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Evaluation of seismic risk on water supply pipelines

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ABSTRACT: An approach to evaluate seismic risk on main water pipelines is presented. The trunk network of water supply system in Lima City has been selected to be analyzed. Earthquake hazard analysis is performed to obtain expected values of peak ground accelerations which are used to scale an accelerogram of a severe earthquake occurred in the region. A procedure to determine soil amplification is proposed by using first, microtremor measurements to estimate predominant periods of soil profiles along the main water pipelines and second, scaled accelerogram as input to compute soil profiles responses in critical zones. A soil pipe model is developed to be used in evaluating its seismic response and to estimate critical extension in longitudinal direction of pipelines as a measure of seismic risk.

1 INTRODUCTION

Recent past earthquakes have provided valuable information on the performance of water pipelines. Damage distribution indicate that it most often occurs at the pipelines joints. Observation of modes of failure shows that extension in longitudinal direction is a major mode of failure. O'Rourke et al (1988) have described serious consequences of this mode of failure as a result of the 1985 Michoacan earthquake in Mexico where approximately 3.5 million residents of Mexico City were left without running water due to a high number of leaks in pipelines caused by seismic wave propagation effects. Other example of this mode failure occurred as a result of the 1970 Ancash earthquake in Peru, a great portion of the water supply system of Chimbote was severely damaged and its reconstruction lasted several months. Buried pipelines are a kind of underground chain structure under control of surrounding soil medium. There are three major causes of earthquake hazards to embedded pipelines: a) Soil liquefaction produced by ground vibration, b) Ground dislocation or rupture caused by fault movement, and c) straining in soils induced by seismic wave propagation. Effects of the first two causes are localized and avoidance of liquefaction areas and crossing active faults may be possible. In this study ground vibration effects on pipelines displacement are evaluated, and characteristics of soils and water pipelines system of Lima City are used to estimate its response behavior.

2 EARTHQUAKE HAZARD ASSESSMENT

In the evaluation of seismic risk of structures and lifelines systems, it is required to analyze the seismic hazard of the region, in particular, for selected sites (vicinity of water treatment plant, booster pump stations, reservoirs, etc). It means to study previously the seismicity, the seismic characteristics of sources and to adopt an appropiate attenuation equation for wave propagation.

The methodology developed by Cornell (1968) and Mc. Guire (1974) to perform probabilistic evaluation of the earthquake hazard has been found to be appropiate in several recent studies in Peru, and will be used in this paper. In the last decades, evaluations of seismicity and characteristics of Peruvian earthquakes have been carried out by Casaverde (1979) and Alva et al (1982). The seismogenic sources defined by Casaverde (1980) and their geographical limits are utilized in the present study. The seismogenic sources determination is based on the epicentral distribution map and the tectonic characteristics of the influenced area. Most of the seismic activity in the country is generated by the interaction of the Nazca Plate that penetrates beneath the South America Plate at variable angles.

There exists historical earthquake data prior to 1963 for the region under study. Information in Catalogues: USGS, and NOAA about seismic magnitudes, Ms, and focal depths are incomplete until 1963. Information and data since then up to date have been used to carry out the statitiscal analysis of seismic recurrence which is based on the known formula established by Richter.

Most of the empirical attenuation equations mainly define a relationship of a ground motion parameter as a function of magnitude, hypocentral distance, and earthquake duration. With the purpose to obtain the seismic response of main pipelines, the peak ground acceleration has been selected as a probabilistic variable; it is usually assumed to be lognormally

distributed.
An attenuation equation for peak acceleration established by Vargas (1979) will be used in this paper. This is:

$$a= 68.7\, e^{0.8Ms}\, (R+25)^{-1.0}\ cm/sec^2 \quad (1)$$

Where Ms is the magnitude for surface waves, and R is the hypocentral distance in Km. Due to a limited number of severe earthquake records available, this expression was obtained by using data of 10 Peruvian accelerograms registered for horizontal components. The seismic events were registered by the Geophysical Institute of Peru in three different places of the Lima Metropolitan Area. It should be noted than Peruvian earthquakes attenuate with the distance lesser than earthquakes occurred in other latitudes.
The probabilities of occurence of a seismic event whose peak acceleration is equal or larger than certain expected values are calculated. Evaluating these probabilities for different sites in a region, a map containing curves of expected accelerations of equal return period can be drawn. A map of Lima with these curves for return periods of 100 and 500 years is represented in Figure 1. Also, a table with these values for a selected site in the vicinity of the Water Treatment Plant (77° W, 12° S) is listed below.

