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Soil-pipe interaction analysis for the water supply system at Lazaro Cardenas, Mexico

L'analyse de l'interaction sol-tuyau pour le système d'approvisionnement d'eau de Lazaro Cardenas, Mexico

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SYNOPSIS: This paper makes a description of the works performed to know the seismic hazard and seismic resistance of the water supply system for the Lázaro Cárdenas Port, located at the pacific coast of México. The analysis takes into account the characteristics, location and amount of failures that occurred during the earthquakes of September 19 and 21 of 1985.

A presentation is made of the seismic countermeasures for water supply facilities the influence of ground conditions on the structural response, as well as the soil-pipeline interaction due to earthquake effects.

Based on the results of this analysis, the observation of damage and the structural characteristics with which the pipeline was constructed, as well as the role of the mechanical behaviour of the soils involved, are pointed out, and are related to the earthquake proof construction of long underground structures.

INTRODUCTION

The Lázaro Cárdenas industrial port is located at the Mexican coast of the Pacific Ocean at Michoacán State in the limits of the Guerrero State (see fig. 1). This zone has an intense seismic activity due to a complex tectonic conformation, which emphasizes the fact that is located precisely over the zone of subduction between the North American Plate and Cocos Plate.

This port has a water supply system for several industries located on the delta of the Balsas River.

Due to the earthquakes of September 1985 several problems related to liquefaction of granular deposits and permanent deformations of the surface that altered the stability of the port structures were detected. Likewise it was detected several distortions of the ground surface sediments due to the seismic waves that affected the buried pipelines of the water supply system.

This paper presents some of the outcomes obtained during the inspection of damage due to the seismic motions of September 1985 at Lázaro Cárdenas and the results of the performed analysis by means of the Seismic Deformation Method, considering seismicity of the zone, the dynamic displacements of the soil and the structural characteristic of the pipelines.

SEISMICITY

According to the geological knowledge at present time the earth crust is formed by plates that are in contact and have relative displacements

between them. The contacts between the plates generally produce a large geological fault or system of faults.

The plates that form and are in contact with the Mexican Republic are: the Pacific Plate, the North American Plate, the Rivera Plate, the Cocos Plate and the Caribbean Plate (see fig.2). The seismic activity of México has his origin in the neotectonics phenomenon product of the interaction between those plates. (see ref. 1).

Large earthquakes along the Pacific coast are caused by the subduction of the Cocos or Rivera Plates beneath the North American Plate. Rivera Plate, a relatively small one, subducts below the state of Jalisco with a relative velocity of about 2.5 cm/yr. The boundary between Rivera and Cocos Plates, although somewhat uncertain, probably intersects the Mexican coast near Manzanillo (19.1° North, 104.3° West). The relative velocity of the Cocos Plate with respect to the North American Plate increases from about 5 cm/yr near Manzanillo, to about 8 cm/yr near Tehuantepec. Large earthquakes also occur in the continent at depths greater than 40 Km that show a normal faulting mechanism reflecting the break-up of the subduction ocean lithosphere; although relatively infrequent, such earthquakes are those which cause greater damage. Finally, less frequent crustal earthquakes also occur within the Continental Plate, depending upon the location; such events can cause considerable damage (see ref. 2).

There has been identified gaps along the Mexican subduction zone with high seismic potential (see ref. 3); the outstanding gaps are Jalisco, Michoacán, Guerrero, Ometepe and Tehuantepec gaps (see fig. 3)

The port of Lázaro Cárdenas is precisely located over the subduction zone of the Cocos Plate beneath the North American Plate, where it is also located Acapulco Trench with a system of geological faults. It can be observed in fig. 4 that according to the seismic macrozonation of the Mexican Republic the Port of Lázaro Cárdenas is located within zone 3, which is the highest seismic zone in the country, and where the magnitude of 7.0 can be easily exceeded.

GEOLOGY

The Lázaro Cárdenas port is located on the delta of the Balsas River whose formation has been complex due to the continuous processes of accumulation and erosion of the materials during several glacial and interglacial ages.

The geological frame of reference useful in civil engineering, is due to there principal aspects (see ref. 4).

- a) The tectonic position of the site.
- b) The geological units of the area.
- c) The processes that generates the units.

The tectonic location of the delta is presented in fig. 5, where the relative positions of the Cocos Plate subducting the North American Plate is indicated; this trench is located 4 Km below sea level and 40 Km offshore, just were some of the most important seismic activity of México has taken place.

In fig. 6, it is observed the different geological units that show the complexity of the delta; in the first place are the sand banks, alluviums and the mangrove swamps near to the beach; second, the coast deposits; third the old deltaic deposits, and finally the new deltaic deposits. These two last deposits are the most important units within the zone.

The old deltaic deposits are formed by conglomerates, alluvium, sands and fine soils with low relative density. The new deltaic deposits are formed by alluvium, gravels and silty sands with loose and semi-compact state, with some deposits of silts and soft clays.

The delta of the Balsas River was formed by means of accumulation and erosion of the materials that were subjected to the changes in the sea level due to the processes of glaciation, that generates erosion, and the accumulation of the materials transported by the Balsas River at interglaciation intervals.

WATER SUPPLY SYSTEM

Due to industrial development of the Lázaro Cárdenas port, it was necessary to design and built a system of water supply for the industrial installations settled there, as well as for the industrial facilities that will be installed in the near future.

In fact, the system is integrated by two water supply systems (see fig. 7).

a) Water supply for industrial use, whose inlet is located in the principal channel of the right edge of "La Villita" dam, going up to the delivery site N° 1 located in the left edge of the right branch of the Balsas River in the Cayacal Island, with a flow of 9 m³/sec. The aqueduct was constructed by means of 2.50 m and 1.80 m prestressed concrete pipe diameters and with a pipeline length of approximately 11 Km. At the crossings sites of the river branches a steel pipeline section of 1.22 m in diameter was used.

b) Interconnection pipeline for wells, in the emergency facilities, integrated by the equipment, electrification and interconnection of 5 wells located in the Cayacal Island, which are connected with the 1.80 m diameter aqueduct at the branch that goes to the delivery site N° 1. An asbestos-cement of 0.51, 0.91 and 1.55 m diameters pipe, was used for this line.

