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Effects of earthquakes on lifelines: Case History – The El Napo 1987 earthquake

Otton Lara
Escuela Superior Politecnica del Litoral, Guayaquil, Ecuador

ABSTRACT: As known, earthquakes have induced damage and failure of lifelines in several parts of the world. In 1987, the El Napo earthquake induced the failure of the slopes of the El Reventador volcano. The tremendous landslide destroyed 17 Km. of the oil pipeline and severely damaged other 23 Km. of it. Since this pipeline is the nerve of ecuadorian economy a study leading to mitigate the hazard has been performed. The results of the study supports the concept that it will be convenient to change the position of the pipeline from the left bank to the right bank of the Coca river.

1.INTRODUCTION

On March 6, 1987, at 05h 10' 45.5" (GMT) a 6.9 Richter magnitude earthquake shaked theNorth-East area of Ecuador (Figs. 1,2)inducing the collapse of part of the slopes of the El Reventador volcano, 35 Km from the epicenter, 5200 m height, which are conformed by loose volcanic material and topsoil always completely water saturated due to the perennial raining that reaches 4500 mm annualy.

According to observations, Lara, Chavez (1987), the gigantic landslide induced by the earthquake reached the numerous rivers that exist in the slopes of the volcano and in the valleys close to it (Fig. 4), conforming several dams that failed a few hours after the occurence of the main event. These failures triggered an enormous flood debris that destroyed almost every civil work existing in the area, such as roads, bridges, an oil pumping station, and even small towns.

Besides, it induced the vanishing of 17 Km of the only oil pipeline that crosses the country from Lago Agrio in the heart of the oil fields to the oil port of Esmeraldas on the Pacific coast (Figs. 4,5), as well as the complete damage of other 23 Km. Lara, Chavez (1987).

The main earthquake was preceeded by a 6.1 Richter magnitude foreshock and followed by more than 1000 tremors of magnitude 5.5 or less.

The earthquake caused some damage tothe 16th century churches located downtown Quito at about 100 Km from the epicenter of the main event, and to the adobe houses of the Andean region, north of Quito, up to the town of San Gabriel (Fig. 1).

About 1000 human beings died during the earthquake and the economic losses reached 1.5 billion dollars, including the 6 months shut down of the oil exports.

Since there is a continous activity of the volcano, the loose and water saturated material of its steep slopes of are unstable, therefore there is a high likelyhood of repeating a similar disaster if another strong motion should occur. Consequently, studies as the present one directed to mitigate future damage on this lifeline due to earthquakes in the area, are needed.

2. OBJECTIVES

1. To study the dynamic stability of the slopes of the volcano in order to estimate the acceleration that could trigger those slopes unstability.
2. To perform a seismic hazard study of the area to determine the probability of having a similar effect in the future and the return period.
3. To study the structural system that supports the oil pipeline to determine its capacity to the March 6 earthquake.
4. To present possible solutions related either, to the structural system or to the position of the pipeline in order to diminish the potential of damage during future strong motions in the area.

3. SEISMIC SETTING

Ecuador, located towards the North-West part of the South America is bounded by the borders of three tectonic plates: Cocos, Nazca and the South-american plates. The motion mechanism among those plates have induced a large amount of earthquakes as it can be seen in Fig. 7 where registered and historic events have been plotted.

The high seismicity of the area is demonstrated by the numerous events, recorded by the World Network during the present century, with magnitudes larger than 6 (Fig.8) and by the greatest earthquakes recorded along the ecuadorian coast with magnitudes larger than 7 most of them induced by the subduction of the Nazca plate into the South american plate (Fig. 9).

4. TECTONIC SETTING

The very active tectonic enviroment of the epicentral

region is conformed by four fault systems: The N-S, the E-W, the N30 to 40 E and the N40W, plus the El Reventador volcano, Lara, Chavez (1987), (Figs. 3,6).