Return Period (Years)	a (cm/sec2)
50	277
100	353
500	593

3 SOIL AMPLIFICATION

Seismic waves propagate mainly through the earth crust. By earthquake hazard analysis, expected values for peak accelerations of ground motions have been evaluated at bedrock level for selected sites. Characteristics of seismic waves are modified when propagate from bedrock through subsoil layers. They usually experiment an amplification in intensity and changes in their frequencies.
Lima City is located on the western coast of South America, on a desertic strip between the Pacific Ocean and the Andean Mountains. It is placed on a fluvio-alluvial deposit of variable characteristics corresponding to the debris cone of Rimac River which comes down from the Andean Range to the Pacific Ocean. The material of the subsoil is mainly a conglomerate of boulders, gravel, and sand in loose-to-compact state and interlayered by fine-to-medium sands, clays, and silts. There are also deposits of eolian and marine sands at the north and south in areas near the sea border. Fine soils are found in La Punta, Callao, Chorrillos and Cono Sur districts.
The theory of unidimensional shear wave propagation through soil layers from bedrock to a selected level is used to determine soil amplification. The amplification analysis has been performed by using the computer program PC-Shake developed by Schnabel et al (1972).
The accelerogram of the component N82W of the earthquake occurred in October 3,1974 was selected to be analyzed. The accelerogram was registered in a place of Lima downtwn. This earthquake with a magnitude mb=6.6 had its epicenter approximately 80 Km west from Lima. The accelerogram has been scaled to have the maximum acceleration equal to 0.35g., which corresponds to the expected peak acceleration for a return period of 100 years. Also, it has been considered a duration of 60 sec. from a total time registered of 90 seconds.
Alva et al (1991) have studied seismic microzonation in several districts of Lima. Results of this study have been considered to select critical zones along main water pipelines. The dynamic amplification analysis has been performed for 4 idealized soil profiles corresponding to selected places in La Punta, Callao, Chorrillos and Cono Sur districts. Surface fills of soft soils have variable depths in these profiles. A map containing critical zones and the main water pipelines network is shown in Figure 2.
Microtremor technique has been used to determine predominant periods of soils. Microtremor is defined as the natural vibration of the ground with a period ranging from 0.05 to 2. sec. and an amplitude ranging from 0.1 to 1 micron. A very sensitive instrument is employed to detect such a vibration generated by natural and artificial causes. During measurement, displacements in two perpendicular horizontal and vertical directions are recorded. The predominant period assigned to one site is the result of averaging the two predominant periods obtained from the two perpendicular horizontal directions.
Mean values for natural periods in selected places have been found ranging from 0.20 to 0.50 sec. The bedrock in this profiles has been assumed to be the firm conglomerate formed by alluvial deposits of Rimac River with a Vs equal to 600 m/sec.
Besides the input excitation data and soil profile characteristics, discrete values of shear modulus, G, and damping factors variations are required to compute the soil dynamic amplification. These values have been estimated from variation curves based on studies of clays and sands by Seed and Idriss (1984).
The analysis results shows the following characteristics:

1. The dynamic amplification of max. acceleration varies from 0.35g at bedrock level to the following values at surface levels of analyzed soil profiles: 0.30g, 0.45g, 0.63g, and 0.66g at La Punta, Callao, Chorrillos, and Cono Sur districts, respectively.
2. Mean square value of frequencies decreses from 5.35 hertz in the original accelerogram to 2.38 hertz as an average value at surface level of soil profiles. This result is because high frequencies of shear waves are filtered when they propagate through soft soils.

Natural periods of excited soil profiles have increased respect to values obtained by microtremor measurement.
In conclusion, several changes have modified the

original accelerogram. Max. accelerations and frequencies content have varied significantly. This accelerogram will be used to evaluate seismic response of main water pipelines network at selected critical places.

4 SEISMIC DISPLACEMENT ALONG PIPELINE AXIS

Most of the extensive seismic damage to buried pipelines in Mexico City, Chimbote and other cities appears to have been due to seismic wave propagation which induce straining in soils. In the case city and surrounding zones. There are some saturated sand deposits in areas near La Punta district and Callao port and liquefaction damage may be expected, however those branches of water pipelines system are rather small and pipe diameters are lesser than 25 cm. This study concentrates on seismic response of buried pipelines due to wave propagation.

