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# SEISMIC MICROZONATION OF LIMA CITY AND EL CALLAO PROVINCE, PERU

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## *Abstract*

The location of Lima city and El Callao Province over the Pacific Ring of Fire and the long history of seismic activity in these places were the main reasons to develop a seismic microzonation study. This study is based on the results of a geological, geotechnical and geophysical exploration. Geology allowed identifying areas with potential rockfall over the hills that surround Lima. The geotechnical exploration consisted of carrying out SPT and drilling boreholes to obtain soil samples which were later tested in a geotechnical laboratory; the results allowed determining the soil mechanical characteristics and consequently identifying their resistance and performance as a foundation material. The geophysical exploration consisted of one-point microtremor measurements, array measurements, MASW and refraction tests, which allowed to find the natural period of vibration, and the P and S-wave velocity profiles, which lead us to know the dynamical characteristics of the soils.

The results obtained from the geology, the geotechnical and geophysical exploration were combined to develop various maps, such as the soil distribution map, the isoperiod map, and the seismic microzonation map for Lima city and El Callao Province. This last map shows five zones, where the zone with the best soil mechanical and dynamic characteristics covers most of the study area.

*Keywords: Borehole tests, Microtremor, S-wave velocity profile, Microzonation map*

## 1. Introduction

Lima city and Callao, the capital and the Constitutional Province of Peru respectively, are constantly exposed to earthquakes due to their location in the circum-Pacific seismic belt. The last large seismic event in the city occurred in 1974, when an earthquake of magnitude Mw 8.0 hit the coast of Lima and Callao, causing severe damage in the buildings of Callao, Chorrillos, La Punta and the La Molina districts. The damage was related to amplification of incident seismic waves by the local surface-soil conditions and the depth of the water table.

By the time of the earthquake, few districts were populated; as a result, the seismic response of the non-populated areas remained unknown.

During the last three to four decades, the city started to experience a large urbanization process, which took place in an informal way. In consequence, a large number of houses were built in non-suitable soils from the engineering point of view.

This problem was regarded to informality, to the indecision of local authorities, and to the lack of a detailed seismic microzoning studies.

The first seismic microzoning study in the area dates from 1991, when Huaman developed a map for La Punta and El Callao districts. This study consisted of geotechnical exploration by borehole tests and single point microtremor measurements.

From 2003 to 2005, CISMID was in charge of developing a microzoning study in forty-two districts of Lima and Callao. New technology and data processing techniques were introduced by that time, such as velocity sensors, specially designed to measure microtremors. The result was a seismic microzoning map of almost all the area of Lima city and Callao.

The resulting map divided the area of study into five zones that describe the geotechnical and dynamic characteristics of soils.

From 2010, an effort to update the microzoning map of Lima and Callao was carried out in the framework of the SATREPS (Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru) Project.

The update of the microzoning map was possible not only by increasing the number of exploration points, but also by introducing various surface wave exploration techniques in order to estimate the S-wave velocity profiles up to the basement rock.

## 2. Seismicity of the study area

Lima city and Callao are the target area of this study. The first one is the capital of Peru, and is located in the central coast of the country; it is also, where approximately one third of the country's population lives. Callao, is the Constitutional Province of Peru, and is located just next to Lima bordering the Pacific Ocean.

Currently, Lima city and Callao together are divided in forty nine districts; the majority of which belong to Lima. By this moment, forty three districts out of forty nine districts were studied for microzoning purposes.

The most notable earthquakes that affected Lima and Callao from 1523 to 1974 are listed in a technical report [1]. From the list mentioned before, strong ground motion with short and long duration, different intensities, and different frequency content were reported. According to this list, the maximum intensity observed in Lima was X MMI; and the predominant period for central Lima was about 0.1 seconds. Damage was observed in Callao, La Molina and Chorrillos district mainly.

It is important to notice that the last strong earthquake reported in Lima was the October 03, 1974; and that since then, more than thirty years have passed, increasing the probability of a seismic event occurrence. According to Pulido et al [2] a Mw 8.9 earthquake is expected to occur in central coast of Peru that will hit directly to Lima City.

