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ABSTRACT

Medellin is an important industrial city of Colombia, which is the capital of Antioquia province (department) and it is located in the northwest of this country. It has a very high population density about 2.000.000 people and an area of just 100 km². Its location makes it very susceptible to suffer earthquakes and its great topographical and geological diversity stand out the importance of local effects associated to earthquakes. These reasons led to carry out the Medellin Seismic Instrumentation and Microzonation Study, which main purpose was to develop and propose new provisions for designing and constructing new buildings in Medellin. The results of this project are also very useful to determine potential damage of existing constructions during earthquake motions. This paper describes the detail methodology of the Medellin Seismic Instrumentation and Microzonation Project and discusses the final results of this study.

INTRODUCTION

Even though Medellin has never been destroyed by an earthquake like other cities in Colombia, such as Armenia and Popayan, there were several important reasons to undertake studies which supply criteria about seismic response, potential damage and seismic protection programs.

A big part of Medellin city was developed using old seismic codes and other zones without fulfilling seismic norms, this condition is specialty critic in poor neighborhoods. These characteristics imply a very variable construction quality, which leads to a relatively high structural vulnerability in Medellin.

Medellin authorities have showed their concern about high costs of damages generated by some small seismic ground motions events in Medellín, like 1979 Mistrato and 1992 Murindo earthquakes, in spite of their very low rock accelerations. The 1992 Murindo earthquake had rock acceleration about 1,5% g and caused damages concentrated in specific sectors of the city, which cost more than 10 million dollars. Studies about damage costs in the nowadays city associated to earthquakes like 1979 Mistrato one (rock acceleration of 3,0% g), estimated losses about 300 million dollars. It is important to point out that earthquakes mentioned above are much smaller than that could affect the city. These conditions made authorities, geotechnical engineers and structural engineers to become aware about great necessity of seismic preventive programs to adapt construction quality to Medellin seismic hazard and in this way to improve seismic security of this city.

The earthquakes mentioned above were also a clear evidence of marked differences in seismic response of different sectors of the city, related to topographic and geotechnical diversity. That is why necessity of defining zones with similar seismic behavior with their own design parameters showed that seismic microzonation was the best way to reduce seismic risk in Medellin.

This study was carried out by requesting of Medellin authorities from 1996 to 1999 and advised by professor Ricardo Dobry, who has great experience in similar projects and has participated in important workshops for defining seismic provisions in the United States and other countries.

The final objective of the Medellin Seismic Instrumentation and Microzonation project was to propose a detailed geotechnical and seismic microzonation of the city, that constituted a compulsory local norm for designing and constructing structures in Medellin. The results of seismic microzonation replaced topics about design spectra in the Colombian Building Code for the particular case of Medellin. This study included the following topics:

- Installation and operation of the Medellin accelerograph network since 1996. This network is composed by 22 superficial accelerographs and two deep ones, which make Medellin the second city with best seismic instrumentation in Latin America.

- Installation and operation of a processing center of seismological information since 1996, which basic function has been the compilation and analysis of registered information by the Colombian Seismological Network about seismic sources with influence in Medellin.

- Geotechnical and seismic Microzonation of the city in base to geological, geotechnical and seismic response of the soils. Soil seismic response was calibrated using real earthquakes registered by Medellin accelerograph network. This part of study permitted to divide the city in homogenous zones according to their expected behavior during earthquakes, in such way every zone has its own design parameter for different types of structures.

- Evaluation of peak rock acceleration which represents seismic hazard of the city. This study involved geologic and tectonic evidences, historical seismicity and instrumental seismicity.

SEISMIC HAZARD OF MEDELLIN

Seismic hazard study considered two important aspects:

- The search for geologic evidence of earthquake sources that included analysis of faults by means of tools and techniques like interpretation of air photos and remote sensing imagery, field reconnaissance and logging of trenches.

- Analysis of regional and local instrumental seismicity that allowed to identify main seismic sources with influence in Medellin and characteristics of past earthquakes.

Medellin is surrounded by several faults, which constitute potential earthquake sources. It is important to stand out that the nearer branch of Romeral fault is located 10 km west from the city. In addition, the city can be affected by other faults like Cauca, Palestine and Murindó systems located farther from Medellin than Romeral fault. Medellin is also exposed to earthquakes associated to subduction of the Nazca Plate beneath South America Plate.

