SEISMOLOGY AND EARTHQUAKE ENGINEERING IN COLOMBIA

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ABSTRACT

This paper describes the development of Earthquake Engineering in Colombia. Briefly relates the tectonics and seismicity of the country. Presents the research that led to the development of the seismic zoning and risk assessment of the country for Building Code purposes. Gives an account of the behavior of buildings during recent earthquakes. The development and content of the Seismic Resistant Regulations of the country are described.

INTRODUCTION

The northwest corner of South America is a very active seismic region. The first settlements of Europeans were subjected to earthquakes since the very beginning and the first description of a destructive earthquake is found in historical records from 1566. The rapid population growth that occurred during the present century specially in the urban centers has increased the chance that a large number of persons living in a large city be affected by a major earthquake. Currently the country has a number of cities with very large populations, all of them located near active faults: Bogotá 5,500,00 inhab., Medellín 2,350,000 inhab., Cali 1,950,000 inhab, Barranquilla 1,200,000 inhab., Bucaramanga 600,000 inhab., and more than ten cities with populations that range between 250,000 and 500,000 inhabitants. The total population of the country presently is around 30,000,000 inhabitants, from 11,550,000 counted in the 1951 census.

The awareness of this increase in vulnerability has been brought into evidence by the occurrence of three large earthquakes that are described ahead, and by the occurrence of a volcanic mud flow that produced more that 20,000 victims. Therefore the need for a group of people trained and proficient in earthquake engineering was a reality. The large engineering consulting firms, engaged mainly in the development of the extensive hydroelectric resources of the country were the first group that had a chance to work with American an European consultants in earthquake engineering. On the other hand a large group of structural and geotechnical engineers were aware of the need of comprehensive earthquake resistant regulations and codes. These two groups decided in 1974 to joint forces and founded the Asociación Colombiana de Ingeniería Sísmica - AIS (Colombian Association for Earthquake Engineering).

This Association has been very active since. At the beginning the main objective was dissemination of earthquake engineering related information through a bimonthly bulletin, followed by a

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program of translation into Spanish of selected references like SEAOC [26] and ATC-3-06 [4] that led in 1981 to the first draft of what became the official Earthquake Resistant Design Regulations by law in 1984 [18]. At the same time the Association directly, or through individual members, participated in a series of research projects related to the actualization of the seismic events catalog (5557 events up to December 1987), geological mapping related to active faulting identification and related works in tectonics that enabled the development of seismic zoning and seismic risk assessment for Building Code purposes. Other activities have been the reporting of damage in recent earthquakes and follow up of post earthquake recuperation, specially after the March 31, 1983 Popayán Earthquake.

SEISMICITY OF COLOMBIA

Historic Seismicity

The first event of which a written record exists occurred in 1566, causing intensive damage in Cali and Popayán in the South West part of the country. The confidence on historic information on earthquakes is of varied quality. It must be taken into account that the country was scarcely inhabited (Colombia had four million inhabitants in 1900 for an area of 1,130,000 km) and the greatest part of the population was concentrated in the Andean part of the country, as it is at the present.

The map in Fig. 1 shows the epicenters of the main events that occurred during this period, before any seismic instruments were installed in the country.

Instrumental Seismicity

The instrumental seismicity of Colombia begins with the installation of the first seismographic station in 1922. Seven permanent seismographic stations scattered through the country have been in operation in the country since 1957 and currently a project of modernization sponsored by the Colombian and Canadian Governments Agencies is being implemented and will start operation during 1991.

Up to the present all seismological information gathering and operation of the stations has been in charge of the Instituto Geofísico de los Andes Colombianos, at the Universidad Javeriana in Bogotá, a private catholic university run by the Jesuits. The new instrumentations will be managed by the Division of Geophysics of Ingeominas, a government agency.

During 1969 and 1970 the formation of the catalog of Colombian earthquakes was initiated at the Universidad de los Andes, Bogotá, under the supervision of Prof. Alberto Sarria. The work by J.E. Ramírez S.J. [20] was used as the main source of information. This first catalog was used in the initial studies of seismic risk and the production of the first seismic zoning maps for Building Code purposes [6].

In 1979 Interconexión Eléctrica S.A. (ISA), a government agency that manages the high voltage electric network of the country, sponsored a joint venture between Prof. Sarria and the Instituto Geofísico to process all the seismographs recorded in Colombian stations that the Institute had in its archives [17]. The computer program HYPO-71 developed by the U.S. Geological Survey was used for the processing of the information. In Fig. 2 the 3886 events that were processed are plotted.

In 1982 an update of the catalog was performed for project SISRA [7], sponsored by the Centro Regional de Sismología para America del Sur - CERESIS (Regional Seismological Center for South America). With this update the number of processed events increased to 4784, 1206 historic and 3758 instrumental. In 1988 a new update was performed [16] which increased the number of registered events to 5557.

The fact that of the 4784 events of the CERESIS 1982 catalog 1026 are historic events, 1908 were registered by five or less stations, and 1850 were registered by more than six stations, gives an idea of the level of confidence on the instrumental information in it. Even in those cases with a large number of stations there is an appreciable level of uncertainty in the location of the event because most of the stations are located in the northern hemisphere and only in very few cases the depth of focus is of the same order of magnitude of the distance from the epicenter to the station. Of the records obtained with the present level of instrumentation approximately 45% of the information has good control in the horizontal plane. The quality of the information of depth of focus is good only in very few events.

New Seismological Network

After the Popayán Earthquake in March 1983 and the mud flow of the Ruiz Volcano in 1985 the Colombian Government decided in 1986 to sponsor the formation of a National Seismological Network to be operated by Ingeominas, a government agency formerly named Colombian Geological Survey. By the same time the Canadian Government through the Canadian Agency for International Development CAID offered to cover an important part of the cost of implementation of the network and training of the Colombian personnel.

The first part of the new network (13 stations) will start operation at the end of 1991 giving support to the existing instruments. In full operation the new network will consist of 25 digital seismological stations with remote digitizing capacity and linked via satellite to four regional nodes in Cali, Medellín, Bucaramanga and Bogotá. The central real time processing will be conducted in Bogotá. In addition to the 25 existing accelerographs, 130 new autonomous digital strong motion accelerographs will be installed, covering most of the territory of Colombia.

Recent Damaging Earthquakes

Three recent earthquakes have had a great influence in the development of the Seismic Resistant Regulations and are worth describing:

- November 23 of 1979 Earthquake. This 6.4 M_s magnitude earthquake [10] had coordinates 4o 30' N - 75° 54' W and a depth of 80 km. It affected the central western part of the country, specially the coffee growing region. It caused 37 death and 493 injured. There was intensive structural damage and even collapse of several buildings in the range of 4 to 6 stories. The cities of Manizales (population 280,000), Pereira (population 370,000) and Armenia (population 280,000) were particularly affected. Buildings well designed and constructed behaved very well with minor or no damage at all.

- December 12 of 1979 Earthquake. This event [10] occurred in the Pacific Ocean (2° 30' N - 79° 30' W) close to the Colombian city of Tumaco (population 35,000). The focal depth was 40 km and had a magnitude M_s of 7.8. In spite that the Pacific Coast of Colombia is scarcely inhabited, the combinations of tsunami and earthquake caused 453 death and 1047 injured. Due to the low development of the area no significant engineered structures were affected, although some damage was reported in Cali (population 1,200,000), located 280 km from the epicenter.