## 3. Geology and Geomorphology

The geology of the Lima region reflects the subduction of the Nazca Plate under the South American Plate, and the consequent uplift and volcanic activity [3].

Sedimentary and intrusive rocks, as well as, unconsolidated deposits are part of the geologic units of Lima.

Rocks of sedimentary-volcanic origin, placed during the Late Jurassic to Cretaceous periods, are found mainly in the northern part of the city. To the East, parallel to the coast, intrusive rocks that belong to the coastal batholith spread as pulsations forming individual bodies of magmatic mass.

The unconsolidated deposits are from the quaternary period, and consist of alluvial, colluvial, marine and eolian deposits. Fig. 1 shows that the majority of the metropolitan area is built on the alluvial deposit that was originated by the Chillon and Rimac rivers, that eroded, transported and deposited the sediments in their path. The alluvial deposits consist of gravel, with boulders of 20cm in the center of the city and of up to 60cm in the east. The sand as well as the silt-clay material creates lenses within the gravels. Occasionally, isolated areas of organic soil of more than two meters depth appears. Along the coastal cliffs the poor horizontal stratification of the debris can be observed through the effects of erosion.

The depth of the alluvial deposits can be expected to be from 400 to 600 m for the area of the alluvial cone of the Chillon River; and the depth of the alluvial deposit from the Rimac River is about 200m.

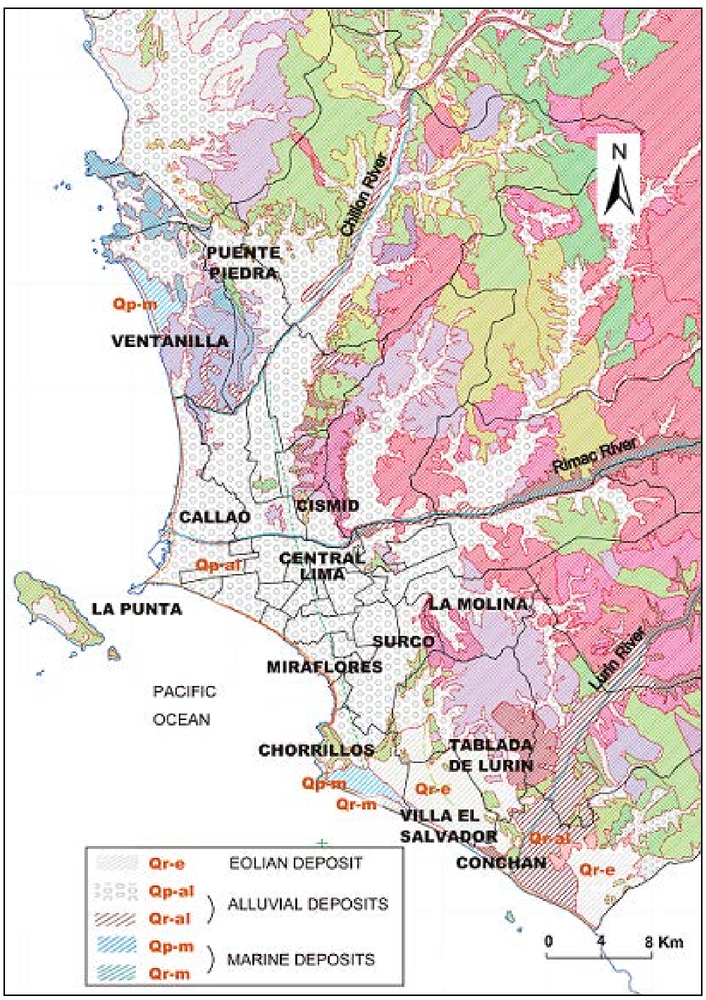


**Fig. 1** Geology of Lima [4] and [5]

Besides the alluvial deposits, there are also marine deposits. These are relatively new-sand deposits, created through the erosive action of the ocean's waves and currents. Furthermore, the more recent eolian deposits are generally found in the areas of the alluvial cones of the Rimac and Chillon rivers [6].

## 4. Geotechnical Aspects

In order to evaluate the geotechnical characteristics of the foundation soil at Lima city, exploration campaigns were carried out. The campaigns consisted of direct exploration through borehole tests.