GEOTECHNICAL CONSIDERATIONS

According to the ground conditions, the seismic force that acts upon the structures tremendously differs even though it may be at the same area. In a good subsoil, these forces have to be small compared to those that generates in a poor subsoil, specially when the thickness of the layers and the geological and topographical features changes are large.

The surface geology has an special influence in earthquake damage upon the structures and is usually investigated in detail. However, earthquake damage cannot necessarily be understood from the surface geology alone; it seems sometimes to be affected by the geology deep underground as well. It is therefore believed that information should be provided, related to the ground type by carrying out deep boring, observing the ground motion due to blasting, or by measuring anomalies in gravitational acceleration.

For the investigation of the relation between soil type and earthquake damage, three points are to be considered:

1. The influence of soil type on the intensity and wave form of the ground motions.
2. The influence of soil type on the vibration damping properties of the pipe structures.
3. The decrease in the strength of soil when subjected to vibration.

In this case the stratigraphical characteristics were determined by means of deep geotechnical borings in which the soil classification profile was determined along with S.P.T. values.

The performed seismic response analysis was based upon the mechanical parameters obtained through the available soil borings at the zone, such as the relative density and S.P.T. values. These values were used to estimate the shear strength characteristics of each one of the analyzed strata and were compared with the shear

moduli of sands of different relative densities and in-situ shear moduli for saturated soils published by Seed and Idriss (see ref. 5).

Using the values of the dynamic shear moduli G , the values of shear wave velocity, and the fundamental period of vibration of each strata were obtained.

For the geotechnical profile along the pipeline, the values of shear wave velocity V_s and the fundamental period of vibration are presented in figs. 8 and 9, where it can be seen that there is not a well defined rock basement; therefore, a 750 m/sec of shear wave velocity was considered as the representative of sound basement for the dynamic response analysis performed.

SOIL-PIPELINE INTERACTION DUE TO EARTHQUAKE EFFECTS

During an earthquake, a relative displacement occurs on the subsoil due to the propagation of the seismic waves along the subsoil, causing the deformation of the buried pipeline. This deformation has different values in places where the rigidity differs, such as where the geological and topographical features change, or where the pipes are connected with a rigid structure.

In the case of an underground structure as a pipeline, the inertia force is not a decisive factor in its earthquake-resistant design; the structure is forced to deform by the displacement of the surrounding soil. Therefore, the displacement of the ground is a decisive factor for the design of this kind of underground structures.

As the seismic wave propagates along a pipeline, axial strains and curvatures are developed due to the relative displacement of the soil.

The Ministry of Construction of Japan (see ref. 6) has specified a procedure to determine the deformation of the ground due to earthquakes (see fig. 10). According to this procedure the computation of seismic deformation of the ground could be carried out as follows:

Ground displacement amplitude at the depth x from the ground surface can be determined by the following equation:

$$U_h = \frac{2}{\pi} S_v T_g k_{oh} \cos \frac{\pi x}{2H} \quad (1)$$

where:

U_h = horizontal displacement amplitude at depth x

S_v = normalized response velocity cm/sec per unit seismic coefficient, which is to be determined according to the predominant period of the surface layer as presented in fig. 11 or fig. 12 for this particular case.

T_g = predominant period of vibration of the unconsolidated ground formation.

H = The thickness of the surface layer.

k_{oh} = design horizontal seismic coefficient to be subjected to the surface layer.

$$k_{oh} = \frac{\Delta_1}{B_g} k_o$$

where:

k_o = standard design horizontal seismic coefficient

B_g = Correlation factor that takes into account the multireflection effect of the seismic waves traveling throughout hard basement into soft soil layers, usually taken to be 1.33 to 2; and

Δ_1 = a regional factor that can be 1.0, 0.85 or 0.7 depending on the seismicity of the region, using 1 for the region of highest seismicity.

The vertical ground displacement amplitude can be obtained with the following expression (see ref. 6):

$$U_v = U_h/2$$

Equation (1) can be introduced by the multireflection theory of the set of unconsolidated soil strata that integrates the surface layer, overlaying the rock bed. The configuration of the soft soil layer under vibration is represented in figs. 8 and 9.

If there is not slippage of the pipeline relative to the surrounding soil, then we can assume that the maximum axial strain in the pipeline is equal to the maximum ground strain. The development of this maximum ground strain in the pipeline is dependent upon whether or not there is sufficient pipeline length and a long enough wave length to establish equilibrium between pipeline-soil frictional forces and strain-induced axial forces in the pipeline without the occurrence of longitudinal slipping (see fig. 10).

Generally, the assumption that pipeline strains equal ground strains is satisfactory if pipeline-soil resistances satisfy the relation:

$$\frac{A_p E_i}{t_u} \leq 10^6$$

where:

t_u = ultimate axial (longitudinal) resistance per unit length of soil on pipeline.

A_p = pipeline wall cross-sectional area.

E_i = initial modulus of elasticity of pipeline.

Methods for calculating the pipeline-soil resistance parameter, t_u are presented in Ref. 7.

Fig. 10 illustrates: (a) idealized subsoil system; (b) horizontal peak displacement at a cross section, and (c) distribution of seismic ground displacement. Seismic ground surface displacement $U_h(x,t)$, at the point "x", just above the straight pipe embedment and just at the time t, can be expressed by: (ref. 6).

$$U_h(x,t) = U_h \sin \frac{2\pi t}{T_i} \cdot \frac{(t-x)}{C_i}, \quad i = 1, 2, 3, \dots$$

Where U_h is the displacement amplitude for the natural period T_i for the i-th vibration mode of the idealized system, and C_i is the apparent velocity of wave propagation of the i-th mode. By simply taking the fundamental mode (i=1) and neglecting the effects of the higher modes, the distribution of displacement at a certain time can be approximately expressed as:

$$U_h(x,t) = U_h(x) \sin \frac{2\pi t}{C_1 T_1} x = U_{hi} \sin \frac{2\pi t}{L_1} \cdot x \quad (2)$$

In eq. (2) $L_1 = C_1 T_1$ denotes the wave length for the fundamental mode.