- March 31 of 1983 Popayán Earthquake. This event destroyed one of the most beautiful cities in Colombia, which contained some of the best examples of colonial architecture in the country. The earthquake was 5.5 M_b magnitude and the epicenter was located 10 km from the city with a focal depth of 5 km. It caused 250 death and 1508 injured in a city with a population of 220,000. It affected all type of construction [11]. The old colonial part of the city was damaged beyond repair. The earthquake produced intensive damage and several collapses to engineered construction [14]. The buildings affected were in the range of 3 to 5 stories. Two buildings designed and constructed using the draft of the Seismic Resistant Regulations developed by the Asociación Colombiana de Ingeniería Sísmica behaved very well with minor or no structural damage.

SEISMIC ZONING AND RISK ASSESSMENT

Initial Stages

The first seismic zoning of Colombia was done in a research project at the Universidad de los Andes, under the direction of Prof. Alberto Sarria. This study [6] developed using epicentral information, both historical and instrumental, a zoning map, Fig.3, intended to be used with earthquake resistant design regulations like SEAOC [26]. The definition of the seismic zones was based in energy release. Each zone contained areas with similar energy release rates.

As the catalog was improved and some understanding of the tectonic process was developed some of the deficient and inconsistent points of the map were corrected and a new version was published [22] in 1978. In 1980 the Universidad de los Andes, using a point source model developed a map of expected peak acceleration for all Colombia [23]. This was the first time some assessment of the risk in all of the country was given in probabilistic terms.

In 1980 the Asociación Colombiana de Ingeniería Sísmica produced maps of Effective Peak Acceleration (EPA) and Effective Peak Velocity (EPV) to be included in the draft, then being developed of the Earthquake Resistant Regulations. The specific values for EPA and EPV were obtained from different seismic risk studies that existed at the time for major hydroelectric projects and some large cities.

General Study of the Seismic Risk in Colombia

These last maps were only a different presentation of the existing information and it was evident that a comprehensive study was needed. The National Department of Planning, a government agency, gave a grant for a study leading to a complete seismic zoning and risk assessment. This new study [12] took three year to be completed and was finished on time for the enactment of the Code in 1984.

The highlights of the study are the following:

The tectonics of the northwestern corner of South America was studied. The fact that the Nazca, South American and Caribbean Plates converge in Colombian territory makes the tectonics of the region specially complex as shown in Fig.4 and Fig.5. The border between the Caribbean and South American plates is undefined. The structural geology of the country had been studied with different degrees of detail. In general a good mapping of large fault systems had been done for mining and petroleum exploration purposes. This had covered specially the northern half of the country. Special exploration have been done on a routine basis for the large hydroelectric projects with participation of leading world consulting firms. All this information was available for the identification of the main faulting systems. For the purpose of the study 22 major systems were used. These are shown in Fig.6. In general the faulting in Colombia has a predominant N-S direction in coincidence with the three main chains of mountains. Of these the Central chain is the oldest and the Eastern the younger.

The main seismotectonic accident is the Subduction zone in the Pacific Ocean. It is caused by the bending of the Nazca Plate as it subducts under the South American Plate. In the Colombian Pacific Coast there is evidence of its existence from 8° North to a point south of the Equatorial Line. The ability to produce very large magnitude earthquakes of this subduction zone is known and the December 12, 1979 earthquake certainly was produced by it. A Benioff zone develops with different dip angles that can be obtained from E-W sections of plots of focus of earthquakes. Its activity varies but earthquakes up to 120-130 km of depth can be assigned to it. Besides this a large number of faults were identified. For the purpose of the study 18 systems of faults were studied in detail.

The seismic events of the catalog were assigned to the different seismogenic accidents. This procedure permitted an assignation of 941 events. These assigned events as well as the unassigned ones were studied statistically in order to obtain B values for the magnitude regression as well as mean occurrence rates. The regressions of all the information assigned to all the seismogenic provinces for different periods are presented in Fig.7 from 1566 to 1984, in Fig.8 from 1922 to 1984 and in Fig.9 from 1957 to 1984. The same procedure was used for all the faulting systems independently. Figure 10 shows the regression for the Romeral Fault, one of the more active faults in Colombia that crosses the country from the border with Ecuador to the Caribbean.

Using a probabilistic line source seismic risk model [8], values of maximum possible horizontal peak ground acceleration were obtained. This model takes into account the contribution to risk at each point of interest of the known and unknown faults, the later represented by the unassigned earthquakes. Curves of peak horizontal acceleration against probability of excedance (or mean return period) were plotted for the main cities of the country and at all the crossings of meridian with parallel. The curves were obtained for different levels of uncertainty correction due to fault rupture length and attenuation equations. The levels of uncertainty correction used were 50%, 90% and 99%. Figure 11 shown this information for Bogotá.

With this information it was possible to plot maps that show peak ground acceleration for a mean period of return of fifty years and probabilities of excedance of 0.363, 0.10 and 0.05 and corrections due to uncertainties of 0.90 and 0.99. Figure 12 shown one of these maps. Using the maps and the historic information a Committee of the Asociación Colombiana de Ingeniería Sísmica, AIS, divided the country first in three zones: high risk, intermediate risk and low risk. These zones are shown in Fig.13.

The intent was to use the map in the Building Code, giving different construction requirements for each zone, with more strict mandatory requirements for the high risk zone. This was done keeping very close contact with the people developing the Code. Two additional maps, one for values of Effective Peak Acceleration, EPA, Fig.14, and one for values of Effective Peak Velocity in terms of Acceleration were developed. These two maps allow the construction a Design Spectra on Rock in all the country. The values given in these last maps were adjusted by the Committee with regard to historic evidence and the availability of strong motion records.

Recent Tectonic Studies of the Region

Recent studies conducted by J.Schneider [25], G.París and A.Sarria [19] and L.A. Rivera [21] have shed more light into the problem. Probably to date the more comprehensive presentation of the state of knowledge of the complex tectonic process taking place is the presentation by A.Sarria [24]. It is evident that a more refined definition of the process is important and that further research is needed.

BEHAVIOR OF BUILDINGS IN RECENT EARTHQUAKES IN COLOMBIA

Structural Systems in Colombia

The unbraced reinforced concrete frame is the most popular structural system in the country, although recently wall type systems built with reinforced or confined masonry have increased in use. For one and two story family dwellings is usual to have bearing walls of clay masonry.

The situation before the enactment of the Code was as follows: reinforced concrete had been designed using the ACI 318 Code [2] for a number of years and at the engineering schools traditionally all teaching of reinforced concrete design were made using the same Code. Lateral loads were calculated using SEAOC [26] although some misconceptions were found in its use. These specially were related with the use of the prescribed loads without full use of the detailing requirements and some times with no compliance at all. Most of the one and two story family dwellings were built using unreinforced masonry in all the country, even in areas with a notorious earthquake history.

Actual Behavior During Earthquakes

The occurrence of the two earthquakes of 1979 and the Popayán Earthquake of 1983 brought up a series of deficiencies in design and construction of structures that could be summarized as follows:

(a) Lack of enforcement of a Building Code in addition to the prevalent misconception that low rise buildings in the range of 3 to 5 stories, needed no seismic design, caused the great majority of the structural damage observed. No structural damage was reported on high rise buildings and the effects on well designed and well constructed buildings was limited to non structural elements.

