's savanna is a huge sedimentary basin from fluvial and lake origin filled with sediments over the past millennium. Sediments have a transition zone from borders where alluvial and colluvial soils are found, they are mainly composed of granule soils of fan-cone-shape towards the ancient lake's center area, where quite soft clays and silts are abundant. Maximum thickness of sediments reaches almost 500 mt. Softer lake origin soils, containing clays and silts, with quite organic horizons and volcanic ashes, show differences on expected values when compared to analysis developed on other soils. These soft soils have a particular structure and composition, which may explain such differences. In accordance with a study developed on dynamic characteristics of Bogota's soft soils (by means of dynamic tests performed at the site and laboratory), it is concluded that soil shear modulus in Colombian capital city have greater surface deterioration than reported by international level technical literature. Damping rate also tends to provide higher values than expected and damping curves tend to deliver inconstant values after surface deterioration of 1% in most of the cases. Soils' elasticity modules reported by (Rodriguez, 2005) vary from 9400 kPa to 240000 kPa. Shear wave velocities also vary from 60 to 300 mm/s and fundamental oscillation periods for soft stratum soils may reach up to 5 seconds. Seismic micro-zoning study of Bogota (Ingeominas and UniAndes, 1977) divided the city into different zones, according to the type of soil existing in each one of them and; their characteristics are summarized below:

- Zone 1 (hills zone): It is characterized by the presence of rocky formations of relative good carrying capacity. It can show local acceleration amplification due to topographic effects.
- Zone 2 (Foothills): It is composed by the transition zone between hills and plain zone. Mainly it has colluvial deposits and material dejection cones with high carrying capacity in general. It has heterogeneous stratigraphy mainly containing gravel, sand, silt and occasionally thin clay deposits.
- Zone 3 (Lakeside A): It is mainly composed by fifty (50) meters-depth soft clay deposits. Occasionally some peat and/or sand deposits of intermediate-low thickness may arise. It has a pre-consolidated surface layer of variable thickness, not higher than (10) meters.
- Zone 4 (Lakeside B): It has the same characteristics as Zone 3 (Lakeside A) but sediments (on first 30 - 50 meters) are consistently softer than above. Furthermore, it is the zone where depth up to the rock base is about 200 - 400 mt or even more.
- Zone 5 (Terraces and cones): It is predominantly located at the city south and it is composed by dry-clay pre-consolidated high thicknesses soils, sand, silt or simply a combination of them, but with higher carrying capacity than sediments in Lakesides A and B.

Figure 2 shows a city map with zones established for seismic micro-zoning.

Precisely due to particularities of Bogota's soils, the current research was made in order to determine the amplitude of traffic-induced ground vibrations generated by heavy two-articulated vehicles (Transmilenio system) or by trains, so as to obtain vibration magnitude values to be used in future massive transportation systems.

Figura 2. Mapa de la microzonificación de Bogotá (Ingeominas y UniAndes, 1997)

Figure 2. Micro-zoning map of Bogota (Ingeominas and UniAndes, 1977)

2. Vibration measurements

High sensibility equipments were arranged to develop vibration measurements, comprising the following elements:

- a) Four (4) high resolution uniaxial seismic accelerometers (see Figure 3). Accelerometers are capable of measuring acceleration within a range from 0.00001 up to 0.5 g. Such sensors response is linear for a frequency range between 0.05 and 200 Hz.
- b) Amplifiers and filters for accelerometers enabling amplifications from 10, 100 or 1000 mV/g and filters over 450 Hz and 100 Hz.

- c) Data collection systems for several channels capable of registering data at a speed of 2000 records per second (2 kHz).
- d) Notebook for control and data collection.
- e) Different length wires up to 50 meters.

Figura 3. Acelerómetros sísmicos usados para la instrumentación
Figure 3. Seismic Accelerometers used for instrumentation

By considering zoning introduced in Figure 2, together with other places where transportation system operates in Colombia Capital City, six measurement points were determined for the city. Four of them were located in high traffic flow of bi-articulated buses (Transmilenio system). At the same time, points were located in 3 out of 5 seismic micro-zoning areas. Figure 4 shows a map indicating measurement sites.

Devices were placed under two arrangements. In the first arrangement, four devices were located at different places alongside a single line measuring uniaxial acceleration on each site (Figure 5a). In the second arrangement, one device was placed near vibrations source, while the other three devices formed a three-axis system at different distances from the source (Figure 5b).

Figura 4. Mapa de Bogotá con la ubicación de los lugares de medición de las vibraciones (Adaptado de (Google Maps, 2010))
 Figure 4. Map of Bogota indicating traffic-induced ground vibrations measurement sites. (Adaptation from (Google Maps, 2010))

Figura 5. Disposición de los acelerómetros en dos diferentes configuraciones
Figure 5. Accelerometers Arrangement under two different configurations

Figure 6 shows devices arrangement example for 148th street and North Highway.