Of those,the N40W, called the El Reventador-Chota-Mira system which is of the strike slip type of fault, is the most important accident since it crosses the country from the volcano area to Esmeraldas (Figs.3,5,6).

The coordinates of the epicenter of the foreshock and those of the main event, according to the USGS, Espinoza (1987), were plotted on the tectonic setting map (Fig. 6) and coincide with one of the fractures of the El Reventador-Chota-Mira system.

5. LANDSLIDES

According to volcanologic studies, INECEL (1976) there has been, at least, three different phases of the El Reventador volcano during its geological time, each of one generating a volcanic building with different geomorphological characteristics since each explosion induced gigantic landslides nd embankments conformed by volcanic material as it can be seen today in the slopes of the volcano.

This material: sand, ash, slag, etc. is very unstable and water saturated and according to the observations, Lara, Chavez (1987), due to the vibrations induced by the earthquake, part of the slopes of the volcano, conformed by the above described material, sliced into the natural channels of the several rivers existing in the area (Fig. 3), forming natural dams that due to the vibrations of the aftershocks and the water pressure collapsed a few hours after the main earthquake, genera≠ting large waves of water, loose volcanic material, mud, etc., with variable heights between 3 and 10 m that destroyed every civil work located between El Salado river and the town of Lumbaqui (Figs. 2,3,4), as well as the enviroment.

The observed extensions of the flood debriswere (Figs 2,3,4,5), Lara, Chavez (1987): 18 Km on the Salado river that destroyed the oil pumping station and caused damage to theenviroment.

9 Km on the Quijos river, damaging theenviroment, the Lago Agrio-Quito highway, destroying a highway bridge.

50 Km on the Coca river that vanished 17 Kmof the oil pipeline and damaged very severely other 23 Km., damaging the enviroment and almost vanishing the small towns of Santa Rosa, San Rafael and Lumbaqui.

10 Km on the Due river damaging small towns and the enviroment.

12 Km. on the Aguarico river that damaged the highway and destroyed an oil pipeline bridge as well as the enviroment.

6. SLOPE STABILITY ANALYSIS

Using the Algor computer program, Algor (1991), a modeling of the slopes of the El Reventador volcano was performed utilizing the solid element and the material characteristics obtained trough field tests of the collapsed slopes, INECEL (1976). (Fig. 10).

The modeling considered the original geometry of the slopes of the volcano according to measures performed by a vulcanologic team that studies its activity, University of Pisa, (unpublised).

Since the material on the surface is different from that of the interior, different propierties were given to the elements that define each one and are indicated in figure 10.

A time history analysis was performed using a 5.6 magnitude aftershock accelerogram obtained close to the volcano area (Fig. 11) which maximum acceleration reaches .09g.

This accelerogram was later scaled and input in the model, without changing its frequency content, until the collapse of the slopes was obtained with an acceleration of .12g.

The stresses obtained on the surface reached values of the order of 0.17 N/mm2 which are sligthly larger than the maximum shear capacity of the loose soil which is 0.15 N/mm2, according to tests of the material, INECEL (1976). Figure 12 shows the deformed shape of the model of the volcano.

7. OIL PIPELINE CHARACTERISTICS

The trans-ecuadorian oil pipeline is a steel tube 650 mm diameter, 18.4 mm thick and it is supported on tubular steel frames of H form (Fig. 13).

The frames are fixed to a 250 mm thick concrete plate which is in contact with the hard strata located bellow the surface at variable depths, but not less than 2000 mm.

The tubes conforming the H shaped supporting structure are 150 mm. diameter and 10 mm. thick. The supporting structures are located at variable lengths, but not larger than 25000 mm.

8. EARTHQUAKE ANALYSIS OF THE PIPELINE

Using the ALGOR, Algor (1991), computer program a modeling of part of the oil pipeline and its supports was performed.

The charactheristics of the tube were introduced in the program utilizing the pipe element and to model the supports, the soil characteristics were considered so lateral, vertical and rotational springs were added (Fig. 14).