Soil samples were taken during the exploration and sent to a geotechnical laboratory where various tests were conducted. The results allowed describing soil profiles that define the conditions of specific areas.

### 3.1 Soil exploration campaigns

Information regarding the soil profile of Lima city was collected from different sources. The main sources were engineering consulting companies that developed geotechnical studies in the districts. The National Water and Sewer Company was another source.

In addition to the gathered information, exploration campaigns were performed. The campaigns were carried out by districts, and the type of exploration was decided based on the soil conditions of the site.

In the majority of the districts, pits were enough to explore the subsurface. The average depth reached by conducting these pits was 3m.

In the districts with surficial loose sand, borehole tests were conducted. The maximum depth was not higher than 10m.

### 3.2 Laboratory tests

The soil samples obtained from the soil exploration were tested in a geotechnical laboratory. Standard and special tests were carried out with the samples; the type of test was chosen according to the soil characteristics found in the visual inspection during the soil exploration. Standard tests were applied to disturbed samples following the Unified Soil Classification System (USCS).

### 3.3 Material types

Based on the information obtained from previous collected studies, field exploration, and from the results of the soil tests, the area of Lima city and Callao was divided according to the soil types with similar geotechnical characteristics.

The material types considered for the division are rock, gravel, sand, silt and clays, and debris and landfill, as can be seen in the Soil Distribution Map of Fig.2.

From the map of Fig. 2 some comments can be made regarding the soil distribution at Lima and Callao.

For example, an alluvial gravel deposit which is composed of a medium to dense coarse gravel with a sandy matrix covers most of the area of Lima. Boulders and pebbles are also part of the deposit. These materials are mostly from the alluvial fan of the Rimac River; except in the districts of Ventanilla, Carabayllo, Comas, Los Olivos, and the northern area of the El Callao and San Martin de Porres districts, where the materials forming the soil deposits are from the Chillon River.

Besides the gravel deposits, there are silty sand deposits situated mainly in the northern districts of Puente Piedra, Comas and Carabayllo; and in the eastern districts of La Molina and Ate Vitarte. This deposit was reported until four meters depth in Puente Piedra (which was the maximum exploration depth), and until around three meters depth in Ate Vitarte, in both sites the deposit overlays a gravel deposit.

Clayey and organic soil deposits were found in a large extension of El Callao district, with a maximum depth of fifteen meters. Swampy soil deposits were identified in Chorrillos and Ventanilla district.

Finally, another important deposit is the eolian sand deposit which covers most of Villa El Salvador and a large area of Ventanilla district. The difference between the sand deposits in Villa El Salvador and Ventanilla is the topography, while in the first district the sands were deposited mainly in a mild slope area, in Ventanilla the sands were deposited over the hills of the Pachacutec locality.

The fact of being over the hills suggests that the thickness of this sand deposit is smaller than in Villa El Salvador, where the sands were found until the maximum exploration depth of 8 meters.

It is worthy to point out that there are some landfill and waste fill areas with depths from 2 to 20 meters in the districts of Surquillo, Rimac, San Juan de Lurigancho, Central Lima (Rimac River borders, Alfonso Ugarte Av. among other places), and San Juan de Miraflores. These landfills were also found in the cliffs of La Perla, San Miguel, Magdalena del Mar, San Isidro, and Miraflores districts.

The landfills originated from old ground removal made with the purpose of construction materials extraction or waste disposal. Although the size of these fills is limited, their presence involves serious problems to the structures founded on it.

The rock basement is found at depths from 100 to 400 meters [6].