Due to the Romeral fault represents the nearest source to the city, it was necessary to carry out studies of geologic evidences. These studies included detailed field reconnaissance and logging of trenches, which permitted to confirm that this fault has produced displacements older than 10000 years. Therefore, the Romeral fault in this zone presents an activity much smaller than towards the south of Colombia, where it has caused earthquakes like Popayan earthquake in 1983 and Armenia earthquake in 1999.

Considering the results of geologic evidence studies and seismicity historical and instrumental information, probabilistic seismic hazard analysis was carried out. This probabilistic approach provides a framework in which uncertainties in size, location, rate of recurrence of earthquakes and so for can be identified, quantified and combined in a rational manner by means of logic or probabilistic trees.

Figure 1 shows the curve of seismic hazard of Medellin in terms of rock acceleration and its rate of recurrence. This curve shows that the earthquakes of small acceleration are caused by distant sources like Murindó fault or subduction, whereas strong earthquakes, which there are not recent records, can only be produced by the Romeral fault. According to this curve the maximum rock acceleration for a return period of 10 years is 0,03 g, and the maximum rock acceleration for a return period of 475 years is 0,15 g.

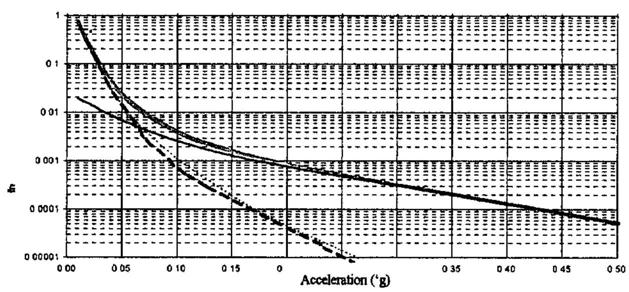

Fig. 1. Result of Medellin seismic hazard analysis.

MEDELLIN ACCELEROGRAPH NETWORK

Medellin accelerograph network is composed by 22 superficial accelerographs and two deep ones, that have allowed to study local effects associated to representative geomorphic and geotechnical formations in Medellin. Figure 2 shows distribution of accelerograph stations in the city.

This accelerograph network started to operate in November of 1996. During this period it has registered about 40 earthquakes that is one event every month approximately. Seismic information registered by these accelerographs, have constituted an invaluable contribution in the process of seismic microzonation, because they have showed marked differences in soil seismic response.

Figure 3 provides an example of marked differences in the accelerations registered at surface level. Every plot represents the response spectra of Armenia earthquake (1999) in 8 different accelerograph stations of the city.

Empirical transfer functions and ratios of response spectra of each site were defined using Fourier spectra and response spectra of different motions registered in each accelerograph station and their corresponding rock outcropping motions of Santa Elena station.

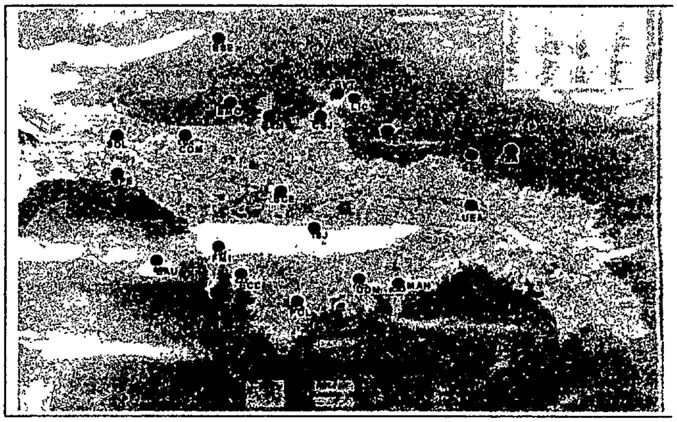

Fig. 2. Location of accelerograph network in Medellin city.