The peak amplitude of the horizontal displacement at the ground surface can be obtained as the peak response displacement at a section when it is subjected to a seismic ground motion $z(t)$ induced at the level of the bedrock, and can be expressed as

$$U_{hi} = U_h = \frac{4}{\pi} \frac{\bar{S}_v}{(2\pi/T_i)} = 0.203 t_i \cdot \bar{S}_v$$

in which \bar{S}_v denotes the velocity response spectrum value when a linear single-degree-of-freedom (SDOF) system is subjected to the bedrock motion with the peak acceleration of $k_{oh} g$ (cm/sec²) (where g denotes the gravity acceleration = 981 cm/sec²) Finally, S_v can be expressed as

$$\bar{S}_v = S_v \cdot k_{oh}$$

where k_{oh} is the horizontal seismic coefficient at the bedrock and S_v denotes the standard response spectral value of a linear SDOF system with the natural period of T and the corresponding damping ratio.

The Ministry of Construction of Japan (see ref. 6) determines the pipe stress (σ_x) by means of the following equations:

$$\sigma_L = \alpha_1 \xi_1 \frac{\pi U_h(x,t)}{L} \times E \quad (3)$$

$$\sigma_b = \alpha_2 \xi_2 \frac{2\pi^2 D U_h(x,t)}{L^2} \times E \quad (4)$$

$$\sigma_x = (\gamma') \cdot (\sigma_L^2 + \sigma_b^2)^{1/2} \quad (5)$$

where:

σ_L, σ_b = Axial stress caused by axial strain and bending during an earthquake.

σ_x = Pipe combined stress.

$U_h(x,t)$ = Horizontal displacement amplitude at depth "x", at a given time "t".

E = Young's modulus of pipe material.

D = External diameter of the pipe.

γ' = Weight modulus of the earthquake wave motion component.

$\alpha_1, \alpha_2, \xi_1, \xi_2$ = functions of young's modulus of pipe material, section area of the pipe wall, moment of inertia of the pipe and wave length.

ξ_1 and ξ_2 are compensating values of the pipe stress for pipelines employing joints with expansion-contraction and flexibility. For pipelines which are uniform at the joint portions (e.g. pipelines with a rigid structure such as steel pipes with welded joints, etc.) and they have no expansion contraction and angular flexibility, $\xi_1 = \xi_2 = 1$. ξ_1 is the value in the axial direction and ξ_2 is the corresponding in the bending direction.

The shear wave velocity values were determined by means of the dynamic shear modulus of elasticity G; the fundamental period of vibration T of the strata was determined from the shear wave velocity, and the shear modulus of elasticity G was obtained by means of empirical correlations based on N values and the profile of effective stresses, (ref. 5). The following equations, corresponding to the first vibration mode, were used.

$$v_s = \sqrt{\frac{G}{\rho}} \quad (6)$$

and

$$T_n = 4 \sum_{i=1}^n \frac{d_i}{(v_s)_i} \quad (7)$$

where:

T_n = The fundamental period of vibration of all of the strata involved.

v_s = shear wave velocity.

G = Dynamic shear modulus of elasticity of soils.

ρ = mass density of the soil material.

d_i = thickness of the "i" stratum.

The seismic input motion was obtained by means of the recordings obtained at the Guerrero array, throughout the duration of the earthquakes of September 19th. and 21st. of 1985. The velocity response spectrum S_v was calculated from the information of the seismic stations located close to the pipeline,

In fig. 12 this velocity response spectrum S_v corresponds to the Villita dam station, which was used in the analysis of the first part of the pipeline.

In order to consider the influence of each one of the strata that integrates the geotechnical profile, the shear wave velocity (V_s) used in the calculation of the pipeline seismic response, was:

$$v_s = \frac{\sum d_i}{\sum \frac{d_i}{v_{si}}}$$

where:

d_i = summation of the thickness of each one of the strata that integrates the geotechnical profile.

v_{si} = shear wave velocity of stratum "i".

This shear wave velocity V_s represents the velocity with which seismic shear waves travel through soft soil formations.

COMPARISON OF THE SEISMIC DAMAGE OBSERVED WITH THE SOIL-PIPELINE INTERACTION ANALYSIS.

Pipeline at Lázaro Cárdenas Michoacán, constructed near the Pacific Coast of México (see fig. 7), may be considered as a rigid type of structures. The pipeline was constructed mainly with prestressed concrete pipes and the joints are of the socket and spigot type which do not offer much expansion-contraction flexibility.

During the earthquakes of September 19 and 21 of 1985, in México, this kind of pipeline offered the most extensive damage due mainly to seismic wave propagation and in a few cases due to densification of the granular supporting soil with shallow groundwater table.

From 4000 meters of pipeline that was in operation, it was necessary to remove 1700 meters due to disconnection of several segments of the pipeline and damage at the joints. There was also some damages in the casings of the wells that were in operation at the moment of the first seismic motion; the damage includes:

- Tilting of 4 casings of the wells.
- Disconnection of pumping equipment at different points of the pipes.
- Rupture in the coupling and valves of the pipeline.
- Leakage at pipeline branch unions.
- Failure of the bearing foundations of pumping equipment.

The failures of the pipeline were principally due to joints dislocation or broken, as the result of forces and blows as two consecutive

pipe sections collided at the joint section. (see ref. 8).

The results obtained for the seismic analysis of the pipeline corresponding to the water supply system for Lázaro Cárdenas Michoacán (figs. 13, 14 and 15), after application of the seismic deformation method, can be summarized as follows:

The seismic deformation magnitude for the Lázaro Cárdenas pipeline is presented in fig. 13, along 6.1 kilometers. In this figure it is appreciated how the variation of soil properties and topographical features, all along the pipeline (see figs. 8 and 9), originates a drastic variation in horizontal seismic deformation magnitude (U_h), as well as some differences in the wave length computed at the level of pipeline embedment, according to the results summarized on table I and presented below and in the axial stresses generated (see fig. 14); these results were obtained from soil-pipeline interaction analysis performed at straight pipeline sections.