(b) The great majority of member failures occurred in columns. Lack of proper transverse reinforcement and in some cases low flexural strength causing weak columns compared with strong beams was the cause of failure. These type of failures again pointed out lack of understanding of the modern earthquake resistant design principles.

(c) Excessive flexibility of frames causing intensive damage to non structural elements. The reasons behind this type of behavior ranged from lack of use of lateral loads in the design of the structure producing very flexible frames, to non observance of the drift requirements in some cases.

(d) Lack of knowledge by architects and engineers of the type of details that are known to produce bad behavior such as short columns, structural walls in one direction only, irregular layouts, etc.

(e) Very bad behavior of unreinforced masonry in the Popayán Earthquake of march 31, 1983. An almost perfect one to one correlation between existence of confining elements and little or no damage.

EARTHQUAKE RESISTANT REGULATIONS

Previous Work

Since it was founded in 1974 one of the main objectives of the Asociación Colombiana de Ingeniería Sísmica, AIS, was the development of a meaningful set earthquake resistant requirements that eventually could be adopted by the Colombian Government as part of a General Building Code, nonexistent at the time. The first step was to translate into Spanish the 1974 SEAOC Requirements [26]. The Spanish version was widely distributed through out the country. The main objective of this translation was to point out the relation between the lateral forces and the special reinforced concrete requirements.

In 1979 the Association deemed the ATC-3-06 [4] document so important for the future development of a local seismic code that the translation of the document into Spanish was undertook. One month after the translation of the Tentative Provision appeared, on November 23 of 1979, the central part of Colombia was affected by the 6.4 M_s magnitude earthquake already described, followed by the December 12, 7.8 M_s event that occurred in the Pacific Coast. The occurrence of these earthquakes brought out the deficiencies already annotated in building practice, both in design and construction, with regard to adequacy for seismic effects [13].

At this point the Association decided to develop a set of regulations for earthquake resistant design and construction. The Committee that wrote the document had the invaluable help of Professor Mete A. Sozen of the University of Illinois. The document was denominated "Norma AIS 100-81, Requisitos Sismicos para Edificios" [5].

Decree 1400 of June 7 of 1984

After the Popayán Earthquake the Association undertook a major revision of the AIS 100-81 document in order to incorporate the recently gained experience specially with respect to masonry, both unreinforced and reinforced, absent from the 1981 document. A section devoted to one and two story dwellings was also included.

The Government of Colombia decided then to enact the Norma AIS 100-83 as the mandatory earthquake resistant requirements. Congress authorized the President to make the Code mandatory in the rest of the country, giving a year for its development [13].

The following outline was then agreed:

TITLE A - GENERAL REQUIREMENTS FOR SEISMIC RESISTANT CONSTRUCTION
TITLE B - LOADS
TITLE C - REINFORCED CONCRETE
TITLE D - STRUCTURAL MASONRY
TITLE E - ONE AND TWO STORY DWELLINGS

TITLE F - METAL STRUCTURES
TITLE G - PENALTIES

For Title A the AIS 100 document was used. It defines the scope of the Code, the design procedures, gives requisites for the approval of materials and procedures not covered by the Code, defines the type of supervision mandatory during construction, specifies the design spectra and the seismic design parameters, sets the type of structural systems and methods of analysis permitted, defines the allowable drift limits and sets the specific requirements of the Code that must be followed in each of the seismic risk zones.

Title B covers all loads different from seismic effects such as dead, live, and wind loading. It was developed from previous recommendations given by the Colombian Society of Engineers.

Title C follows for reinforced concrete ACI 318-83. It has changes with respect to ACI 318-83 with regard to different Colombian construction practices.

Title D covers all type of structural masonry. Unreinforced masonry is prohibited with the exception of some parts of the low seismic risk zones. It gives requirements for different types of masonry and imposes mandatory supervision in all structural masonry construction operations. It is based in three document's suitable adapted for local materials and quality of construction; these documents are Chapter 12 of ATC-3-06 [4], Standard ACI 531 [1] and the Mexican Code [27]. All previous experimental research on Colombian masonry materials was incorporated.

Title E gives requirements for the construction of one and two story dwellings build on masonry bearing walls. The intent of this Title was to give a set of empirical rules that will guide a person, not necessarily architect or engineer, on how to build an earthquake resistant house. Its intent was to lessen the impact of forbidding unreinforced masonry.

Title F is based on the Specifications [3] of the American Institute of Steel Construction, AISC. Metal structures are not widely used in Colombia, except for long span roof trusses.

Title G contains the legal penalties that non compliance with the code carries.

The Code was enacted by Decree 1400 of June 7 of 1984 [18]. It was given a transition period to the end of 1984 before being fully mandatory.

CODE ENFORCEMENT

It is natural that the enactment of a mandatory Code in a country where no document of this type was in use produces some sort of reaction from different groups of the sector engaged in design and construction.

During the development of the Code great care was exercised to alleviate those aspects that could be accommodated without a reduction in safety. This was not always easy and the most difficult task was to try to bring the discussion to a plane where all involved has a similar perception of what the real problem was.

It could be said that the main concern of the groups involved were related to the real ability of the Government to enforce de Code. The economic impact on people complying with the Code competing with people barely doing so under a lax enforcement was one of the main arguments. This motivated the Government to establish the same type of penalties both on the government official and on the constructor and designer. These penalties on the personal point of view go up to loss of the capacity to practice his profession for life and in the material point of view to demolition of the non complying building. Not everybody is happy with the interest that the Code has awaken in lawyers.

The degree of enforcement varies from city to city but in general the response has been better than expected and it could be said that a real concern to comply with the Code has developed at least at the level of plans submitted to obtain building permits. It is difficult to judge on real compliance during construction but the introduction of mandatory supervision has been generally accepted.

A Committee devoted to periodical updates of the Code, approval of design and construction techniques not covered by it and sponsoring of code related research was established by the Government in 1984. This Committee has been working in an update of the Code to be enacted in 1992. Guidelines for upgrading and modification of the structural system of structures built before the enactment of the Code were produced by the Committee [15]. It has approved five precast systems for which experimental research was presented which has been a very interesting by-product of the Code.