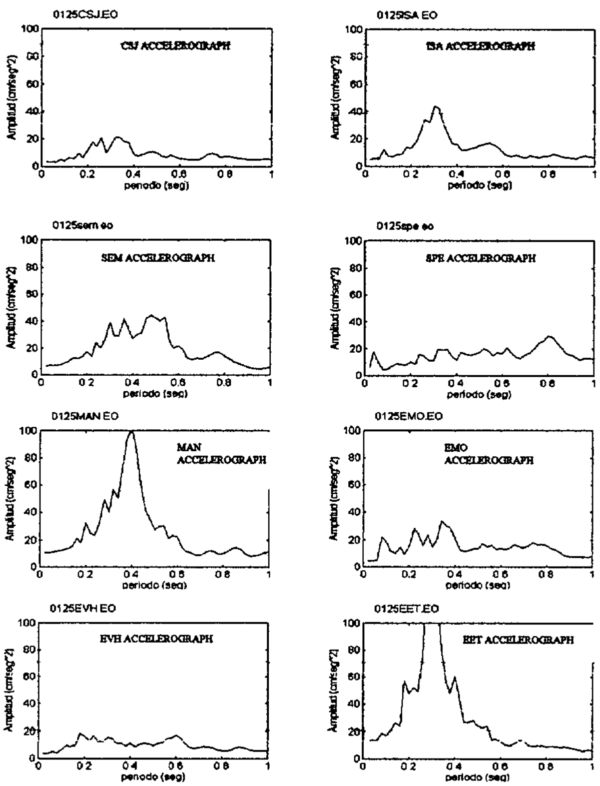

Fig. 3. Recorded response spectra at different soil sites of Medellin, 1999, Armenia (Colombia) earthquake.

Figure 4 shows an example of marked stability of tranfer funtions for one station of Medellin accelerograph network. These kind of functions were very useful to calibrate numerical models for seismic microzonation.

SEISMIC MICROZONATION

The study of microzonation included the following topics:

- Detailed studies about geology and geomorphology of Medellin, that showed a very important diversity of soils in an area of only 110 km². There are residual soils of three different types of igneous rocks (gabbro, granodiorite and dunite), residual soils of metamorphic rocks (anfibolite and gneiss), alluvial and coluvial deposits of different age and composition. Figure 5 shows geologic map of Medellin, which was carried out with a very high detail (scale 1:10000). The geomorphology of the city varies from flat zones in the alluvial plain of Medellin river to steep slopes.

- Compilation of geotechnical information, which final result was a database of 1000 boreholes distributed in all the city area. In addition, it was carried out a complementary geotechnical exploration composed of 32 boreholes located in different geotechnical formations, 22 of those boreholes were located in accelerograph sites. Average depth of these boreholes was 30 m, but many of them were deeper than 45 m. Geotechnical exploration also included seismic down-hole tests, which were performed in 32 boreholes mentioned above, for evaluating variation of shear wave velocity with depth in representative soil profiles of Medellin.

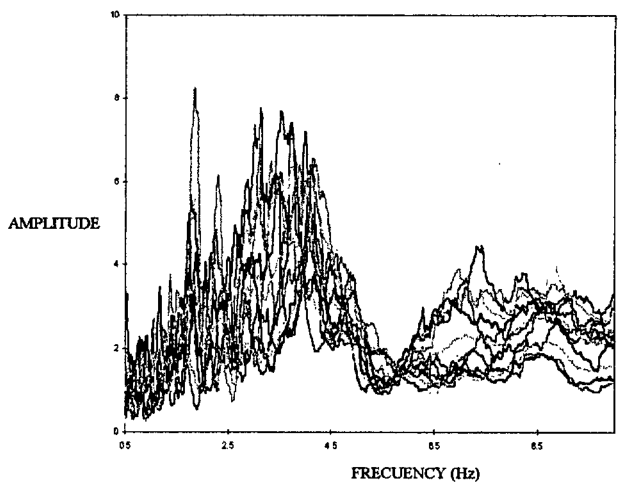

Fig. 4. Transfer funtions of recorded earthquakes at CSJ accelerograph.

- Performance dynamic laboratory tests such as piezoelectric bender element, cyclic triaxial and cyclic torsional shear, in order to study variation of shear modulus and damping ratio with shear strain. Results of these tests confirmed that dynamic behavior depends on origin of soils and stood out necessity of considering its variability range for every kind of soil.

- Analysis of motion records obtained from different accelerographs located in the city, in order to calibrate results of numerical methods. The main condition considered to carry out the Medellin seismic microzonation always was to achieve an acceptable adjustment between records and numerical analysis. It is very important to point out that numerical analyses considered uncertainties associated to measurement of soil dynamic properties. Figure 6 provides an example of this adjustment process between Ratio of Response Spectra of real motion records and those obtained by theoretical analyses.