Figura 6. Disposición de los acelerómetros en dos diferentes configuraciones
Figure 6. Accelerometers Arrangements under two different configurations

Based on previous paragraphs, acceleration records were registered against time, as depicted in Figure 7.

From such recordings and based on numerical techniques three fundamental parameters were established: maximum acceleration records (maxA), particles peak velocity (PPV) and dominant frequency for each record. From these records acceleration and velocity attenuation curves regarding to distance were determined. Such results were obtained for vehicular traffic (ref. Figure 8 to Figure 12) and for a passenger touristic train (ref. Figure 13). The latter record shows the highest acceleration (293 mg) and speed (13.2 mm/s) values. In the case of vehicular traffic maximum velocity value was 1.04 mm/s (136th street and North Highway) and maximum acceleration value was 9.6 mg (46th street and Caracas Avenue). Both maximum values were registered by accelerometers placed closest to the road.

Figura 7. Registros de los acelerómetros ubicados a 0.5m (a), 15.5 m (b) 30.5m (c) y 45.5 m (d)

Figure 7. Records by Accelerometers placed at 0.5m (a), 15.5m (b), 30.5m (c), and 45.5 m (d)

Figura 8. Atenuación de la aceleración (a) y de la velocidad (b) en los registros tomados en la Calle 40 con Carrera 7a

Figure 8. Acceleration (a) and Velocity (b) attenuation in recordings measured at 40th street and Carrera 7a

Figura 9. Atenuación de la aceleración (a) y de la velocidad (b) en los registros tomados en la Calle 46 con Avenida Caracas
Figure 9. Acceleration (a) and Velocity (b) attenuation in recordings measured at 46th Street and Caracas Avenue

Figura 10. Atenuación de la aceleración (a) y de la velocidad (b) en los registros tomados en la Calle 127 con Avenida Suba
Figure 10. Acceleration (a) and Velocity (b) attenuation in recordings measured at 127th Street and Suba Avenue

Figura 11. Atenuación de la aceleración (a) y de la velocidad (b) en los registros tomados en la Calle 136 con Autopista Norte
Figure 11. Acceleration (a) and Velocity (b) attenuation in recordings measured at 136th Street and North Highway

Figura 12. Atenuación de la aceleración (a) y de la velocidad (b) en los registros tomados en la Calle 148 con Autopista Norte
 Figure 12. Acceleration (a) and Velocity (b) attenuation in recordings measured at 148th Street and North Highway

Figura 13. Atenuación de la aceleración (a) y de la velocidad (b) en los registros tomados en la Calle 153 con Avenida Novena (paso de tren)
 Figure 13. Acceleration (a) and Velocity (b) attenuation in recordings measured at 153th Street and Ninth Avenue (train crossroad)

When comparing above values to international standard references, particles peak velocities induced by vehicular traffic would not be meaningful for buildings. However, train particles peak velocities could become dangerous for weak buildings located at less than 15 meters from railroad, where soil induced velocities would be higher than 3 mm/s (limit value for weak structure damages on highly sensitive vibration buildings). It is worthy to point out that former statements are supported on experimental evidence as long as velocity range for measured vehicles is not highly variable. According to standard reference (Watts a, 2000) if vehicles velocity is increased, particle peak velocities will automatically increase.

Based on limits obtained from regulations included in the reference chapter and previously mentioned, graphs have been created in order to include limits associated with human comfort conditions as well as limits for structures, foundations and machinery. These graphs depend on motion amplitude calculated from acceleration recorded by accelerometers (by means of numerical techniques and involving the simple oscillator theory). They also depend on dominant frequency signal. That is why Figure 14 includes measurements developed by the current research. Displacements were estimated from acceleration records by means of basic structural dynamic numerical techniques.

Figura 14. Límites asociados con confort en función de la frecuencia del registro
Figure 14. Limits associated to comfort conditions in function of record frequency

Accordingly, most vibrations can be classified as easily perceptible, perceptible by human beings and only train-induced ground vibrations would be classified as intense for human population.

It is worth to mention that entry signal (induced by traffic or by train in Bogota savanna) directly depend on motion velocity of such vehicles. According to developed measurements bi-articulated vehicles run at a maximum speed range between 28 km/hr and 53 km/hr. On the other hand, the train runs at a speed of 33 km/hr in Bogota savanna. Taking into account that a portion of soil entry energy depends on kinetic energy and considering that wagons running speed of Bogota subway would be clearly higher than 33 km/hr, it is likely that vibration could reach levels classified as severe for human beings (Bahrekazemi, M., 2004).

On the other hand, it was intended to establish correlations between average "S" wave velocity for instrumented soil stratum and dominant frequencies of measured acceleration records. Geo-technique information was obtained from geo-technique studies available for each zone according to standard references (JEOPROBE, 2003), (JEOPROBE, 2005), (JEOPROBE, 2006), (JEOPROBE, 2007), (JEOPROBE, 2008), (JEOPROBE, 2009). Correlations between recorded displacement amplitudes and average "S" wave velocities on soil stratum were also determined. Such figures are presented in Figures 15 and 16 together with trend lines and their respective limit curves at confidence intervals of 99%.