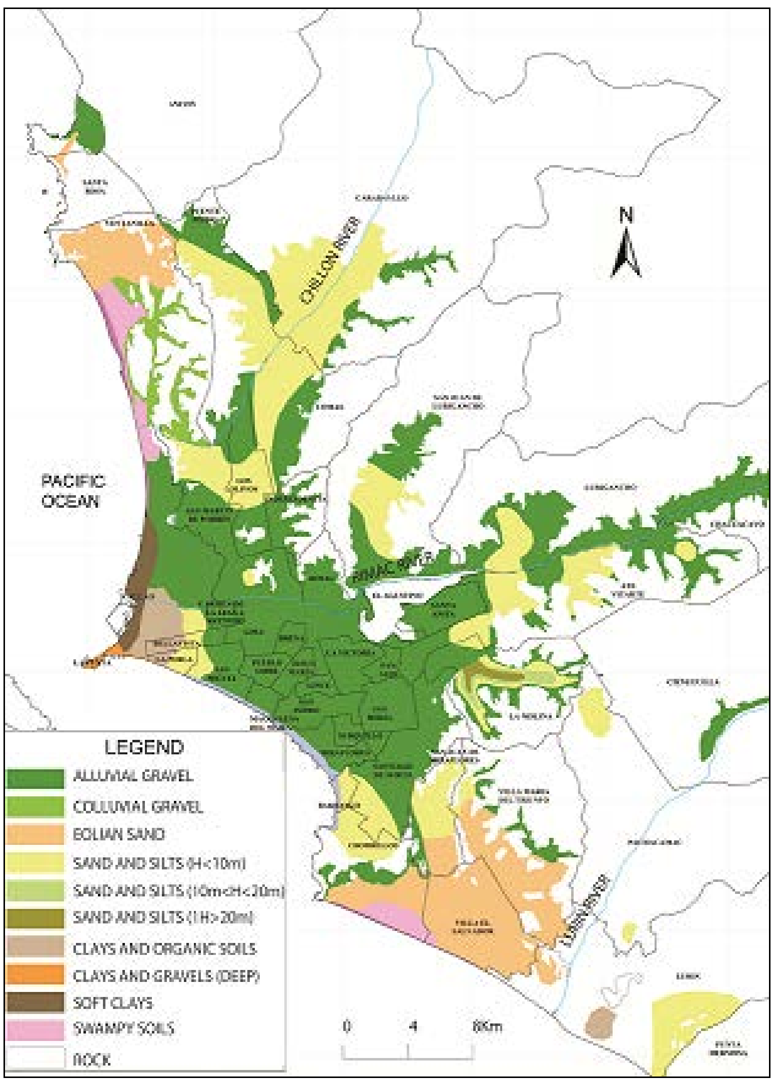


**Fig. 2** Soil Distribution Map [6]

### 3.3 Geotechnical Microzonation Map

The area of Lima city was divided in zones according to the geotechnical characteristics of the soils. The purpose of this grouping is to develop a map that allows to identify the most convenient and inconvenient zones for soil foundation of common structures.

The allowable bearing capacity was estimated at each zone. This parameter was calculated for a typical building with a strip foundation of 0.60m width and with a minimum foundation depth of 0.80m. The bearing capacity theory proposed by Terzaghi was applied with the bearing capacity factors proposed by Vesic.

In all the zones, foundations must rest over the natural soil deposits and not over landfills.

## 5. Dynamic Characteristics

The dynamic analysis of the soils is a fundamental tool in the microzoning study because it allows determining the seismic soil response.

### 5.1 Calculation of the Fundamental Period of vibration

The period of vibration is a dynamic parameter that defines the seismic soil response.

Researchers agree that the fundamental period of vibration of the soils can be determined by microtremor measurements. Microtremors are defined as ambient or noise vibration [7] and [8]. These vibrations contain Rayleigh and Love waves that are affected by the geological structure of the site where they are measured [9].

In 1989, Nakamura [10] developed a method to calculate the fundamental period of vibration of soils from microtremor records. The method, often called the H/V spectrum method, consists of the division of the horizontal Fourier component with the vertical Fourier component. The fundamental period is the period correspondent to the maximum value of the H/V spectrum.

#### 5.1.1. One-Point Microtremor Measurement Campaigns

The first attempts to measure microtremors in the study area started in 1991, when Huaman conducted surveys in El Callao district [11].

From 2003 to 2005 CISMID carried out microtremors measurement campaigns massively in the study as part of the microzoning project APESEG.

Finally, from 2010 up to now, in the framework of the SATREPS Project, a more detailed measurement campaign was carried out by CISMID; the campaign consisted in increasing the number of measurement points in the study area.