Three main sections along the 6.1 kilometers of pipeline analyzed were selected according to the different soil response characteristics presented in figs. 13, 14 and 15. The amplitude of seismic deformation U_h , as well as the wave length L_n (see fig. 10) obtained at the depth of pipeline embedment are shown graphically in figs. 16, 17 and 18 for pipeline sections 1, 29 and 45 respectively. These results are summarized on table I, and presented below. From these results it can be concluded that the seismic response differences are due mainly to the dynamic soil properties, thickness of soft subsoils formations and the topographical profile and that the axial stress level generated can be reduced considerably by the installation of flexible joints at proper intervals, as can be seen in fig. 14.

TABLE I
MAIN RESULTS OF THE SOIL-PIPELINE INTERACTION ANALYSIS

	maximum seismic deformation (cm)	wave length (m)	axial stress (ton/m ²)
0+050 km section 1	6.52	55.76	3,030
2+450 km section 29	9.00	63.35	3,240
6+110 km section 45	9.42	58.70	3,300

The most critical section studied was section 45, in which the largest angular deflection between successive pipes was according to this analysis on the order of 0.5 degrees.

One of the outstanding points of this kind of analysis, and in particular for the case of Lázaro Cárdenas pipeline, is the stated relationship between mechanical properties of the soils and the magnitude of seismic response. For example, from the section located 2 kilometers from the beginning of the pipeline (see fig. 8 and 9) which has N values larger than 50 blows at shallow depths, in comparison to the section located about 2.5 kilometers where the

N values are on the order of 20 and 30 blows up to 16 meters depth for these sections it can be observed in fig. 13 a differential seismic response, with the corresponding difference in magnitude of axial stresses generated, (see fig. 14).

In order to complete this kind of analysis, a detailed examination should be performed to determine the field changes of flexibility due to special structures along the pipeline, changes of direction, as well as topographical features (including nearby earth structures).

On the other hand the wave length does not depend exclusively on the amplitude of seismic deformation but it is mainly a function of the dynamic soil properties and the thickness of the soft soil deposits, according to equations 2 and 10.

Another kind of outstanding failures detected at Lázaro Cárdenas pipeline is due to the change of flexibility of the pipeline, originated at the point where the pipeline joints with a valve box, and special structures in general.

A very important source of damage for the Lázaro Cárdenas Mich. pipeline is represented by the liquefaction or densification of the loose saturated sandv soils, typical of that area. There it was found a settlement of about 20 centimeters which could generate important differential movements that stops the function of different parts of the pipeline system; in this case, the collapse of a pumping well and its pipe interconnections was generated.

CONCLUSIONS

It is important to state that according to the dynamic deformation of the pipeline, obtained in this pipe-soil interaction analysis and the amount of failures detected after the México September earthquake, it can be concluded that, due to the seismic drag, stress concentrations are generated which induce local pipe failures at the joints as well as pipe dislocations.

The socket and spigot joints are responsible of the high axial stress concentrations at Lázaro Cárdenas pipeline because of the lack of longitudinal and angular flexibility, as well as of pipe dislocations, in case that two pipes move away from each other. Therefore the joints should be redesigned, giving them the appropriate flexibility.

It can be concluded that the seismic risk for this aqueduct is quite high and that it should be kept in mind that this pipeline was not constructed earthquake proof. It is important to say that this is the first time that the seismic forces were considered for a soil-pipe line interaction and the results of this kind of analysis have not been applied up to now to the design of a pipeline in México, mainly because there was no evidence of failure of this kind of pipes, used at areas with this kind of soils and because there was not a suitable method of analysis.

At this time the authors are working to bring

to completion this research with the design of dynamic tests, applied to the pipe joints as well as with field instrumentation of the Lázaro Cárdenas water supply system in order to record directly the seismic behaviour and then be able to perform the necessary adjustments to the method of analysis presented in this work.

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Fig. 1:- LAZARO CARDENAS INDUSTRIAL PORT LOCATION

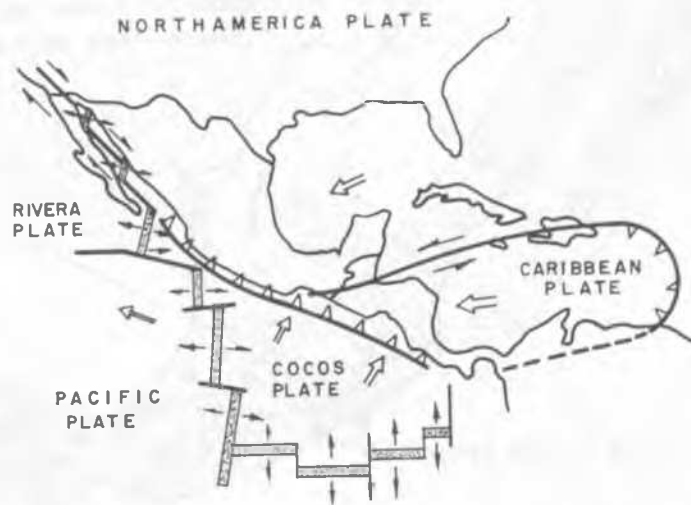


Fig.2:- TECTONIC PLATES IN MEXICO.