In the last 20 years, the expansion rate of Lima City has been very fast, more than 4% per year, reaching at the present time a population of about 9 million inhabitants. New human settlements have occupied sites around Metropolitan Lima; most of them are on desertic areas of loose sand deposits. In the last decade, the trunk pipelines network has been extended to these soft soils, having a total length of 6000 km. Besides it has not occurred a strong ground motion since 1974 in Lima.

Because soil strain is close related to wave propagation damage, this is heavier in soft or transition zones than in firm soil and tends to be greater for brittle than to ductile materials.

Due to the primary dependance of wave propagation damage on soil strains, it can be stated. That there is a certain limit in the total length of a pipeline to avoid its failure given the soil strain level and mechanical properties of the pipeline.

Buried pipelines are usually assumed as a sort of under ground chain structure, characteristics of soils and pipelines have been studied and soil pipe models have been developed by Wang (1988), Shinozuka (1984) and others, to evaluate their response and behavior under seismic loading.

The model shown in Figure 3 is proposed to represent the soil-pipe interaction. The surrounding soil is represented by axial and lateral spring sliders they support the pipe and transmit ground vibration to it. Although there are axial and rotational rigidities in the joints, they are assumed free to rotate and slide an allowed relative displacement. The pipe segment is modeled as a beam element. There is not available information to determine dinamic values for friction coefficients of soils to be used in calculating soil spring sliders.

Bowles (1982) has investigated the static values for modules of subgrade reaction in footings and lateral supported piles. This modulus mainly depends on elastic modulus and footing width. Axial soil spring sliders have been assumed to vary with shear modulus. They can be approximately calculated by the expressions:

$$K = 0.35\, K_s\, A_l$$

Where K_s and A_l represent the modulus of subgrade reaction and lateral area of the pipes respectively, considering a value for Poisson ratio equal to 0.4. A value of $K_s = 4.8$ N/cm^2 for loose sand and $K = 0.17\, A_l$ (Kg/cm) will be used to calculated axial spring sliders in the examples.

The scaled accelerogram obtained by soil amplification analysis has been used to obtain seismic response for several cases in critical zones of the main water pipelines system of Lima.

Pipelines of pretensioned concrete have been used in the trunk network extension. Diameters of the pipelines vary between 1880 mm to 305 mm. and pipe segments are 600 cm. and 300 cm. of length.

Results of maximum relative joint displacement for pretensioned concrete with rubber gas keted joints and 1000 mm. of diameter are given below:

Total length (m.)	Max.D_j(cm)	Period (sec)	Ground Strain
60	0.05	0.14	5×10^{-4}
150	0.40	0.80	6.5×10^{-4}
450	0.90	2.42	8×10^{-4}

Figure 4 shows a curve of max. joint displacement vs. total length of the system.

CONCLUSIONS

A complete procedure has been presented to evaluate soil strain and maximum joint displacements as a measure of seismic risk on pipelines systems. The method used to determine earthquake hazards, soil amplification, and to developed a selected accelerogram has proved to be efficent.

More occurate values for soil springs and rigidities in pipeline joints may be obtained by experimental dymanic test. There is a great deal of research needed on these topics.

Because most of main pipelines system in Lima is oriented in north-south direction, say parallel to the causative fault, seismic wave propagation is assumed perpendicular to pepilines. In order to have more efficient result, orientation of pipelines respect to fault and damage at hard points of the system may be considered.

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REFERENCES

Alva, J.and Torres, R.E. 1982. Seismic risk study of Lima-Ricardo Palma highway. Report prepared to P.

and V. Consultant Engineers. In spanish.

Alva, J., Meneses, J.F., Martinez, J.A. and Huaman, C.E. 1991. Advances on the seismic microzonation of Lima City, Perú. In spanish.

Casaverde, L. and Vargas, J. (1980). Seismic zonation of Perú. II Latin American Seminar on Earthquake Resistant Engineering. Organization of American States and Pontificia Universidad Católica del Perú. Lima, Perú. In spanish.

Casaverde, L. 1979. Seismic risk in Lima region. Published by Pontificia Universidad Católica del Perú. In spanish.