The equipment used in the measurement campaigns is a velocity sensor CR 4.5-1S, which natural period is one second, with the data acquisition system GEODAS 15HS manufactured by Anet Co., Ltd. (Photo 1).

The measurements are performed over the soil surface, using high sensitive sensors. Velocities of microtremors are recorded and then stored digitally for data processing.

Currently, around one thousand four hundreds of one-point microtremors were measured in the city. The fundamental period in the study area ranges from less than 0.1 to 1.2s. Fig. 3 shows the distribution of the one-point microtremor measurements.

**Photo 1.** Microtremor Measurement

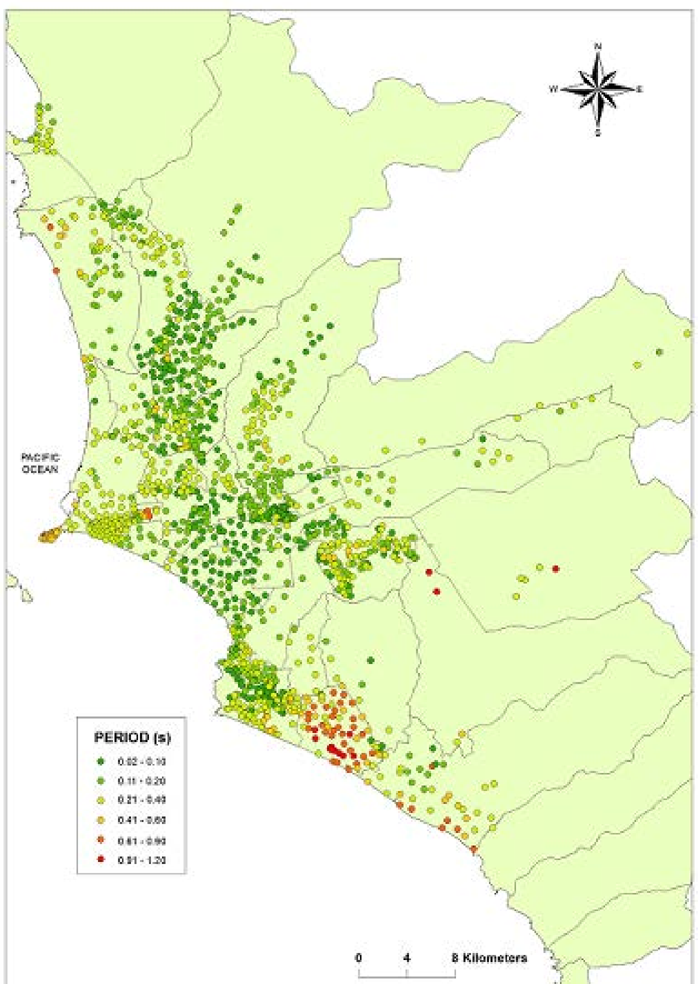


**Fig. 3** Distribution of One-Point Microtremor measurements

### 5.2 Estimation of the S-wave Velocity Profile

In addition to the predominant period of vibration, the S-wave velocity profile defines the seismic response of the soil structure in the study area.

There are many techniques to estimate the S-wave velocity profile. In this study, we had used the MASW, the microtremor array, and the P-S logging test.

These methods are based on observing the wave propagation through the soil structure. For the MASW and the microtremor array test, surface waves are measured, while for the P-S wave logging test the P and S-waves are measured directly.

The analysis followed in the MASW and microtremor array tests consists on computing a dispersion curve of Rayleigh waves, which is then inverted in order to obtain the S-wave velocity structure.

The analysis for the P-S wave logging test is different, it consists of identifying the first arrival time of the P and S waves, so that the velocity can be computed at each depth where the sensor is placed.

Small and large microtremor array measurements were conducted in places like Central Lima, Callao, Puente Piedra, Villa El Salvador, La Molina, Ventanilla district among others [12]. Photo 2 shows an array measurement in Ventanilla district.

In Central Lima, high velocity values were found at shallow depths, meaning that soils have a rigid dynamic behavior. On the contrary, in Callao and Villa El Salvador, thick layers with medium velocity values were identified. These layers are associated with the long periods observed there.