The model was subjected to the above mentioned record normalized to 0.12g (Fig.11).

The results of the dynamic analysis showed that the natural period of the system was 0.08 secs. and that the second period was 0.04 secs. Figs. 15 and 16 show the first and second modes of vibration and Figs. 17 and 18) the maximum displacements of the structural system which reached only about 0.3 mm. The stresses are quite lower than the allowable ones, so no damage could have occurred due to the vibration induced by the earthquake.

9. SEISMIC HAZARD STUDY

Utilizing the Extreme Value Theory, that is, Gumbel I for Magnitudes and Gumbel II for accelerations, as well as the data base provided by the USGS, Espinoza (1987), a seismic hazard analysis of the epicentral area, limited by the meridians 76.7 W y 78.7 W and the

parallels 1.05 N and 1.05 S, has been performed. Fig. 19 shows the epicenters of the earthquakes registered by the USGS, Espinoza (1987), within that area.

The attenuation law used in this study, already obtained by the author, Lara (1984), was corrected, in view of latest events, to the following expression:

$$Ln\ a = 0.63\ M + 6.1 - 1.31\ Ln\ (R+25)$$

Where: a = acceleration, M = Body wave magnitude, R = epicentral distance The seismic hazard study indicated that a 6.9 Richter Magnitude earthquake can be expected every 60 years in the area (Fig. 19) and that for a 10% probability of being exceeded and 50 years lifespan and a return period of 475 years an acceleration of .16g can be expected which results quite larger than the one capable of producing the collapse of the slopes of the volcano according to the studies of slope stability above mentioned. Figure 20 shows the variation of the expected acceleration for different lifespans and for a 10% probability of being exceeded. Note that for this probability and 30 years lifespan, an acceleration of .13g, similar to the one that, according to the dynamic slope stability analysis caused the failure of parts of the slopes of the volcano, can be expected. It should be noted that applying the expression for the attenuation law to the volcano coordinates, 35 Km from the epicenter, a 0.13g acceleration is obtained as the one that struck the slopes of the volcano, value that again is very similar to that obtained in the slope stability analysis as the one that trigered the collapse of part of the slopes of the volcano.

10. POSITION OF THE OIL PIPELINE

On the other hand, there is a continuous activity of the volcano. In the last 32 years there have been eruptions between 1960 and 1961 and between 1974 and 1976, and the eruptive products have deposited in the amphitheatre and in the slopes of the volcano.

Therefore new eruptions are expected during the oil pipeline lifetime which means that new non-cohessive material wil be deposited on the slopes of the volcano which, being saturated, is highly susceptible of failing due to a similar earthquake as that of 1987.

Looking at figures 2,4,5 it is clear that the oil pipeline is located on the left bank of the Quijos-Coca river and therefore subjected to the landslides that can occur due to the vibrations induced by an acceleration larger than about .13g which corresponds, according to the above attenuation law, to a 6.9 magnitude earthquake which return period is 60 years and which probability of being
exceeded is 98.2% (Fig. 21).

Besides, according to the seismic hazard studies, considering 30 years lifespan and 10% probability of excedance, a .13g acceleration can be expected in the volcano area.

Finally considering that there exists important oil deposits in the area, that the oil exploitaition will continue,that the costs involved in a shut down of the oil pipeline are very high: 1.5 billion dollars as of 1987 costs, and that the social costs involved are invaluable, it appears reasonable to change the position of the pipeline to the right bank of the Quijos-Coca river since the river itself would act as a wide channel (200 m wide) where part of the landslide can be deposited.