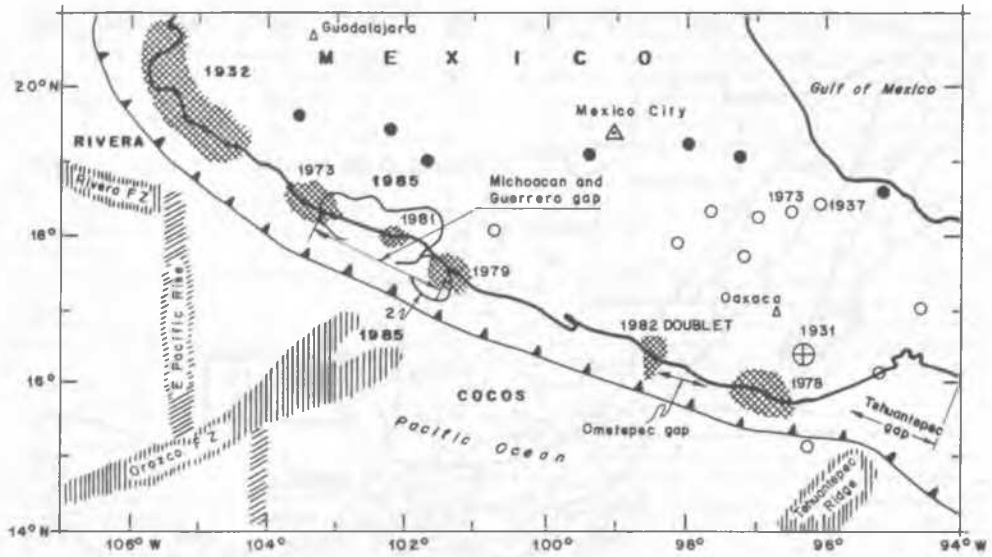


Fig. 3:- OUTSTANDING GAPS ALONG THE MEXICAN SUBDUCTION ZONE (AFTER SINGH ET AL 1981)



Fig. 4:- SEISMIC MACROZONATION OF MEXICO.

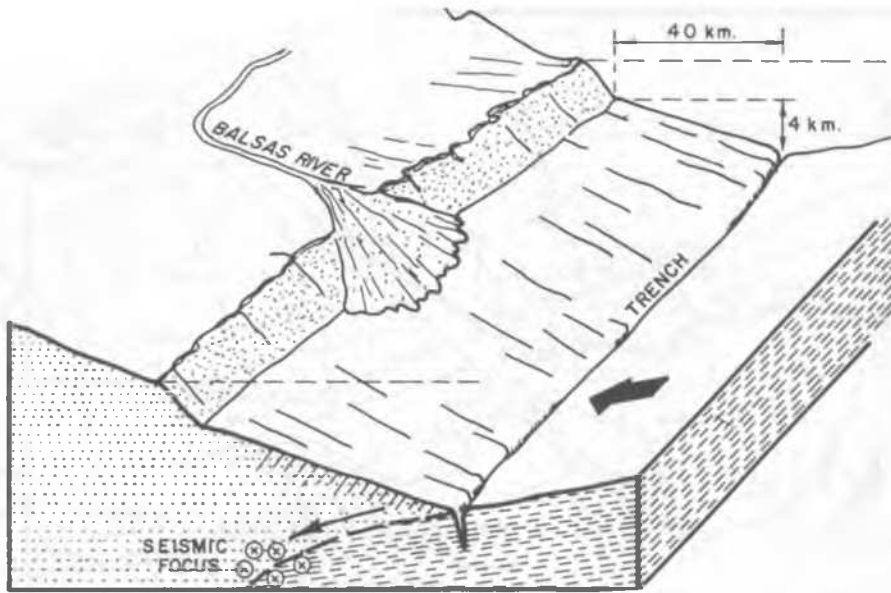


Fig. 5:- TECTONIC POSITION OF THE BALSAS RIVER DELTA.

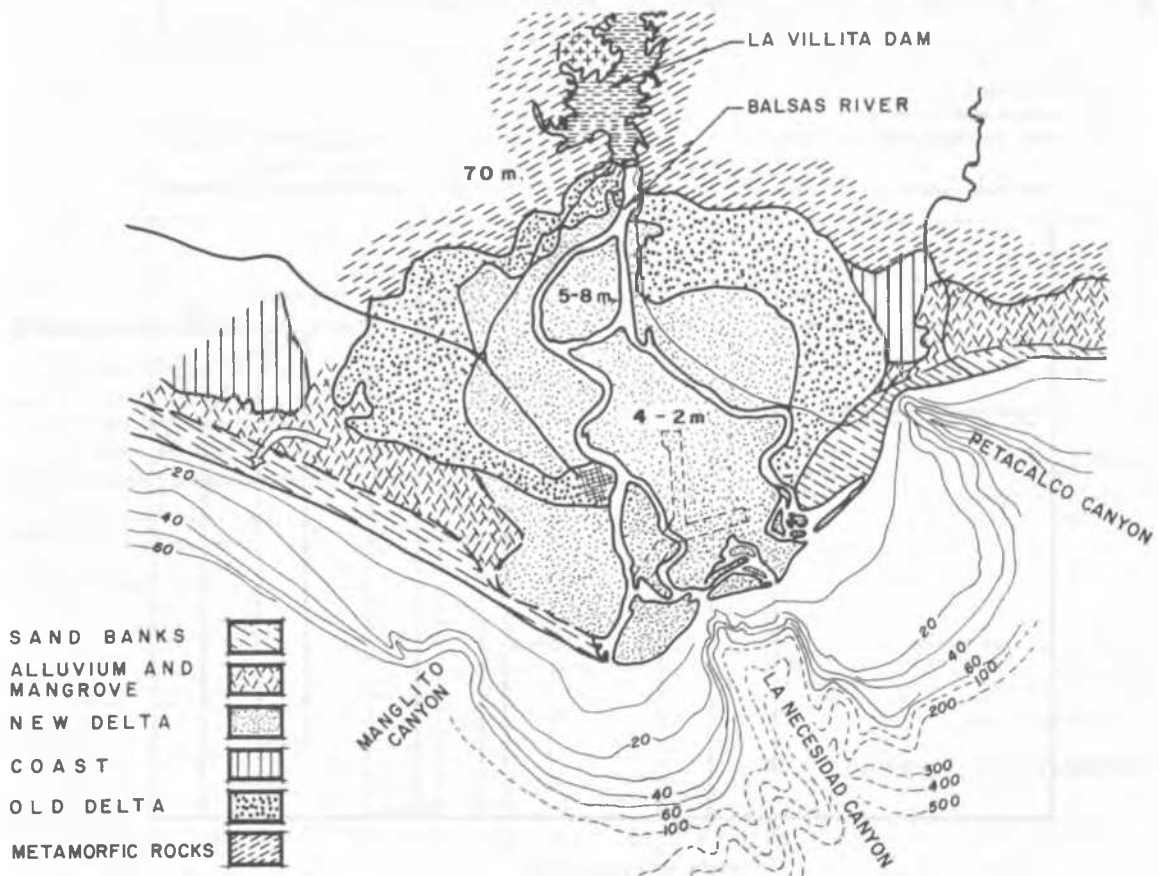


Fig. 6:- GEOLOGICAL UNITS OF THE BALSAS RIVER DELTA (after Moser)