Figura 15. Correlación de la frecuencia de los registros en función de la velocidad de onda de los lugares bajo estudio

Figure 15. Records frequency correlation in function of wave velocity for sites under study

Figura 16. Correlación de la amplitud de desplazamiento de los lugares instrumentados en función de la velocidad de onda de los lugares bajo estudio

Figure 16. Displacement amplitude correlation of instrumented sites in function of wave velocity for sites under study

Although there are other variants affecting this correlation (such as vehicle velocity or distance from data registration), measured data shows that at higher “S” wave velocity, registered displacement amplitudes tend to decrease and records frequency tends to rise due to the increase of soil stiffness. This is in line with the simple oscillator theory and agrees with Structural Dynamic principles. However, for the first time these kinds of curves under traffic loads were established for the soils in Colombia capital city.

3. Conclusions and recommendations

- Different kinds of traffic-induced ground vibrations were registered for different soft soil conditions in 6 sites of Colombia capital city. In general it was found that maximum acceleration and velocities at distances higher than 45m from the source, tend to be similar to base noise values
- Estimated displacement ranks are between 0.0001 mm and 0.1 mm. Peak velocity for recorded particle under vehicular traffic was 1.04 mm/s and maximum registered acceleration for vehicular traffic was 9.6 mg. Such data were established for vehicles speeds between 28 and 53 km/h.

- On the other hand, recordings taken for the passing of savanna train (running at 33 km/h) show the highest acceleration (293 mg) and speed (13.2 mm/s) values.
- Most vibrations registered at 0.1 m from the source up to 50 meters distance from it, can be classified as easily perceptible by human beings. Only train-induced ground vibrations would be classified as intense for human population.
- In the light of these experimental results, at higher "S" wave speed, registered displacement amplitudes decrease and frequency records rise due to the increase of soil stiffness.

4. Referencias / References

- Bahrekazemi M. (2004), Train-Induced Ground Vibration and Its Prediction. ISSN 1650-9501 .
- BS 7385 (1990), Evaluation and measurement for vibration in buildings. Guide for measurement of vibrations and evaluation of their effects on buildings.
- DIN 4150 (1999), Structural Vibration. Part 1: Prediction of Vibration parameters. Part 2: Human exposure to vibration in buildings.
- Francois L. P. (2007), The influence of dynamic soil-structure interaction on traffic induced vibrations in buildings. *Soil Dynamics and Earthquake Engineering* , 655-674.
- Watts, V. K. (2000), Ground-borne vibration generated by vehicles crossing road humps and speed control cushions. *Applied Acoustics* , 221-236.
- Google maps. (2010), Recuperado el 10 de diciembre de 2010
- Haoa H., Anga T. y Shen J. (2001), Building vibration to traffic-induced ground motion. *Building and Environment* , 321-336.
- Ingeominas y UniAndes. (1997), Microzonificación sísmica de Santa Fé de Bogotá; publicaciones Ingeominas; Santa Fé de Bogotá; Ministerio de Minas y Energía (MZSB,1997)
- ITME (1985), Instituto Tecnológico Geominero de España. Manual de perforación y voladura de rocas.
- ISO 2631. (1997), Mechanical Vibration and shock Evaluation of human exposure to whole-body vibration.
- ISO 6897. (1984), Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion.
- JEOPROBE. (2003), Asesoría geotécnica y sísmológica para la evaluación de la amenaza sísmica del edificio en la calleja. Bogotá.
- JEOPROBE. (2005), Estudio particular de respuesta local de amplificación de ondas sísmicas lote de la carrera 7 con calle 45, Bogotá.
- JEOPROBE. (2006), Asesoría geotécnica y sísmológica para la evaluación de la amenaza sísmica del proyecto portal de la autopista. Bogotá.
- JEOPROBE. (2007), Asesoría geotécnica y sísmológica para la evaluación de la amenaza sísmica del proyecto urbanización Córdoba I, Supermanzana I. Bogotá.
- JEOPROBE. (2008), Estudio particular de respuesta local de amplificación de ondas sísmicas Edificio Uriel Gutiérrez. Bogotá.
- JEOPROBE. (2009), Estudio particular de respuesta local de amplificación de ondas sísmicas para la Av. 9 con calle 145. Bogotá.
- Rodríguez J. (2005), Comportamiento dinámico de suelos blandos de Bogotá. Congreso Chileno de Sismología e Ingeniería Antisísmica. Concepción, Chile.

- Rodríguez J., Velandia E. (2008), Análisis de registros de impactos en suelos blandos de Bogotá. XII Congreso Colombiano de Geotecnia. Bogotá.
- Sarria A. (2004), Investigación no destructiva y cargas extremas en estructuras. Bogotá: Ediciones Uniandes.
- Sarria A. (2006), Métodos geofísicos con aplicaciones a la ingeniería civil. Bogotá D.C.: Ediciones Uniandes.
- SN 640. (1978), Effects of vibration on construction. Swiss Association of Standards