11. CONCLUSIONS

1. The earthquake analysis of the pipeline clearly prooved that its failure was not induced by the collapse of the supporting structure due to vibrations but, due to the tremendous landslide of parts of the slopes of the El Reventador volcano.
2. The ground acceleration that triggered the landslide that vanished 17 Km of the oil pipeline and damaged other 23 Km of it, was between .12 and .13g.
3. The very active tectonic enviroment of the east part of Ecuador could trigger a 6.8 earthquake, every 60 years.
4. Considering 30 years lifespan, an acceleration of .13g which probability of excedance is 10%, can be expected in the volcano area.
5. A lifeline should be constructed in the basis of deep studies on seismic hazard and its effects such as fault, rupture, landslides, etc.
6. Since there are good posibilities of continuing oil explotation in the area, it will be very convenient from the economical and social point of view to change the position of the oil pipeline to the right bank of the Quijos-Coca river, which is plane and very stable.

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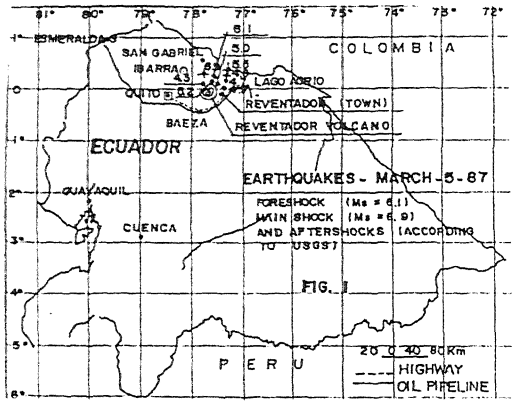


Fig. 1

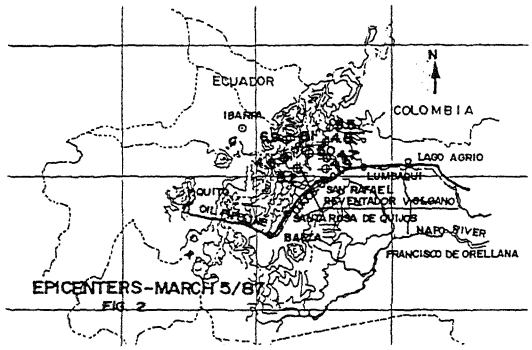
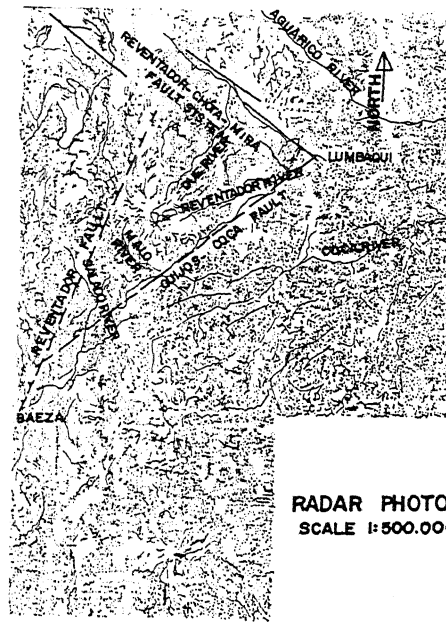


Fig. 2



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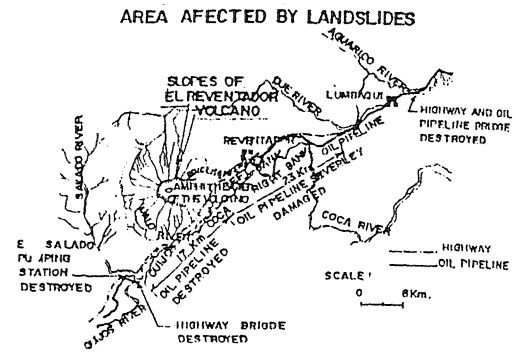

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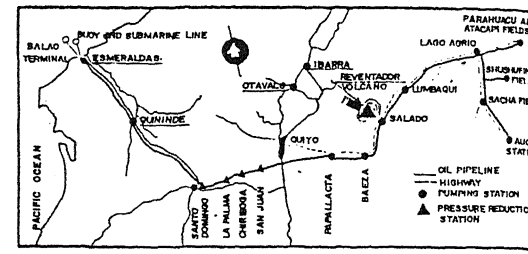