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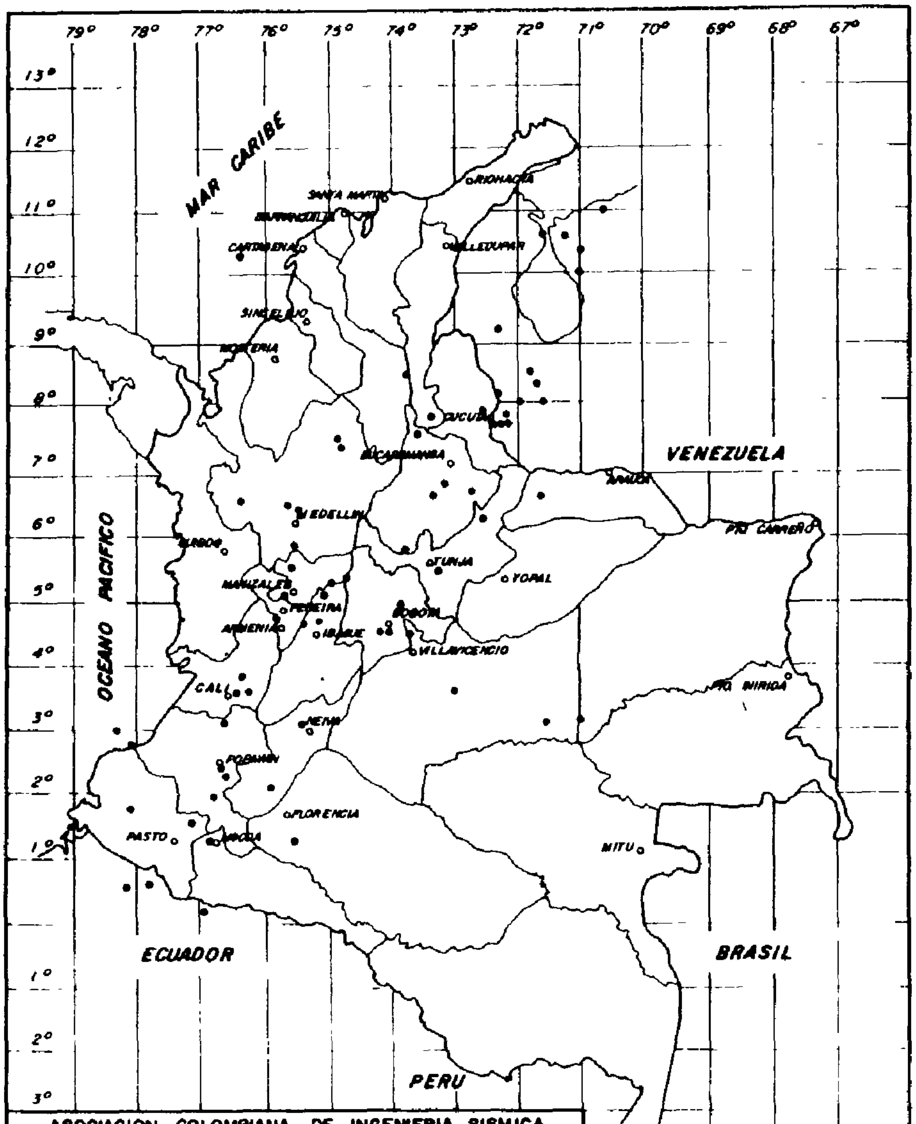
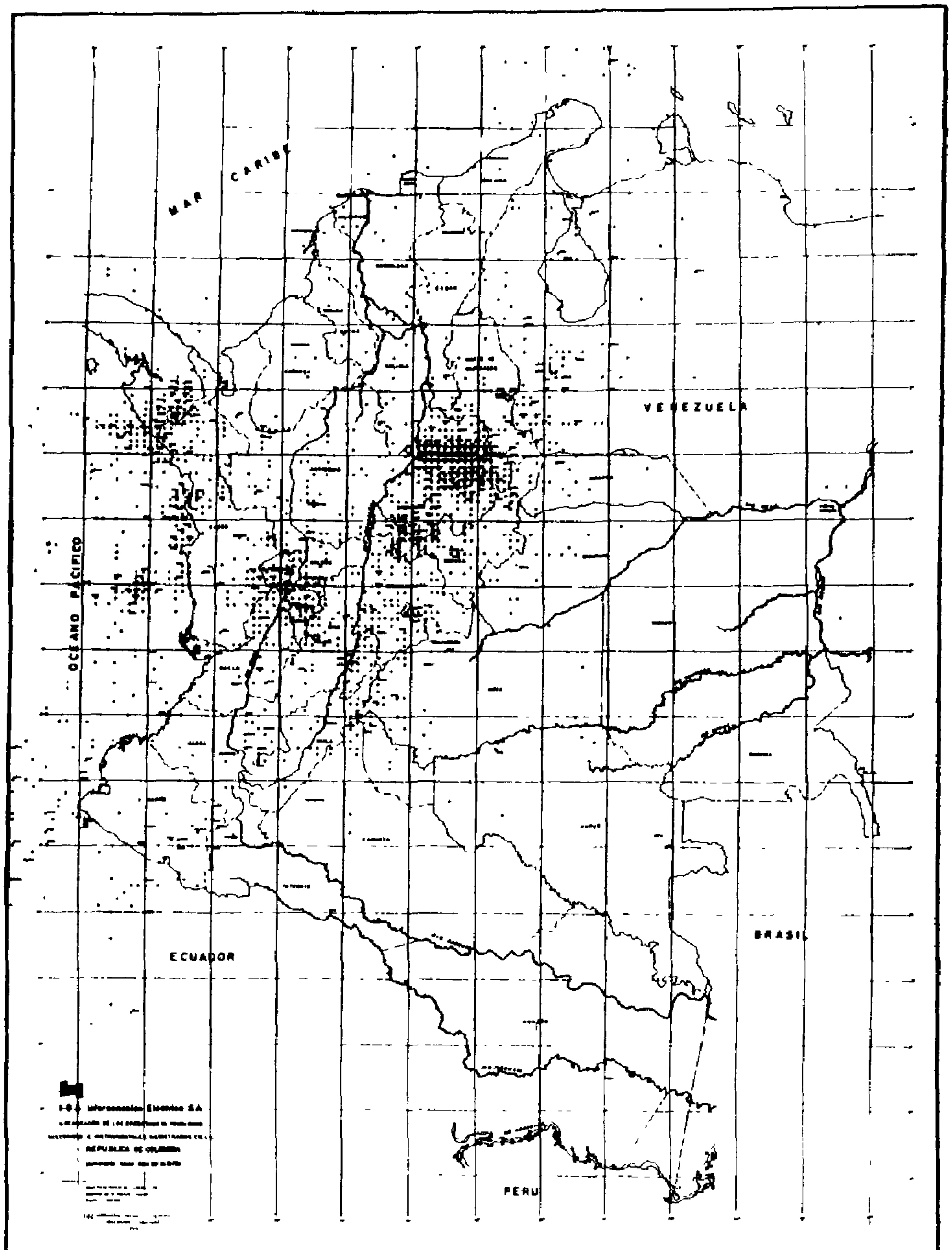


ASOCIACION COLOMBIANA DE INGENIERIA SISMICA
ESTUDIO GENERAL DEL RIESGO SISMICO DE COLOMBIA
BOGOTA, COLOMBIA, 1984

EPICENTROS DE LOS SISMOS EN COLOMBIA
INFORMACION HISTORICA (Epicentros principales)