Cornell, C.A. 1968. Engineering seismic risk analysis. Bulletin of the Seismological Society of America. Vol.58, N°5,pp. 503- 1606.

Mc.Guire, R. 1978. Computer Program for seismic risk analysis using faults as earthquake sources. Open-file Report 78-1007, United States Geological Survey.

Vargas, J. 1979. Historical monuments and seismic risk. Seminar on Protection of Monuments in Seismic Areas. Antigua Guatemala.

O'Rourke, M. and El Hmadi, K.1988. Effects of parameter variability on response of buried segmented pipelines. Proceedings of IX World Conference on Earthquake Engineering. Vol. VII pp. 61-66. Tokyo-Kyoto, Japan. 1988.

Schnabel, P., Lismer, J. and Seed, H. 1972. Shake: a computer program for earthquake response analysis *of horizontallly layered sites.* Earthquake Engineering Research Center, Report N. EERC 72-12. College of Engineering, University of California, Berkeley, California.

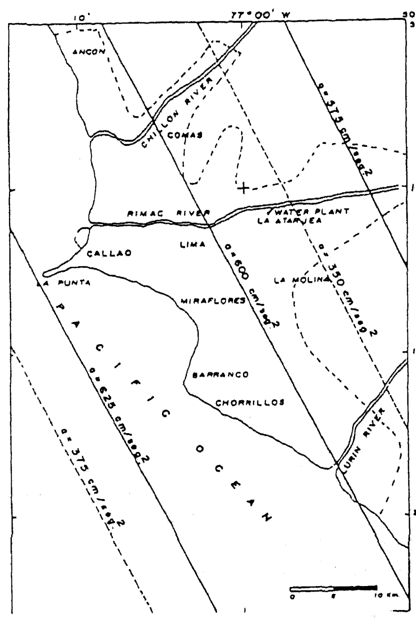

Figure 1. Distribution map of expected accelerations for return periods of 100 years---, and 500 years——

Seed, B., Wong, R., Idriss, I. M., and Tokimatsu, K. 1984. Moduli and damping factors for dinamic analysis of cohesionless soils. Report No.VCB/EERC-84. College of Engineering, University of California, Berkeley, California.

Bowles, J.E. 1982. Foundation analysis and design. Mc.Graw Hill Book Co. New York. 1982.

Shinozuka, M., Kameda, H., and Koike, T. 1983. Ground strain estimation for seismic risk analysis. Journal of Engineering Mechanics. ASCE (1): 175-191.

Wong, L.R.L. and Lau, Y.C. 1988. General elastic responses of buried pipeline systems due to ground wave propagation. Proceedings of IX World Conference on Earthquake Engineering. Vol VII. pp. 73-78. Tokyo-Kyoto. Japan. 1988.

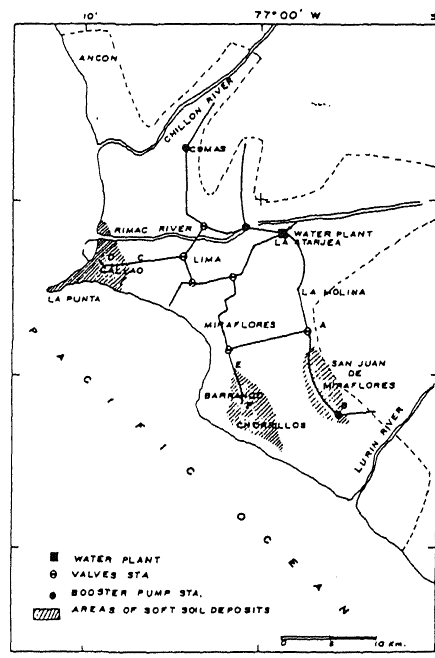

Figure 2. Map of main pipelines in Lima

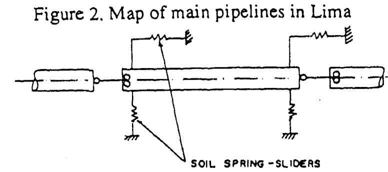

Figure 3. Pipeline model

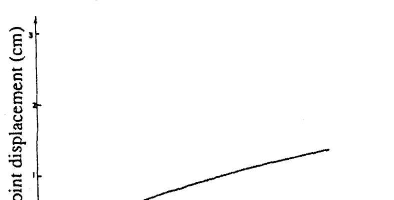

Figura 4. Curve of max joint displacements