TRANSECUADORIAN OIL PIPELINE

Fig. 5

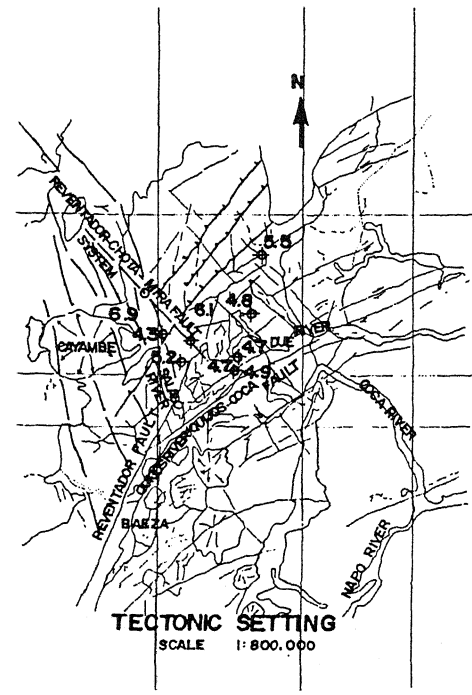


Fig. 6

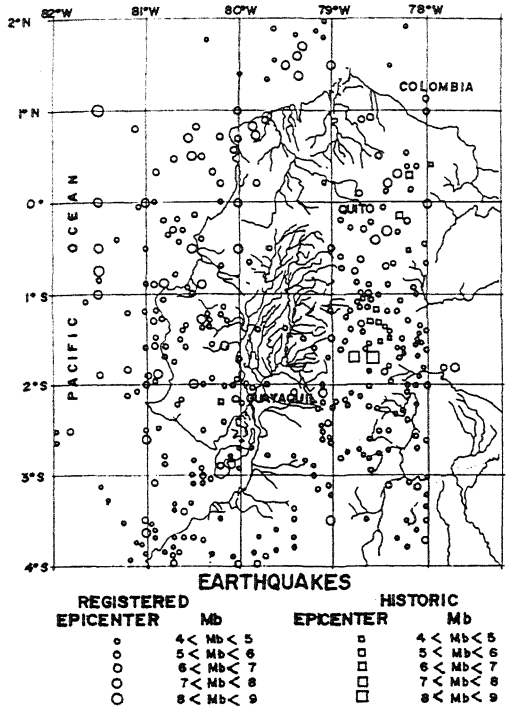
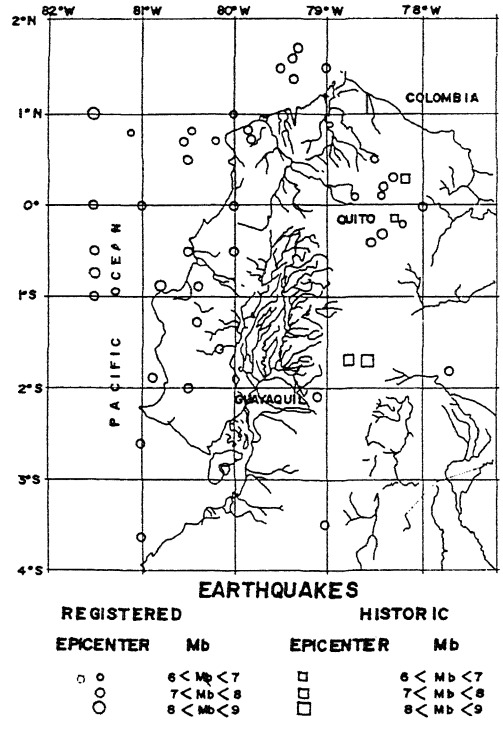