FIG. I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ECUADOR
BRASIL
PERU
REPUBLICA DE COLOMBIA

FIGURA 2

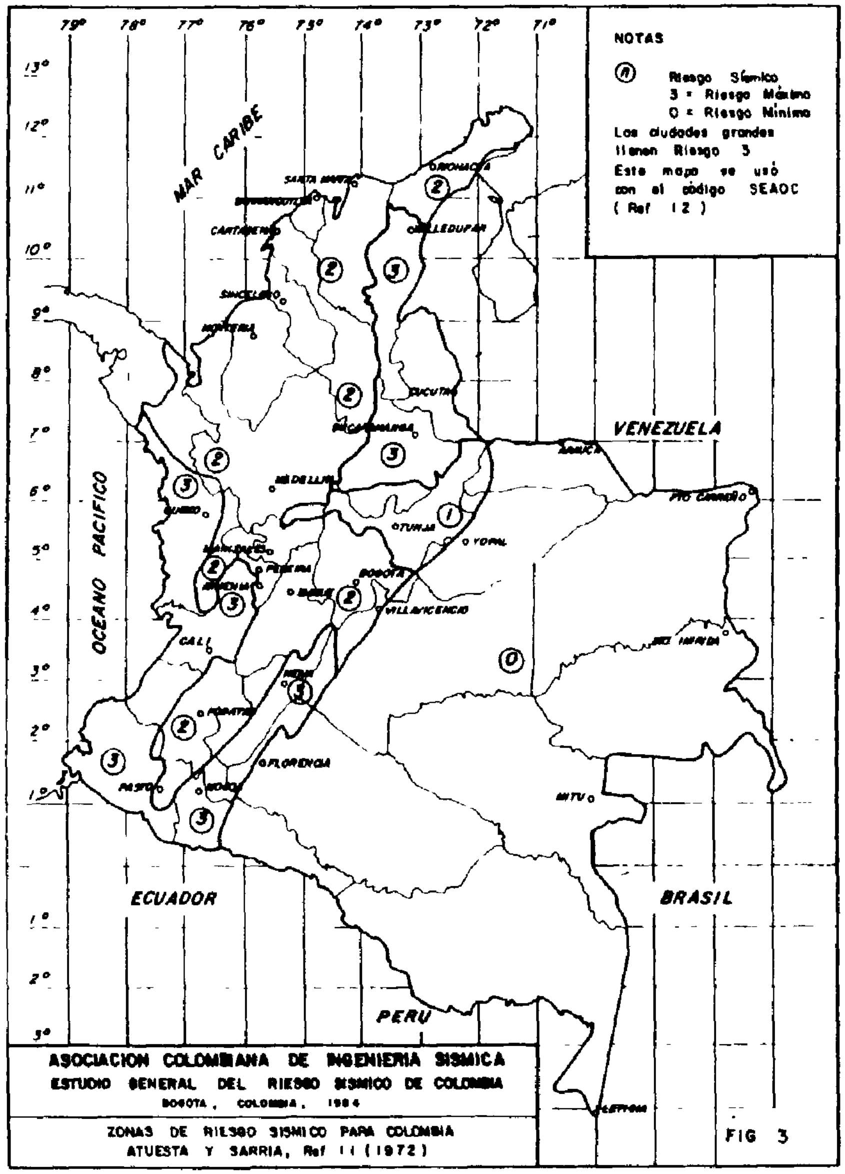


FIG 3

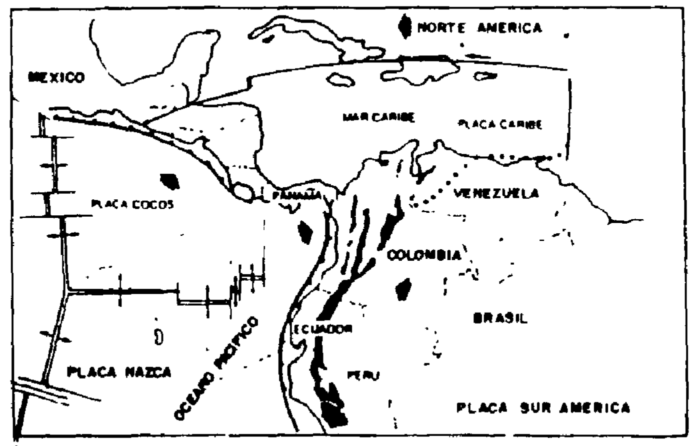


Figura 4 Ambiente tectónico regional en el Nor-occidente de Sur América

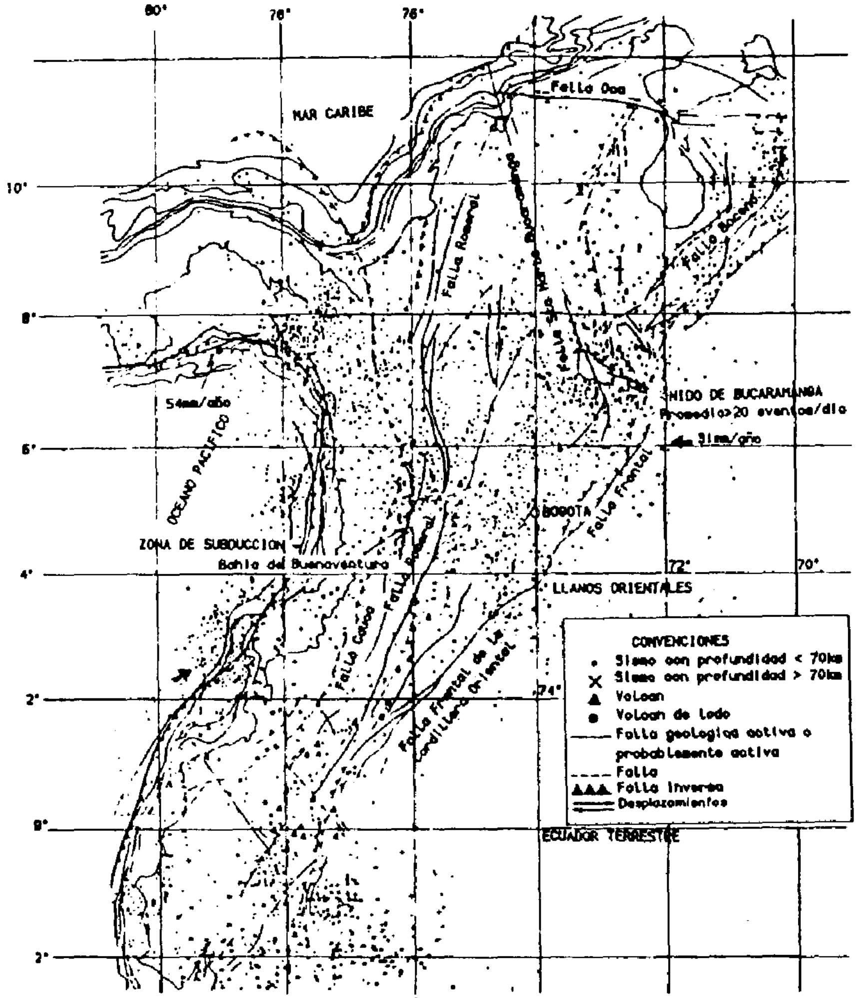
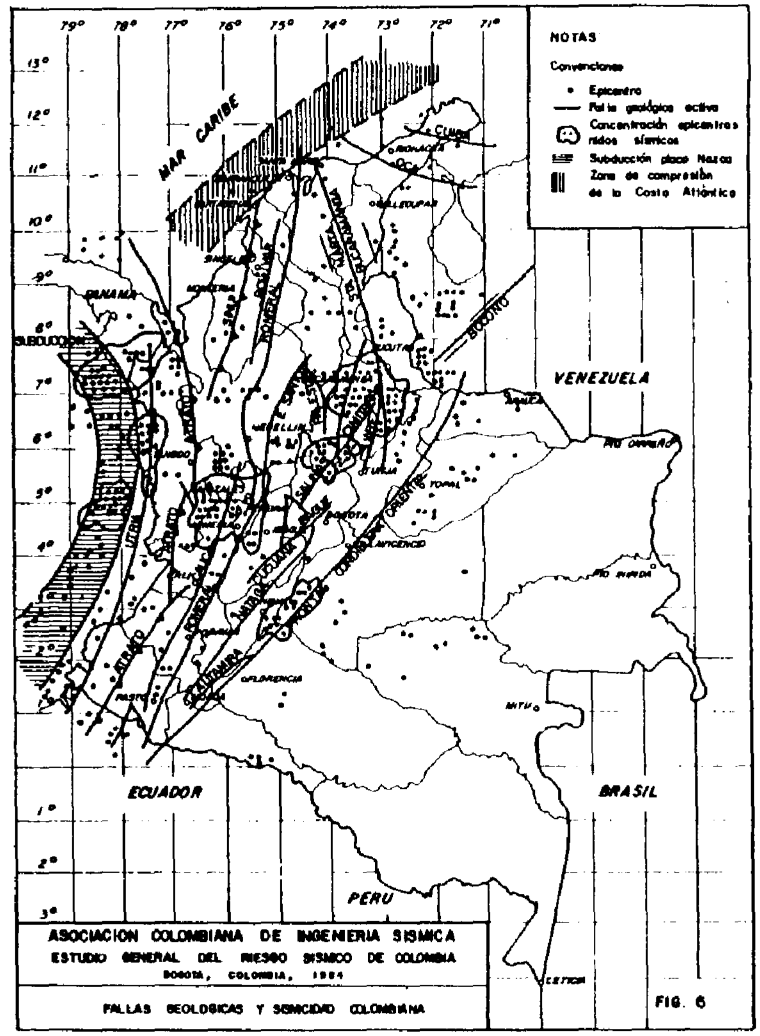


