SEISMIC DESIGN CRITERIA FOR BURIED WATER PIPELINE IN PUERTO RICO

by Rafael Jimenez-Pérez, Principal Investigator
Department of Civil Engineering
University of Puerto Rico
Mayaguez, Puerto Rico 00708

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I- Introduction:

Current structural design methods for water distribution systems constructed in Puerto Rico do not consider the strains induced by earthquake loadings even though numerous examples of water distribution systems heavily damaged by earthquake have been reported in the literature (2, 6, 9, 12). Various research programs have been conducted elsewhere to determine the response of buried pipelines to earthquakes and to develop design procedures that can be used to determine the stresses induced by seismic activities on the pipelines.

The design procedures proposed by these researchers rely on site dependent parameters that must be acquired before such procedures can be practically implemented. Thus, the research reported herein was directed primarily to the acquisition of the required site dependent data and to the development of a design methodology that could be easily used to ascertain the maximun strain experienced by buried water pipelines in Puerto Rico during the ocurrence of an earthquake.

II- Objectives:

The following objectives were originally proposed to obtain the desired goal:

a- To determine the earthquake parameters, such as the maximum ground displacement, velocity and acceleration, and their time history variation expected in Puerto Rico.

b- To evaluate and possibly modify the analytical methods available to determine the response of a typical buried water pipeline placed over various soil conditions.

c- To establish a procedure for the Puerto Rico Aqueduct and Sewer Authority for the revision of the seismic design of buried pipelines.

III- Previous Research:

The behavior of buried pipelines during earthquakes have been documented for the past years in order to determine an analytical model that can be used to predict their behavior in future seismic events. The recorded failures were caused by at least one of the following conditions:

A- Pipeline crossing a major fault. The pipeline may be ruptured and the joints may be disconnected by the excessive transverse displacement experienced on the pipeline.

B- Soil liquefaction and slides: The pipe continuity is affected by both the vertical and lateral displacement induced by the unstable soil mass.

C- Stresses and strains induced by seismic activity combined with those induced by gravity and pressure loads result in a material failure of the pipeline.

The failure conditions A and B described above where not considered in the work reported herein as there are no major faults lines crossing the island of Puerto Rico and the failures caused by slides or liquefaction pertain primarily to a soil instability problem. The main thrust of this work was directed to the development of a rational but simple analytical tool to predict the stresses ans strains induced by earthquake in a buried pipeline.

A survey of the recent papers published on lifeline earthquake engineering indicates that at the present time a complete analytical model is not available to predict the behavior of buried water pipelines. This task is extremely complicated when it is desired to include different soil properties in the three orthogonal direction and different pipe axial and flexural stiffness along the pipeline layout.

Among the analytical techniques available, the simplest models are provided by the simplified method and by the quasi-static method. The first method allows the calculation of the maximum pipe axial and flexural strain once the maximum ground velocity and aceleration induced by the earthquake are known. The simplified method is derived from the constitutive relations of a wave travelling through a linearly elastic, homogenous soil, assuming that the there is no relative motion between the pipe and its surrounding soil.

The axial and flexural strains are given by

$$\varepsilon_a = V_m/C_p \tag{1a}$$

and

$$\varepsilon_f = A_m R/C_s^2 \tag{1b}$$

where

ε_a = pipe axial strain

ε_f = pipe flexural strain

V_m = maximum ground velocity

A_m = maximum ground acceleration

R = radius of pipe

C_p = longitudinal wave propagation velocity

C_s = transverse wave propagation velocity

The pipe strains computed by the simplified method provide an upper bound of the maximum strains induced by the earthquake in the buried pipeline. Once these strains are computed, they can be used to determine the principal strains and stresses induced in the pipeline material by the combined action of the gravity, pressure and earthquake loads.

The quasi-static method can be derived from the dynamic equation of equilibrium, for an n degree of freedom continous pipeline where only the axial degree of freedom are considered, once the inertia term is disregarded. The equilibrium equation is then given by:

$$[K]_p \{u\}_n = [K]_s \{u\}_g \quad \ldots\ldots\ldots \qquad 2$$

where:

$[K]_p$ = axial stiffness matrix of pipe

$[K]_s$ = soil resistance matrix

$\{u\}_n$ = nodal displacement vector

$\{u\}_g$ = ground displacement vector

For a given instant, once the ground displacement vector is defined, the resulting nodal displacement vector can be established from Eqn. 2.