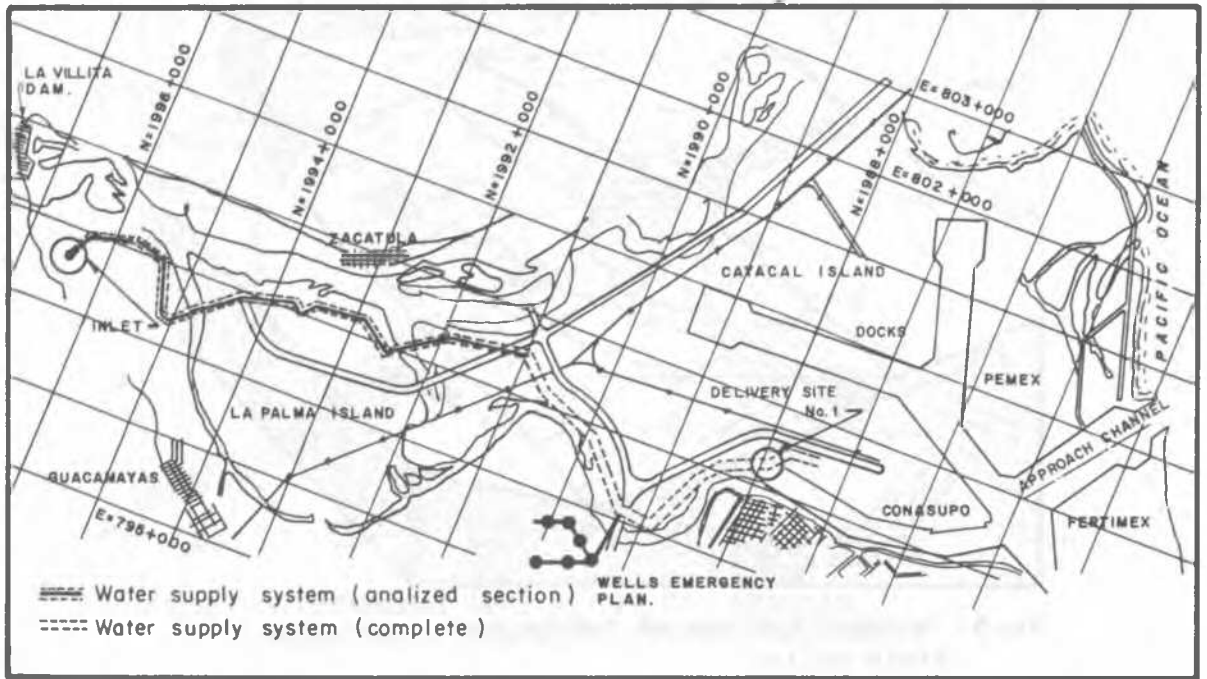


Fig. 7 .- Pipelines for Water Supply at Lázaro Cárdenas Port.

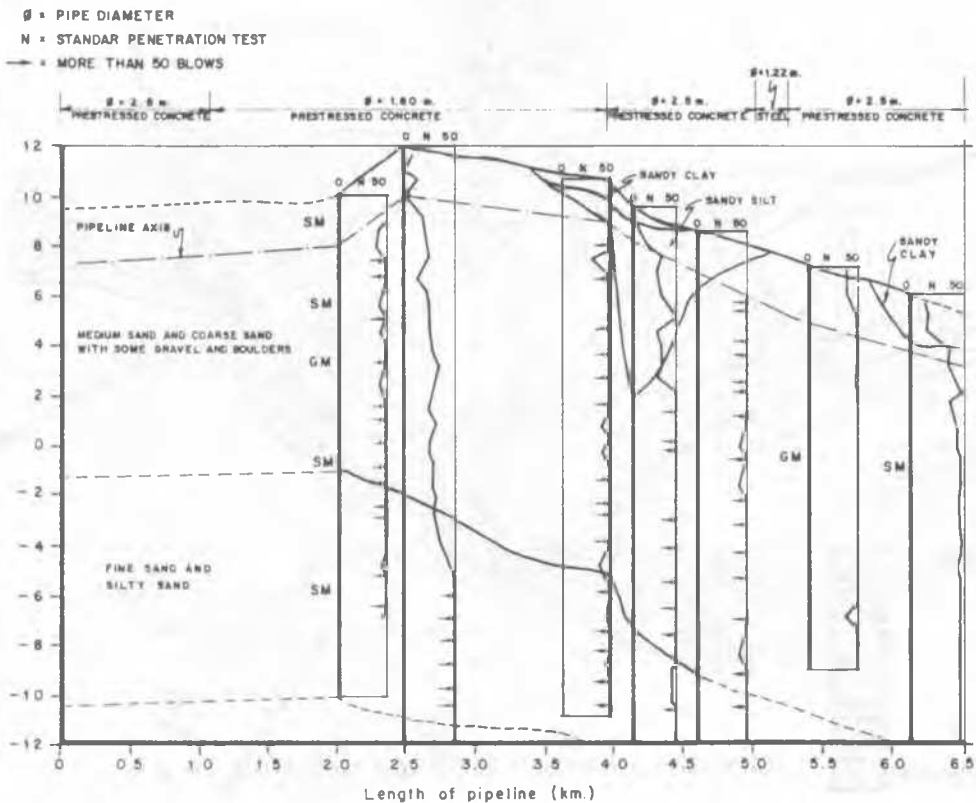


Fig. 8.- Configuration of the soft soil layers under vibration and pipeline main characteristics