Figura 5. Mapa Sismotecnico del Nor-occidente de America del Sur



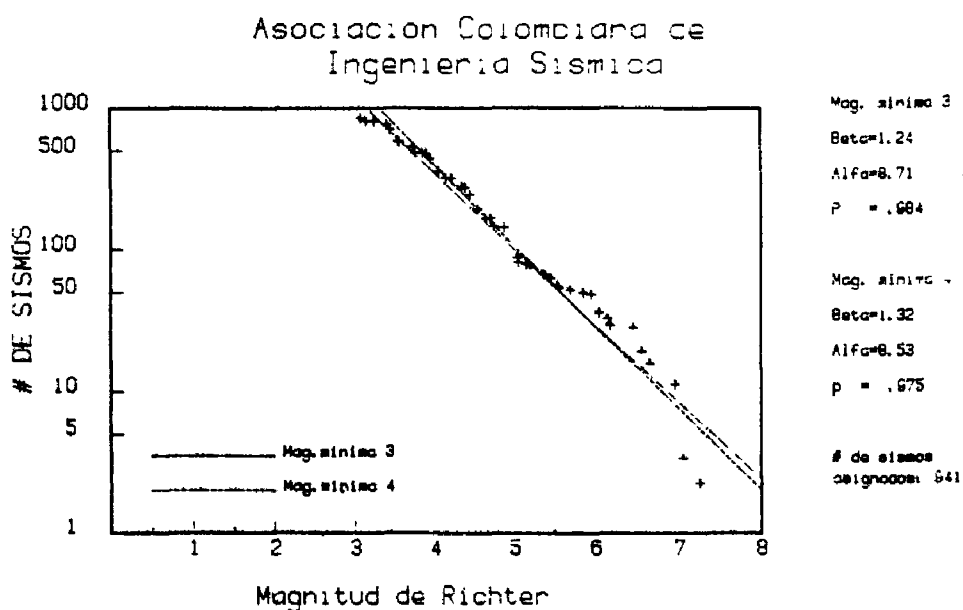


Figura: 7	Datos recolectados a partir de: 01/01/1566	Temblores asignados a fallas en el Territorio Colombiano

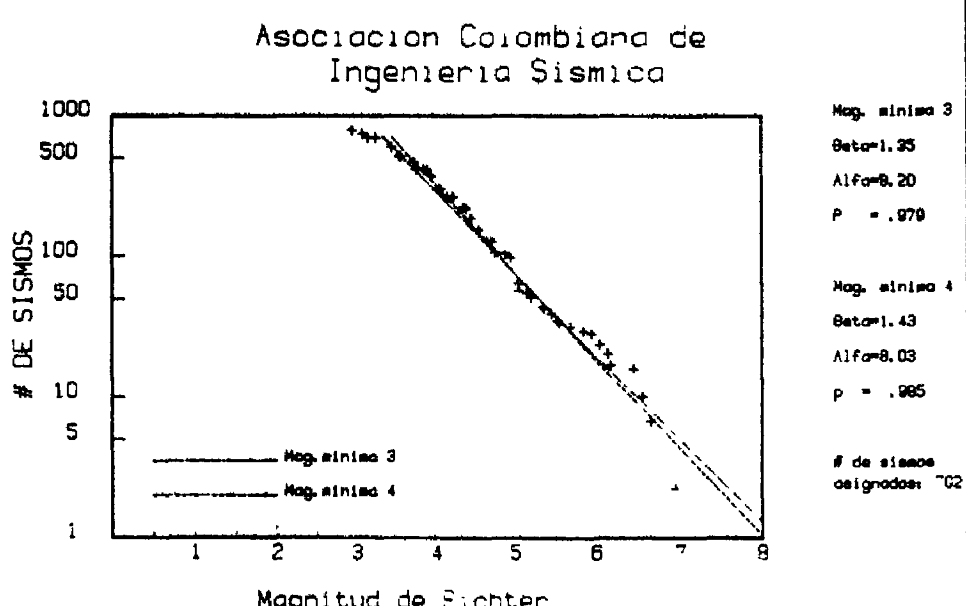


Figura: 8	Datos recolectados a partir de: 01/01/1922	Temblores asignados a fallas en el Territorio Colombiano