The advantage of the quasi-static method over the simplified method is that in the former, a time history of the nodal axial displacements is obtained instead of only the maximum values predicted by the later method.

Additional analytical techniques have been reviewed and pursued in this work for the determination of the periods of vibration of buried pipelines in an attempt to determine the maximum response from the contribution of the particular vibration modes. This techniques, however, are not presented in this report as the computational methods are quite complicated and do not lend themselves for practical design approaches.

IV- Seismic Design Parameters

The seismic activity in Puerto Rico is caused by the Mona Canyon Fault on the western part of the Island, by the southern component of the Puerto Rico Trench fault located on the northern part of the island and by the Anegada through fault located on the eastern part of the island. The epicenters of the registered earthquakes are confined within the regions shown in Fig. 1 where earthquake with magnitudes ranging from 4.5 to 7.5 have been experienced during the last 100 yrs.

Based upon this historical record, various estimates for the design earthquake expected for a 100 yr. recurrence interval have been proposed. Housner (7) has proposed a 7.7 magnitude design earthquake for the 100 yr. recurrence interval while Der Kiureghian (4) proposed an 8.6 magnitude design earthquake for a similar recurrence period. An additional seismic risk analysis based upon a point source model (11) has been conducted by Jiménez (8) where it has been concluded that for a recurrence period of 100 yrs. the design earthquake should have a magnitude of 6.0 on the Ritcher Scale. Based upon an analysis of these studies, the design earthquake proposed by Housner has been selected for the design earthquake in this work.

Housner (1) identified the Tehachapi, California earthquake of July 21, 1982 as a typical event for the design earthquake to be used in Puerto Rico. Two records from this earthquake were selected to represent the elastic and the ultimate design earthquakes. The record proposed by Housner for the elastic case was the Hollywood Storage Basement record with a maximum ground aceleration of 0.05g shown in Fig. 2, while the ultimate design earthquake proposed was represented by the Taft record, with a maximum ground acceleration of 0.18g, as shown in Fig. 3. The terms elastic and ultimate design earthquakes in reference to buried pipelines imply that for an elastic design earthquake all components of the pipeline should not suffer any damage while for an ultimate design earthquake, serious damage and line interruptions are tolerated on secondary systems of the pipeline, but the primary supply system should survive this earthquake without service interruptions.

Thus the acceleration records proposed by Housner (7) will be used to obtain the seismic parameters such as maximum ground displacement and velocity required to estimate the pipe strains and stresses induced by the earthquake.

V- Simplified Dynamic Response Method

As discussed in the preceding sections, the quasi-static method can predict the pipe axial strains as a function of time once the structure and soil stiffness matrices are known. These matrices can be established once the pipeline geometry and materials are selected and a complete soil study along the pipeline layout has been conducted.

The quasi-static method can be simplified, however, if it is assumed that the soil mass and the pipeline react to the earthquake ground excitation as a unit and there are no relative displacements between the soil and the pipeline. In this case, the seismic ground displacement as a function of time are allowed to travel along the idealized pipeline shown in Fig. 4, and for a given time interval the pipeline axial strains in a segment between two nodes can be calculated from the nodal displacement induced by the earthquake. This simplified method can then be used, with the aid of a small microcomputer, to determine the axial pipe strains induced by the records of ground displacement versus time shown in Figs. 5 and 6 for the Taft and Hollywood Storage recordings.