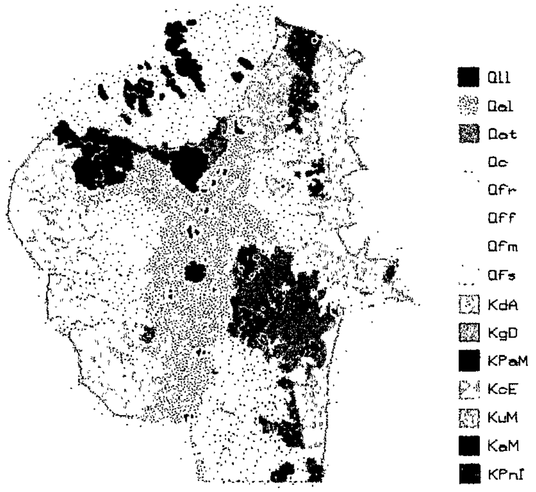

Fig. 5. Geologic map of Medellin.

- Processing of geotechnical data was carried out using Geographical Information Systems, which allowed to associate databases, consult information, prepare soil profiles and make a geotechnical three-dimensional model of Medellin. The geothecnical and geologic three-dimensional model of the city was result of analyzing soil profiles generated each 150 m in all the city area. This 3D-model allowed spotting possible thickness variation of different layers and identifying differences in layer sequences of representative soil profiles. Figure 7 Approximately 400 different soil profiles were identified, which were simplified to 100, considering thickness variation. These last ones were used for ground response analysis, taking into account calibration of theoretical models in base to motion records of Medellin accelerograph network.

- Evaluation of ground response for developing of design spectra was carried out by means of one-dimensional analysis of wave propagation through different soil profiles, using the Shake program. Resulting response spectra of these analyses were gathered considering conditions that reflect similar seismic response for different representative soil profiles from the city. Design spectra were defined for different site conditions and shaking intensities, these last ones according to results of seismic hazard study, and that is why rock acceleration coefficients used (0,03 and 0,15) correspond to return periods of 10 and 475 years, respectively. Coefficient for low accelerations was adopted considering great importance of local effects in these cases for Medellin soils and taking into account regulations of 1998 Colombian Builiding Code related to damage control for low shaking intensities. Figure 8 illustrates a typical case of design spectra definition for Medellin seismic microzonation.

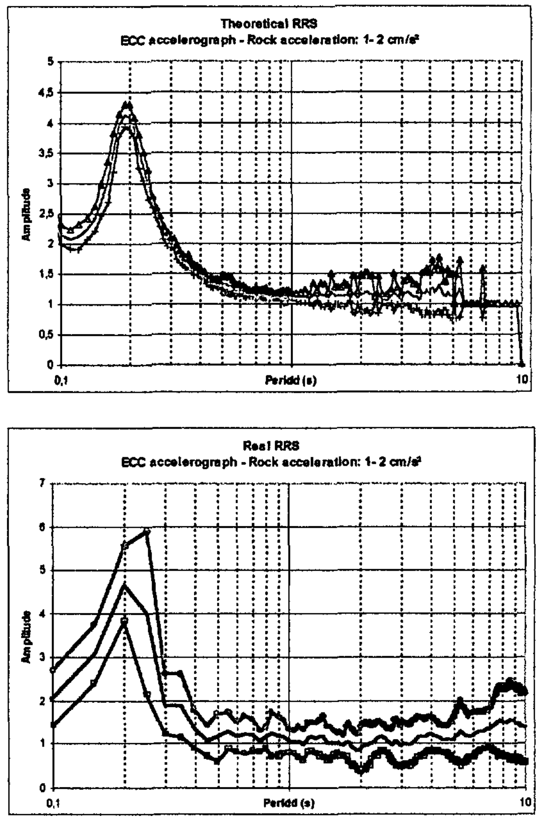

Fig. 6. Example of adjustment procedure of theoretical analysis of seismic response using motion recorders by means Ratio of Response Spectra (RRS).

Fig. 7. Geological and geotechnical three-dimensional model of Medellin city.