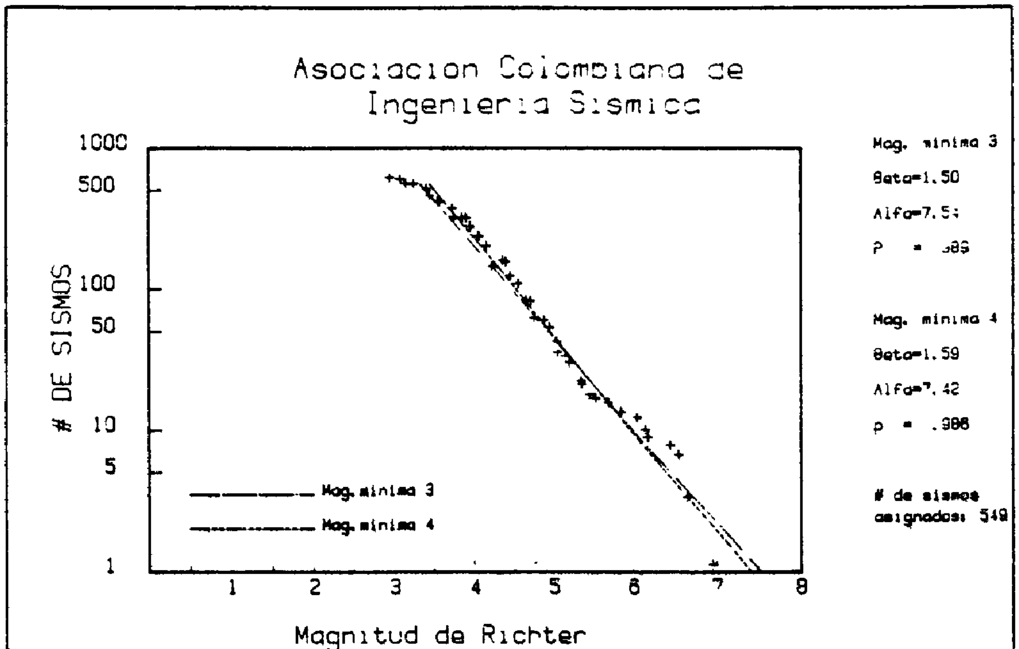


Figura: 9	Datos recolectados a partir de: 01/01/1957	Temblores asignados a fallas en el Territorio Colombiano

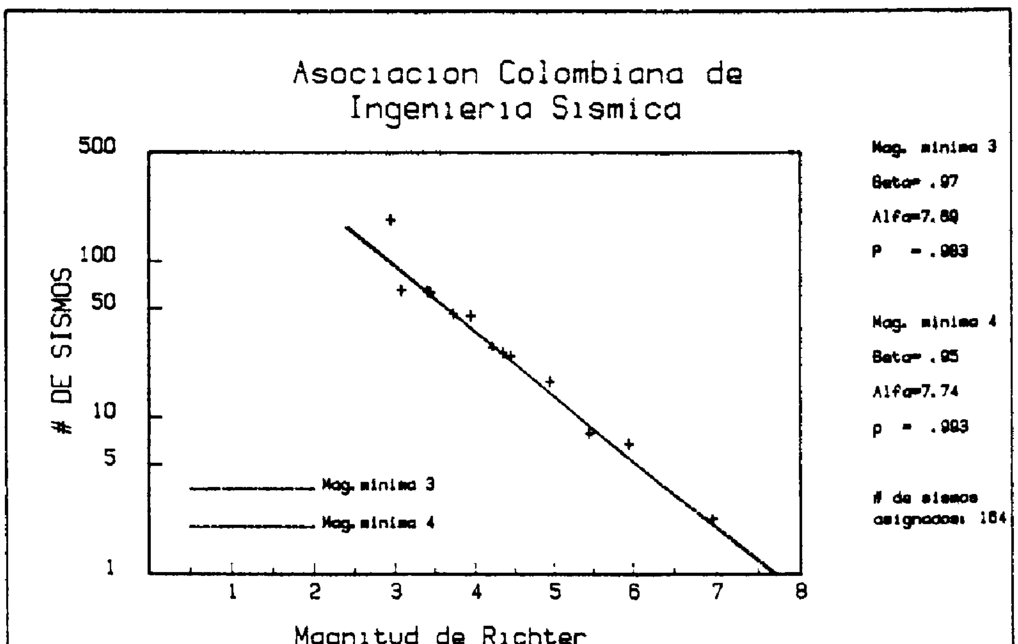
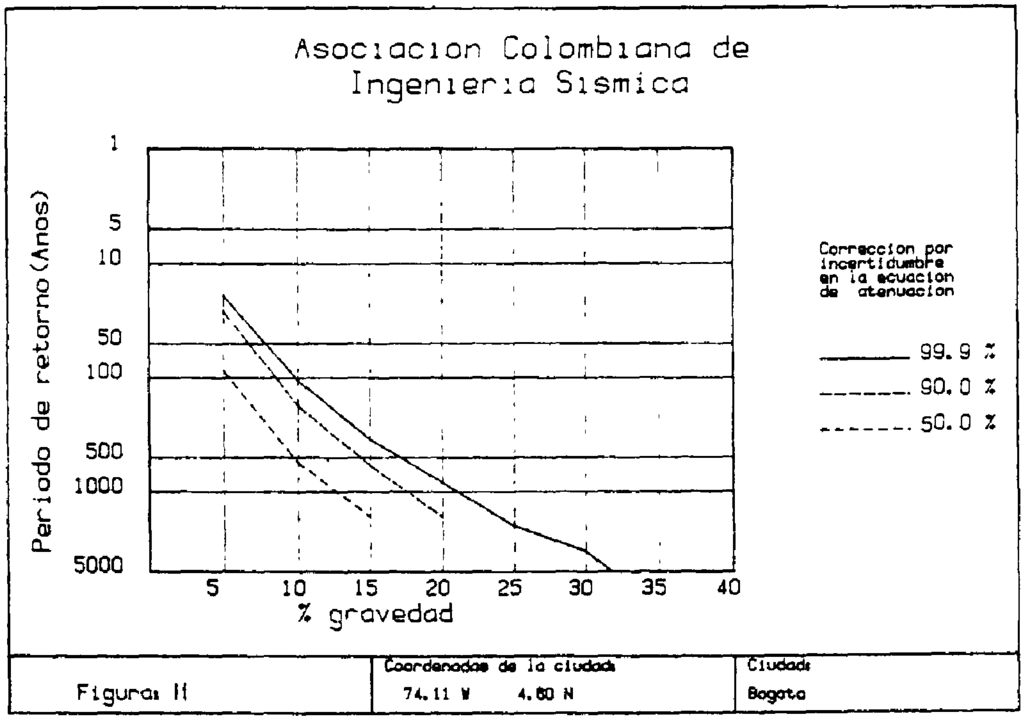
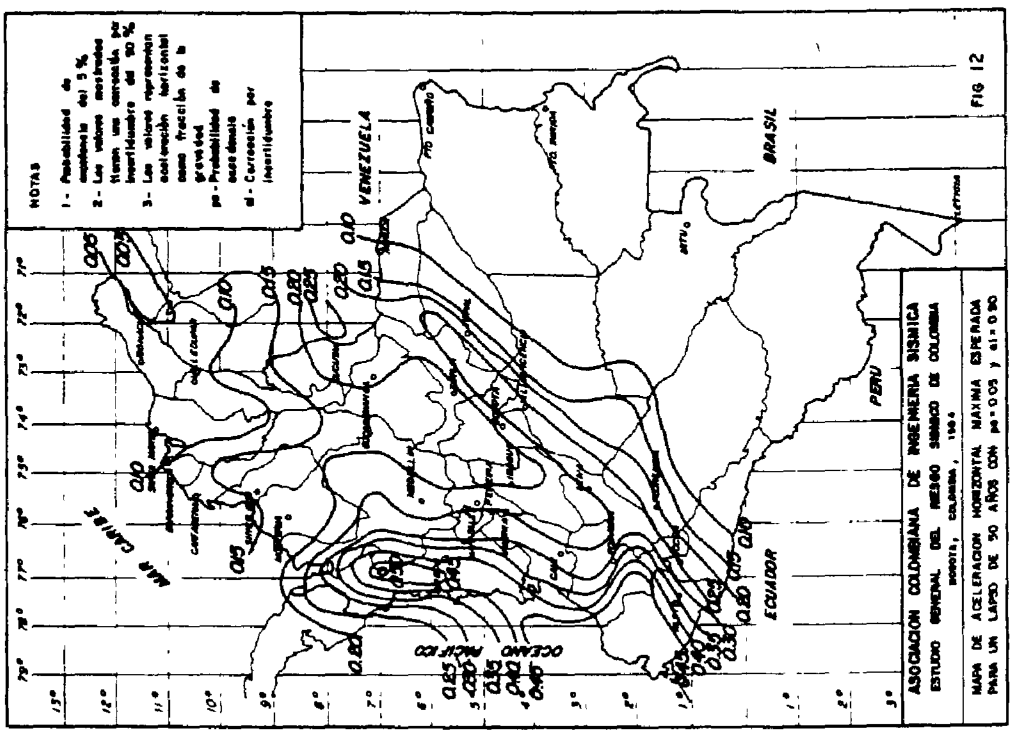