ϕ = PIPE DIAMETER
 V_s = SHEAR WAVE VELOCITY

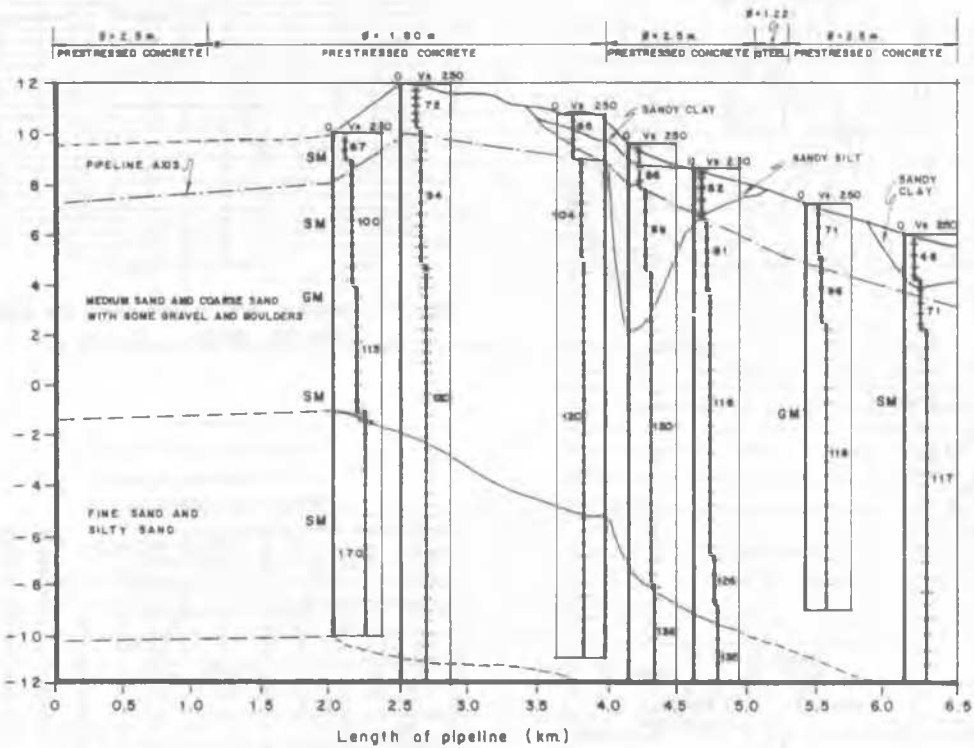


Fig. 9:- Configuration of the soft soil layers under vibration and pipeline main characteristics

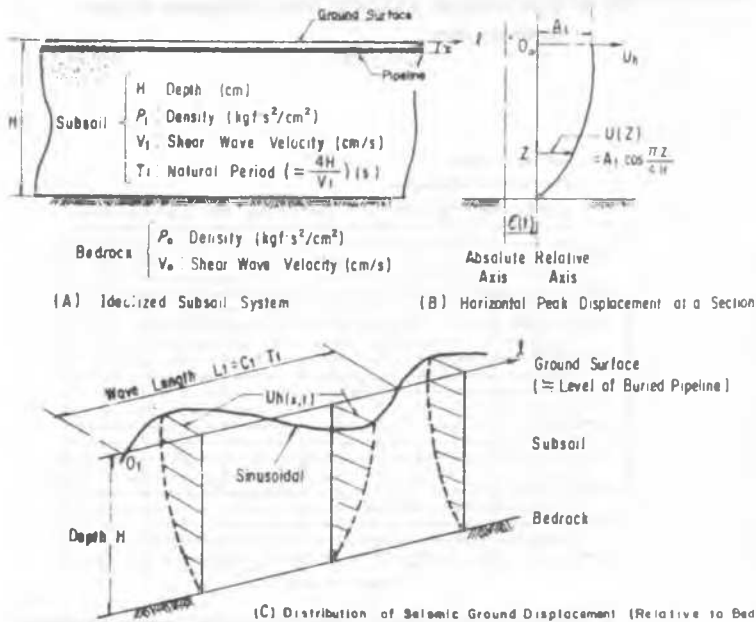


Fig.10 - Assumption of Seismic Ground Displacement

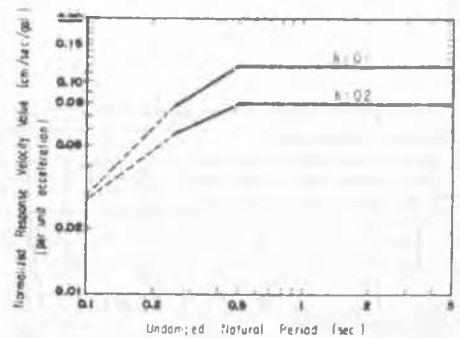


Fig. 11.- Normalized Velocity Response Value S_v

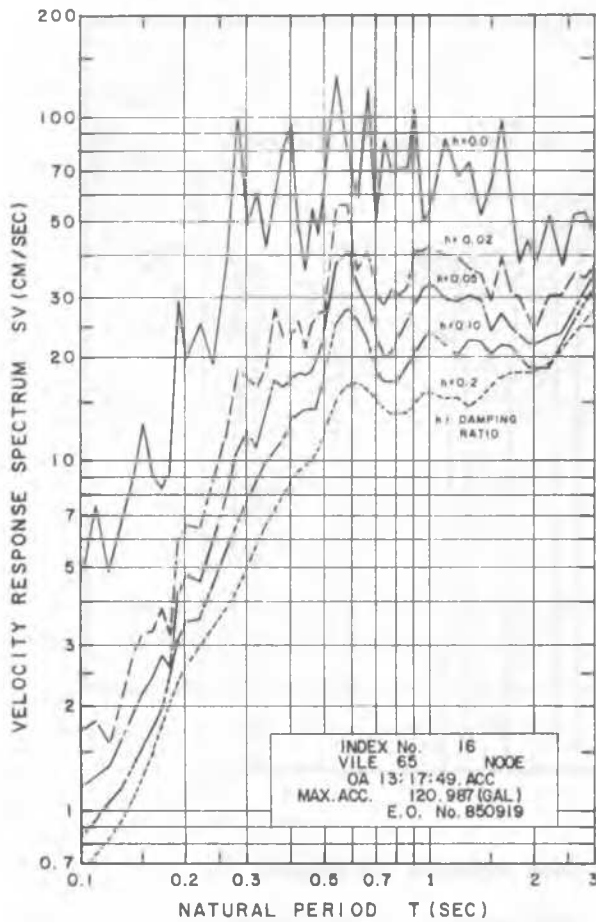


Fig.12:- Velocity response spectrum used for the analysis of seismic response of Lázaro Cárdenas pipeline system