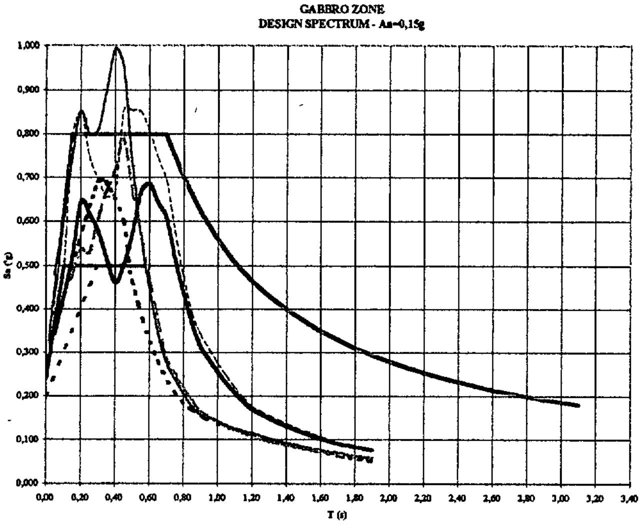

Fig. 8. Definition of design spectrum of gabbro residual soils.

- Delimitation of zones where similar ground response is expected and assignation of design spectra for each one of them. Figure 9 shows seismic homogenous zones of Medellin. Figure 10, Table 1 and 2 supply the recommended spectra for shaking intensities of 0,03 g and 0,15 g. Recommended spectra for each homogenous zone are function of local site conditions.

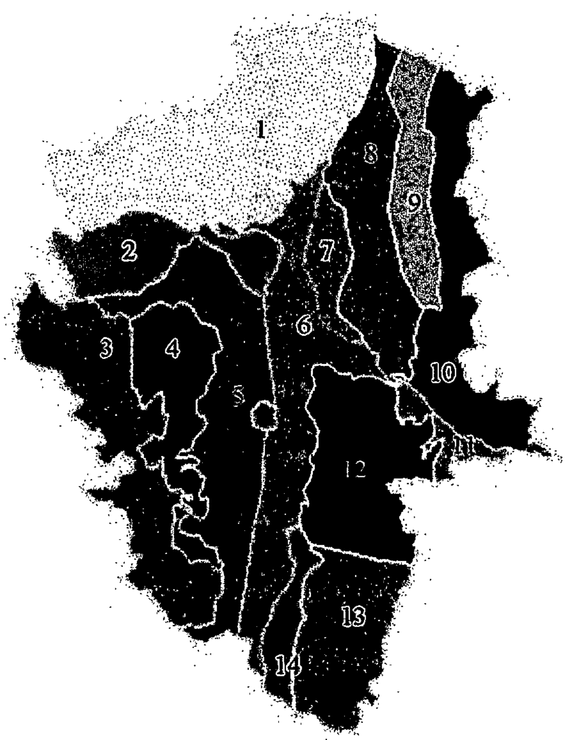

Fig. 9. Medellin seismic microzonation.

Table 1. Factors of design spectra of Medellin seismic microzanation for rock acceleration of 0,03 g.

HOMOGENOUS ZONE	Shaking intensity Rock acceleration = 0,03						
	amáxs ('g)	Sa max ('g)	To (seg)	Tc (seg)	Tl (seg)	Fa	Fv
1	0,05	0,23	0,10	0,50	4,10	3,00	3,75
2	0,08	0,22	0,10	0,30	1,80	2,99	2,24
3	0,07	0,25	0,10	0,50	3,60	3,33	4,17
4	0,05	0,18	0,10	0,60	4,00	2,40	3,60
5	0,06	0,22	0,10	0,50	3,40	2,93	3,67
6	0,05	0,14	0,10	0,40	2,20	1,87	1,87
7	0,06	0,22	0,10	0,50	3,40	2,93	3,67
8	0,08	0,18	0,10	0,65	3,05	2,40	3,90
9	0,06	0,23	0,10	0,40	3,00	3,00	3,00
10	0,09	0,25	0,10	0,40	2,20	3,33	3,33
11	0,06	0,23	0,10	0,50	3,70	3,00	3,75
12	0,06	0,25	0,10	0,65	5,35	3,33	5,42
13	0,06	0,25	0,10	0,40	3,10	3,33	3,33
14	0,05	0,14	0,10	0,50	3,00	1,87	2,33

Table 2. Factors of design spectra of Medellin seismic microzanation for rock acceleration of 0,15 g.