Fig. 7



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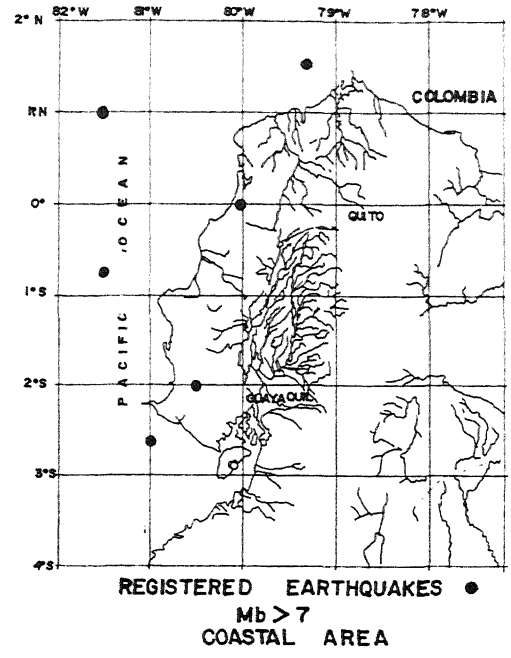


Fig. 9

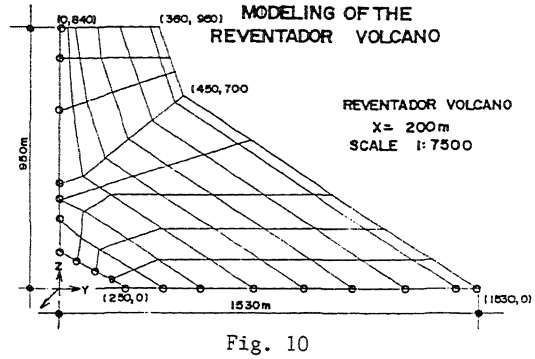


Fig. 10

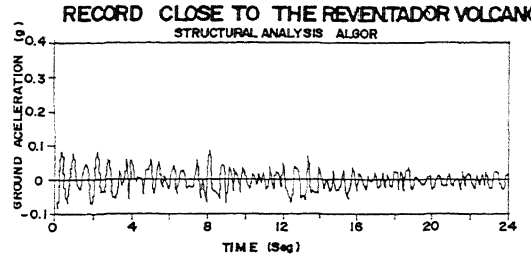


Fig. 11

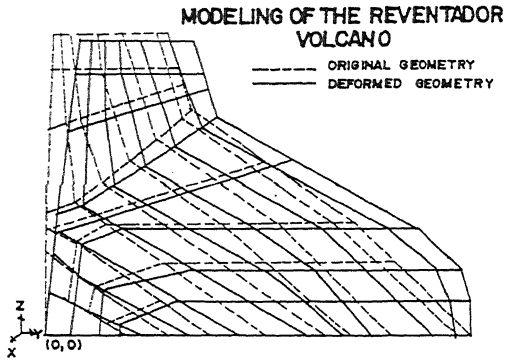
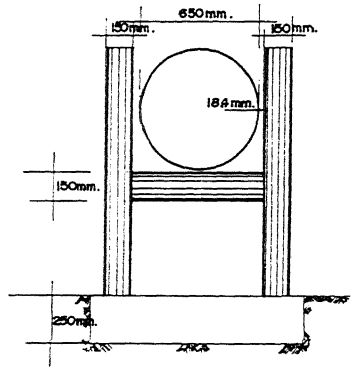


Fig. 12

SUPPORTING STRUCTURE OF THE OIL PIPELINE



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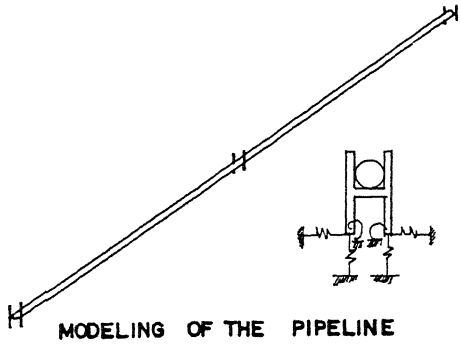
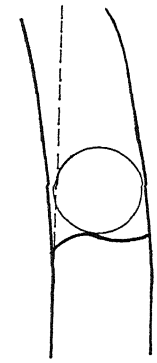