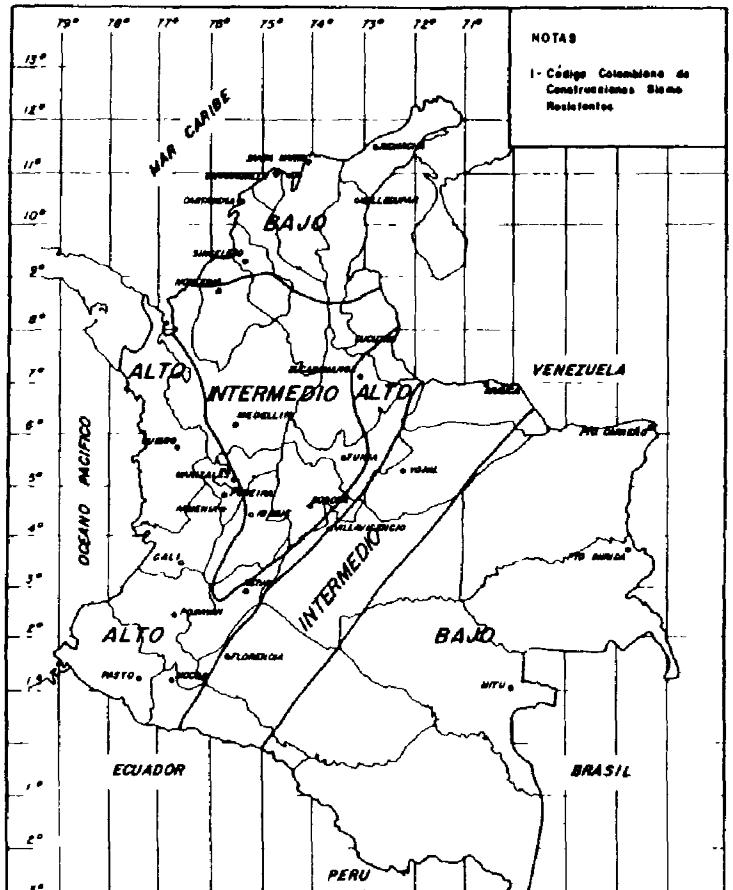
Figura: 10	Datos recolectados a partir de: 01/01/1566	Temblores asignados a falla: ROMERAL



Asociacion Colombiana de
Ingenieria Sismica
Periodo de retorno (Anos)
1
5
10
50
100
500
1000
5000
5
10
15
20
25
30
35
40
% gravedad
Correccion por incertidumbre en la ecuacion de atenuacion
99.9 %
90.0 %
50.0 %
Figura: 11
Coordenadas de la ciudad
74.11 W 4.60 N
Ciudad:
Bogota



NOTAS
VENEZUELA
BRASIL
PERU
ECUADOR
OCEANO PACIFICO
MAR CARIBE
ASOCIACION COLOMBIANA DE INGENIERIA SISMICA
ESTUDIO GENERAL DEL RIESGO SISMICO DE COLOMBIA
MAPA DE ACELERACION HORIZONTAL MAXIMA ESPERADA
FIG 12



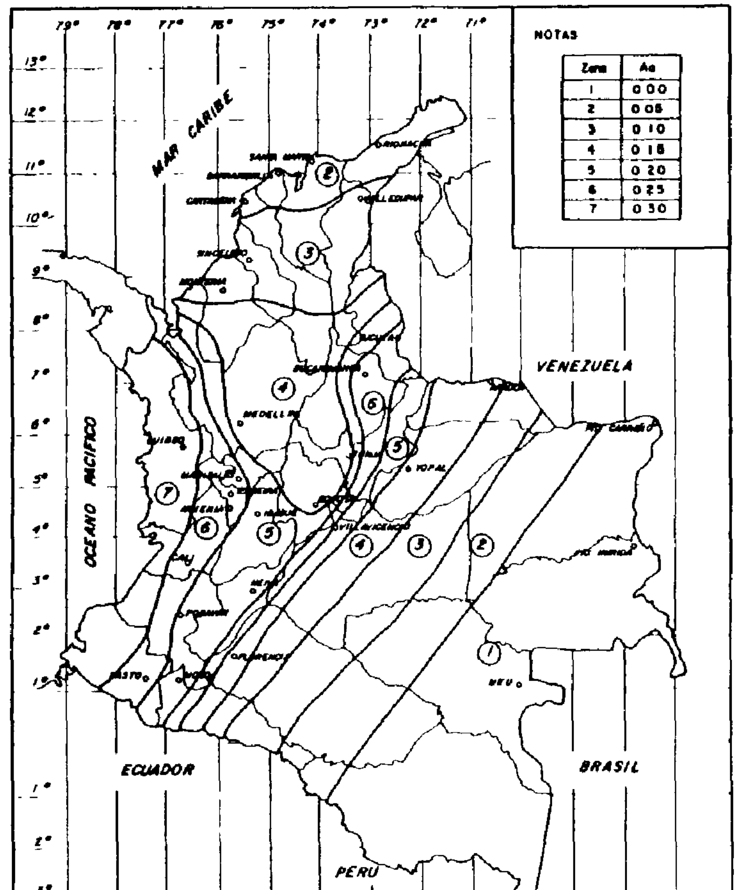
NOTAS

1- Código Colombiano de Construcciones Sismo Resistentes

ASOCIACION COLOMBIANA DE INGENIERIA SISMICA
ESTUDIO GENERAL DEL RIESGO SISMICO DE COLOMBIA
BOGOTA, COLOMBIA, 1984

ZONAS DE RIESGO SISMICO DEL CODIGO COLOMBIANO DE CONSTRUCCIONES SISMORESISTENTES DECRETO 1400 DE 1984

FIG 13



NOTAS

Zona	Aa
1	0.00
2	0.05
3	0.10
4	0.15
5	0.20
6	0.25
7	0.30

ASOCIACION COLOMBIANA DE INGENIERIA SISMICA
ESTUDIO GENERAL DEL RIESGO SISMICO DE COLOMBIA
BOGOTA, COLOMBIA, 1984

MAPA DE VALORES DE Aa CODIGO COLOMBIANO DE CONSTRUCCIONES SISMORESISTENTES DECRETO 1400 DE JUNIO 7 DE 1984

FIG 14