HOMOGENOUS ZONE	Shaking intensity Rock acceleration = 0,15						
	amáxs ('g)	Sa max ('g)	To (seg)	Tc (seg)	Tl (seg)	Fa	Fv
1	0,27	0,70	0,10	0,60	3,10	1,87	2,80
2	0,34	0,80	0,10	0,40	1,90	2,13	2,13
3	0,30	0,80	0,20	0,70	3,80	2,13	3,73
4	0,23	0,50	0,10	0,65	2,95	1,33	2,17
5	0,18	0,60	0,10	0,60	4,00	1,60	2,40
6	0,18	0,50	0,10	0,50	2,80	1,33	1,67
7	0,18	0,60	0,10	0,60	4,00	1,60	2,40
8	0,23	0,55	0,10	0,75	3,65	1,47	2,75
9	0,26	0,70	0,10	0,55	2,95	1,87	2,57
10	0,38	0,80	0,10	0,50	2,20	2,13	2,67
11	0,26	0,75	0,10	0,65	3,85	2,00	3,25
12	0,26	0,80	0,15	0,70	4,40	2,13	3,73
13	0,26	0,80	0,10	0,50	3,20	2,13	2,67
14	0,20	0,60	0,10	0,55	3,45	1,60	2,20

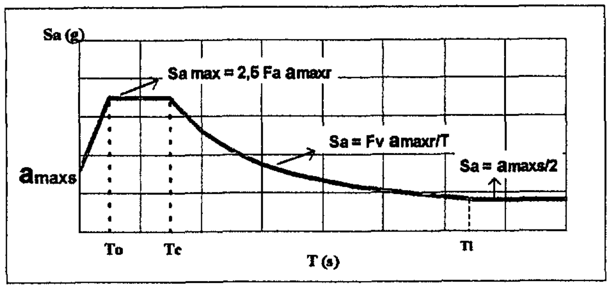

Fig. 10. Parameters of recommended design spectra.

Taking into account maximum ground accelerations and maximum spectral accelerations of recommended design spectra for Medellin, the homogenous zones where earthquakes can be felt with greater intensity are identified with number 2, 3, 10, 12 and 13. These zones correspond in general to residual soil profiles, where impedance ratio is responsible for appreciable amplification phenomena.

EVALUATION OF SUSCEPTIBILITY TO LANDSLIDE ASSOCIATED TO EARHQUAKE IN MEDELLIN

Final phase of Medellin seismic microzonation was concentrated in evaluating susceptibility to landslide associated to earthquake, using geographical information systems. These analyses considered representative characteristics of site behavior like slope, water table, soil properties and so for. In addition, analyses took into account as trigger factor the influence of the expected maximum soil acceleration, according to local effects. Every one of these factors was represented in different thematic maps, which were superposed by means of Geographical Information System, considering relative importance of each factor.

The final result is a map that permitted to identify the zones most susceptible to suffer landslides during and after earthquake. This map showed a relatively low area of the city with characteristics of high (10,3%) and very high (1,2%) landslide risk related to earthquake. The zone with medium risk represents 14.1% of the city area. These results point out that 74,4% of this city presents low and very low landslide susceptibility associated to ground motions, which corresponds to sectors with low slopes.

CONCLUSIONS

- Medellin seismic instrumentation and microzonation project was carried out using not only detailed information about geologic, geomorphic and geotechnical conditions of the city, but also motion recorders of local accelerograph network, which permitted calibrate theoretical models. This characteristic stands out that seismic microzonations are not static results, on the contrary, they must be modified considering new resulting information of accelerograph networks. In this way seismic building codes can evolve and improve seismic security of our cities.
- Results of geologic and geotechnical studies point out that according to properties and composition of Medellin soils, liquefaction phenomena lack of importance in this city.
- Even though landslides can be associated to earthquakes in Medellin, studies about site characteristics such as slope and water table showed that they play a more important role in landslides than earthquakes.
- Amplification is the most important seismic phenomenon in Medellin, and the marked differences in ground seismic response make necessary to design, construct and review structures according to local effects represented by resulting design spectra of this study.
- Medellin counts on one of the most complete accelerograph network of Latin America, and has reliable results on characteristics of expected ground motions for the different sectors in which it was divided.

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