## 6. Seismic Microzonation Map

Based on the geotechnical and the dynamic characteristics of the soils, the area of study was divided into five zones. The map showing the zones is called the seismic microzoning map (Fig.4). The description of each zone is mentioned below.

*Zone 1*

This zone includes the rock formations with different fracturing degree that form the hills. The dense to very dense gravel and sand deposits are also considered in this zone; as well as, the hard and very hard silt and clay deposits.

**Photo 2.** Microtremor Array Test in the Ventanilla district

The different types of materials described in this zone show the best geotechnical characteristics for building foundation.

The allowable bearing capacity in this zone, for a strip foundation of 0.60m width varies between 196 and 392 kPa, if it lies over the gravel at a minimum depth of 0.80m; and it is more than 491 kPa if the foundation lies over a slightly fractured rock at a minimum depth of 0.40m. If the foundation rests on the sand, silt or clay deposit, it is suggested to take values around 196 kPa.

The period of vibration in this zone is less than 0.3s.

*Zone 2*

This zone includes the medium dense to dense sand deposits, and, the medium stiff silt and clay deposits.

Additionally, the areas with medium geologic hazard that are found in the hillside and in the small hills of Los Olivos district, where potential landfill instability is probably to occur in a seismic event, are included.

The types of soils described in this zone show good geotechnical characteristics for foundation purposes.

The allowable bearing capacity in this zone, for a strip foundation of 0.60m width and at a minimum depth of 0.80m, varies between 98 and 294 kPa, if it lies over the sand and it varies between 69 and 98 kPa if the foundation lies over the silt or clay deposits.

The period of vibration in this zone is less than 0.4s.

*Zone 3*

This zone includes the loose to medium dense sand deposits, and the soft to firm clay and silt deposits.

The type of soils described in this zone show bad geotechnical characteristics for building foundation.

The allowable bearing capacity in this zone for a spread foundation of 0.60m width and between 1.0 and 1.5m deep varies between 49 and 98 kPa. The natural period of vibration in this zone is longer than 0.4s.

*Zone 4*

This zone includes marine and eolian deposits that comprise loose to very loose sands that are prone to liquefaction, and swampy soil deposits with long periods of vibration.

Steep slope hills prone to suffer external geodynamic phenomena such as rock block falling are also considered in this zone.

*Zone 5*

This zone includes the debris and waste materials identified at isolated points of the city, and old mining excavations.

According to the Peruvian National Standard E-050 Soil and Foundations [1997], in this zone, building construction is not allowed since the material shows a bad seismic response, and it is not possible to estimate the bearing capacity on landfills.

Historical cases have demonstrated that buildings constructed over this kind of soils suffer large settlements and severe damage. If these areas are required for urban development uses, it is suggested the removal of the debris and landfill, and the replacement with suitable materials. The urban development will be possible only if the results of the soil mechanics studies support this decision. Sanitary landfill cannot be considered for urban development.