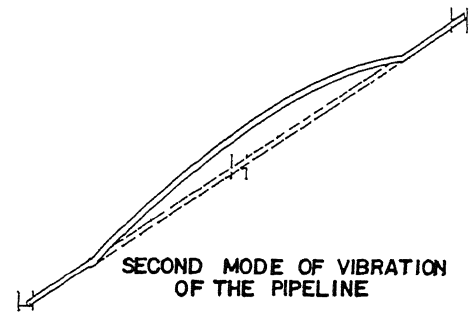
MODELING OF THE PIPELINE

Fig. 14



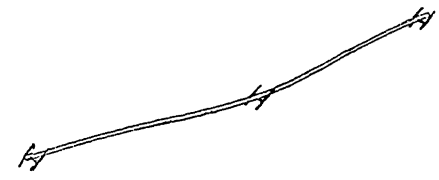
FIRST MODE OF VIBRATION OF THE PIPELINE IN THE SUPPORT ZONE

Fig. 15



SECOND MODE OF VIBRATION OF THE PIPELINE

Fig. 16



DYNAMIC DISPLACEMENTS OF THE OIL PIPELINE

Fig. 17

DISPLACEMENTS OF THE SUPPORTING STRUCTURE OF THE OIL PIPELINE

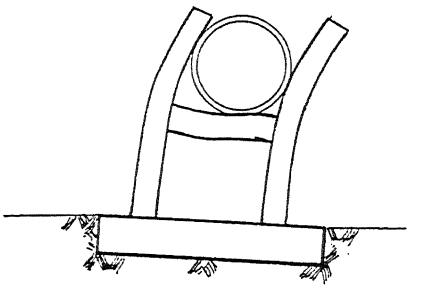


Fig. 18

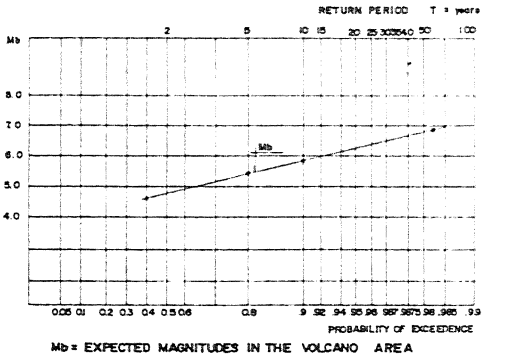


Fig. 21

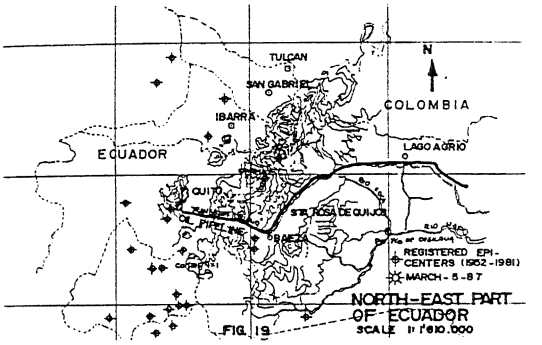
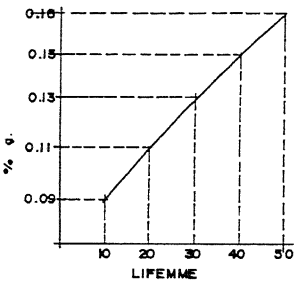


Fig. 19

VARIATION OF EXPECTED ACCELERATION WITH LIFE SPAN FOR 10% PROBABILITY OF BEING EXCEEDED



% Prob exc.	life time	g
10%	50	0.16
10%	40	0.15
10%	30	0.13
10%	20	0.11
10%	10	0.09

Fig. 20