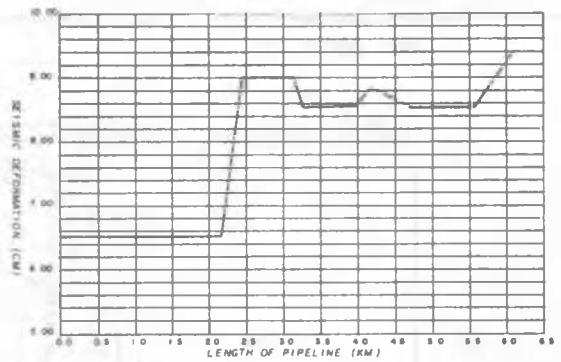


Fig.13:- Seismic deformation along the pipeline at Lázaro Cárdenas, Mich.

- ① Without flexible joints
- ② With flexible joints at each 50 m
- ③ With flexible joints at each 30 m
- ④ With flexible joints at each pipe

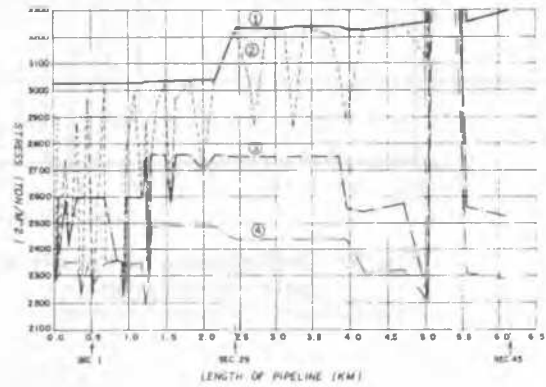


FIG. 14. Axial stresses generated along the pipeline at Lázaro Cárdenas, Mich.

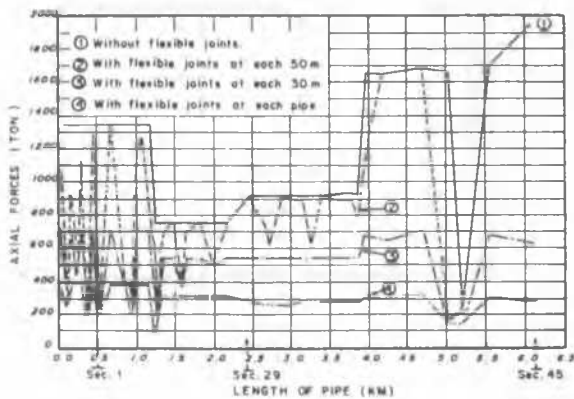


Fig. 15. Axial Forces Generated along the Pipeline at LAZARO CARDENAS, MICH.

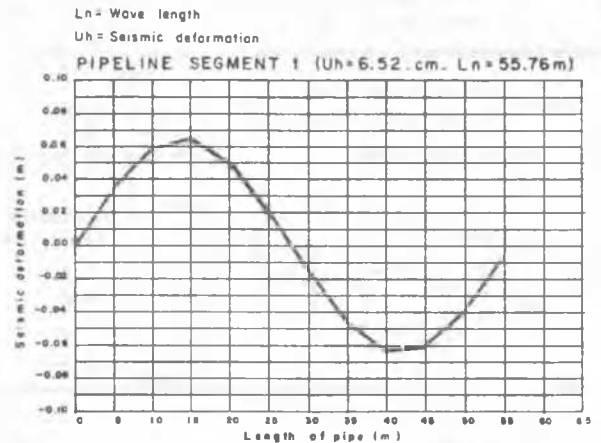


Fig.16 Seismic deformation generated at the pipeline segment no 1

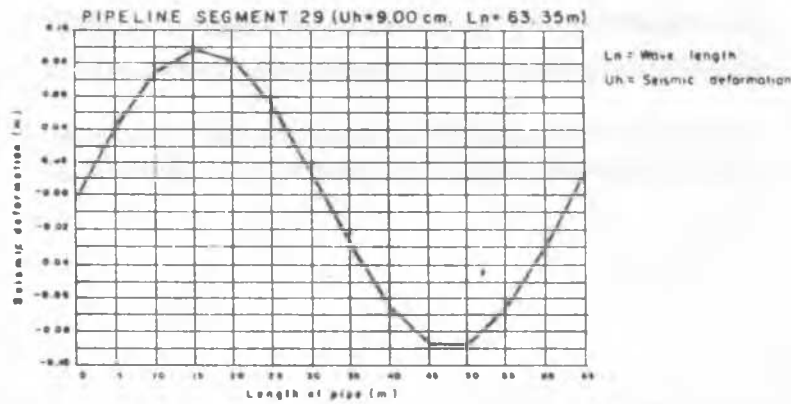


Fig. 17- Seismic deformation generated at the pipeline segment no. 29

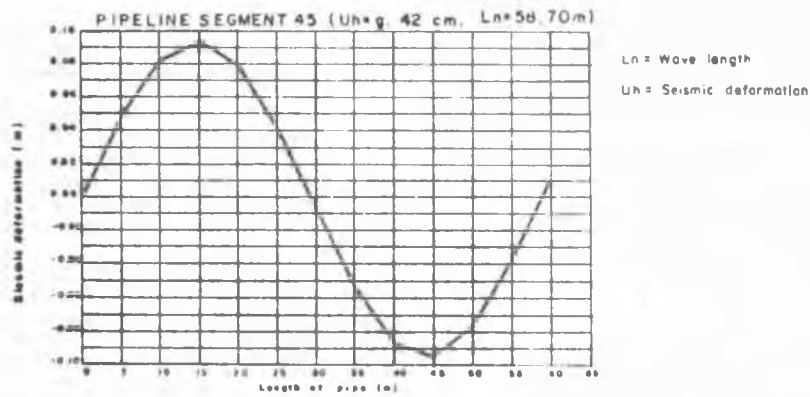


Fig. 18- Seismic deformation generated at the pipeline segment no. 45