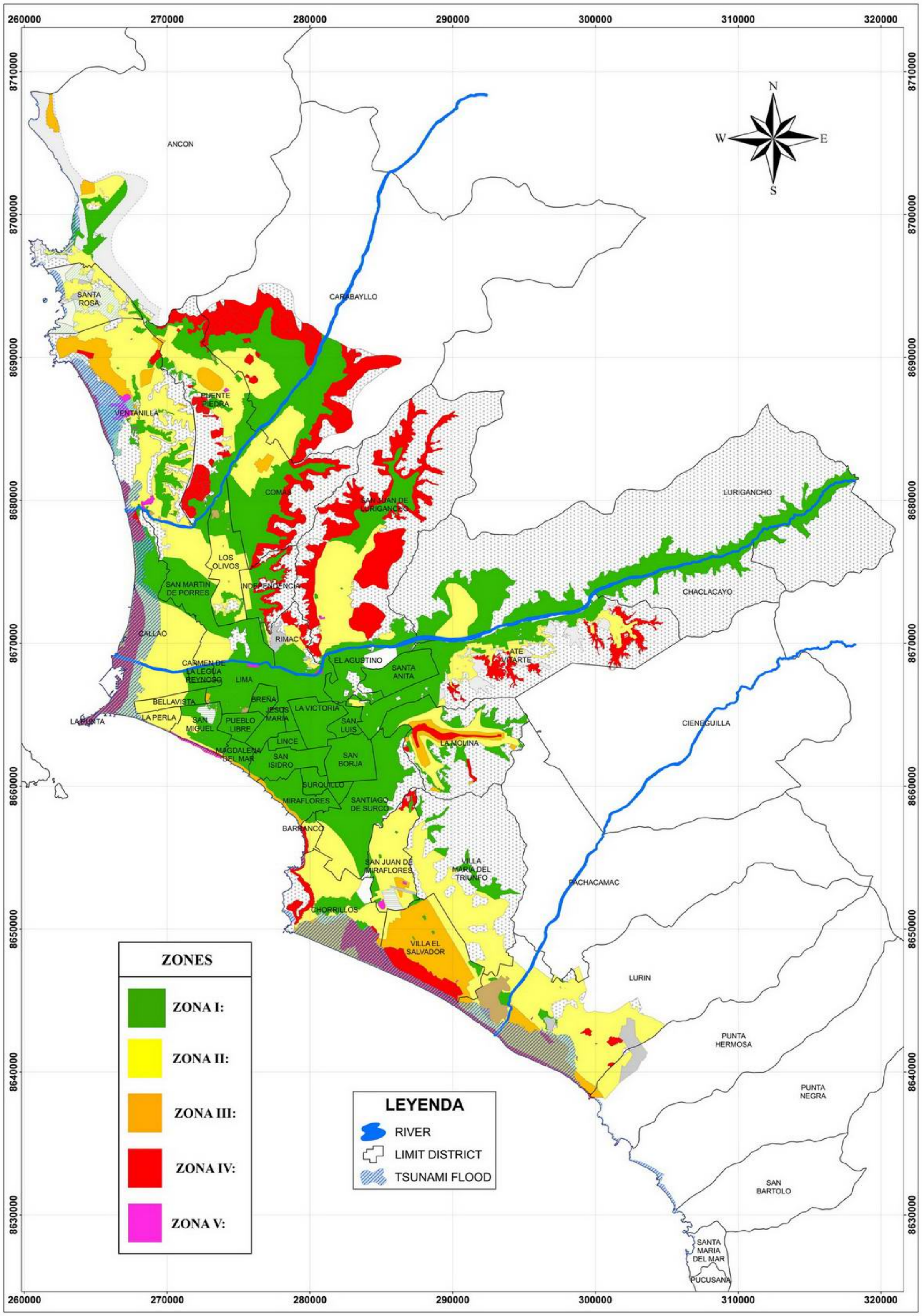


**Fig. 4** Seismic Microzonation Map

## 7. Conclusions

a) At Lima, the alluvial gravel, composed of a medium to dense coarse gravel with a sandy matrix covers most of the area of the city. This soil shows high allowable bearing capacity for foundation purposes.

b) At Callao, on the other hand, clayey, organic, and sandy deposits predominate. These deposits were found until the maximum exploration depth of fifteen meters.

c) The S-wave velocity profile obtained at Central Lima city shows that the soil is rigid below few meters depth. The short values of the fundamental period of vibration support this rigid characteristic.

d) The most flexible soils are located in El Callao, and Villa El Salvador district, where long period of vibrations were observed.

e) The area of study was divided into five zones according to their geotechnical and dynamic characteristics.

f) Zone 1 covers most of the area of study and shows the best geotechnical and dynamic characteristics.

g) Zone 2 shows good geotechnical characteristics. However, areas with potential landfill instability during a seismic event were identified in this zone.

h) Zone 3 is made up of soils with large periods of vibration, which is associated with bad geotechnical characteristics.

i) Zone 4 includes areas covered by problematic soils. Therefore, according to the Peruvian National Standard E-050 Soil and Foundations [1997] any construction project must have a specific geotechnical study.

j) Zone 5 is identified at specific places, and building construction in this zone will be possible only if landfill is removed and technical studies support this decision.

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