The technique can be used for pipelines on soils with different properties by specifying the longitudinal wave propogation velocity between given nodes. Thus, the spacing of the nodes should be selected based on the pipeline geometry and on the different soils properties encountered along the pipeline layout. It should be noted that once the longitudinal wave propagation velocity and the pipeline nodes are established, the time required for a particular displacement in the ground displacement vs. time record to travel from one node to the adjacent node can be calculated from:

$$t_i = \frac{L_i}{C_i} \; \ldots\ldots \qquad (3)$$

where

t_i = travel time of particular ground displacement from one node to the adjacent node

L_i = length of pipe segment between nodes

C_i = longitudinal wave propagation velocity for given soil

The Simplified Dynamic Response method was used to determine the maximum pipe axial strains in a pipeline buried in homogenous soils subjected to the Taft ground motion record. Twelve cases were computed using the length and wave propagation velocities shown in Table 1. The maximum strains are shown in Fig. 7 where it can be concluded that the pipe axial strain induced by the earthquake decreases considerably as the wave propagation velocity of the soil increases or as the soil is stiffer. The length of the pipe does not affect the maximum pipe axial strain induced by the pipeline. A typical record of the maximum pipe axial strain variation with time is also shown in Fig. 8.

The Simplified Dynamic Response Method was also used to determine the behavior of a pipeline on two different soil masses with different embedment lenghts and wave propagation velocities subjected to the Taft ground motion record. The parameters used in each of the six analysis are summarized in Table 2 together with the maximum pipe axial strains computed. This parametric study evaluated the effect of pipe embedment in a given soil layer and of the wave propagation velocities.

A typical record of the maximum axial strain experienced by each segment of the embedded pipe is shown in Fig. 9. It can be concluded that the pipe segment embedded in the stiffer soil experiences considerably smaller strains than those experienced by the segment embedded in the very soft soil regardless of the length of embedment on each soil.

It should be noted that the maximum strains calculated for both parametric studies exceed in various cases the cracking and crushing strain for concrete and the yield strain for steel pipes. Thus, the results obtained from these analysis indicate that the buried pipelines may be severely damaged by the occurrence of a seismic activity similar to the Taft record.

VI- Concluding Remarks

The method outlined above can be practically used to determine the maximum axial strains induced by the expected earthquake in Puerto Rico on buried water pipelines placed over various soil types. The axial strains determined from this analysis have to be added to the hoop and axial strains produced by the gravity and pressure loadings applied to the pipeline. From this combined strain state the principal strains and stresses should be compared with an adequate failure theory for the material used to determine if the applied stresses have an adequate safety factor with respect to the ultimate strength of the pipeline material.

TABLE 1

PARAMETERS USED FOR ANALYSIS OF BURIED PIPELINES IN HOMOGENOUS SOILS AND MAXIMUM AXIAL STRAINS COMPUTED

Case	Length of Pipeline (ft)	Wave Velocity (fps)	Max. Strains
I-1-A	32.8	328	3.4×10^{-3}
I-1-B	32.8	262.5	4.2×10^{-3}
I-1-C	32.8	3280	3.5×10^{-4}
I-1-D	32.8	1640	6.9×10^{-4}
I-2-A	164	328	2.8×10^{-3}
I-2-B	164	262.5	3.5×10^{-3}
I-2-C	164	3280	3.4×10^{-4}
I-2-D	164	1640	6.8×10^{-4}
I-3-A	328	328	2.7×10^{-3}
I-3-B	328	262.5	3.1×10^{-3}
I-3-C	328	3280	3.4×10^{-4}
I-3-D	328	1640	6.5×10^{-4}

TABLE 2

PARAMETERS USED FOR THE ANALYSIS OF BURIED PIPELINES IN TWO DIFFERENT SOILS AND MAXIMUM AXIAL STRAINS

	Embedment Lenght (f$_t$)		Wave Velocity (f$_t$/sec)		Maximum Strains	
Case	Pipeline 1	Pipeline 2	Soil 1	Soil 2	Tube 1	Tube 2
II-1-A	82	246	328	3280	3.18×10^{-3}	7.68×10^{-4}
II-1-A	82	246	3280	328	3.44×10^{-4}	2.75×10^{-3}
II-2-A	164	164	328	3280	2.83×10^{-3}	2.59×10^{-3}
II-2-B	164	164	3280	328	3.44×10^{-4}	2.59×10^{-3}
II-3-A	246	82	328	3280	2.85×10^{-3}	8.25×10^{-3}
II-3-B	246	82	3280	328	3.42×10^{-4}	2.31×10^{-3}

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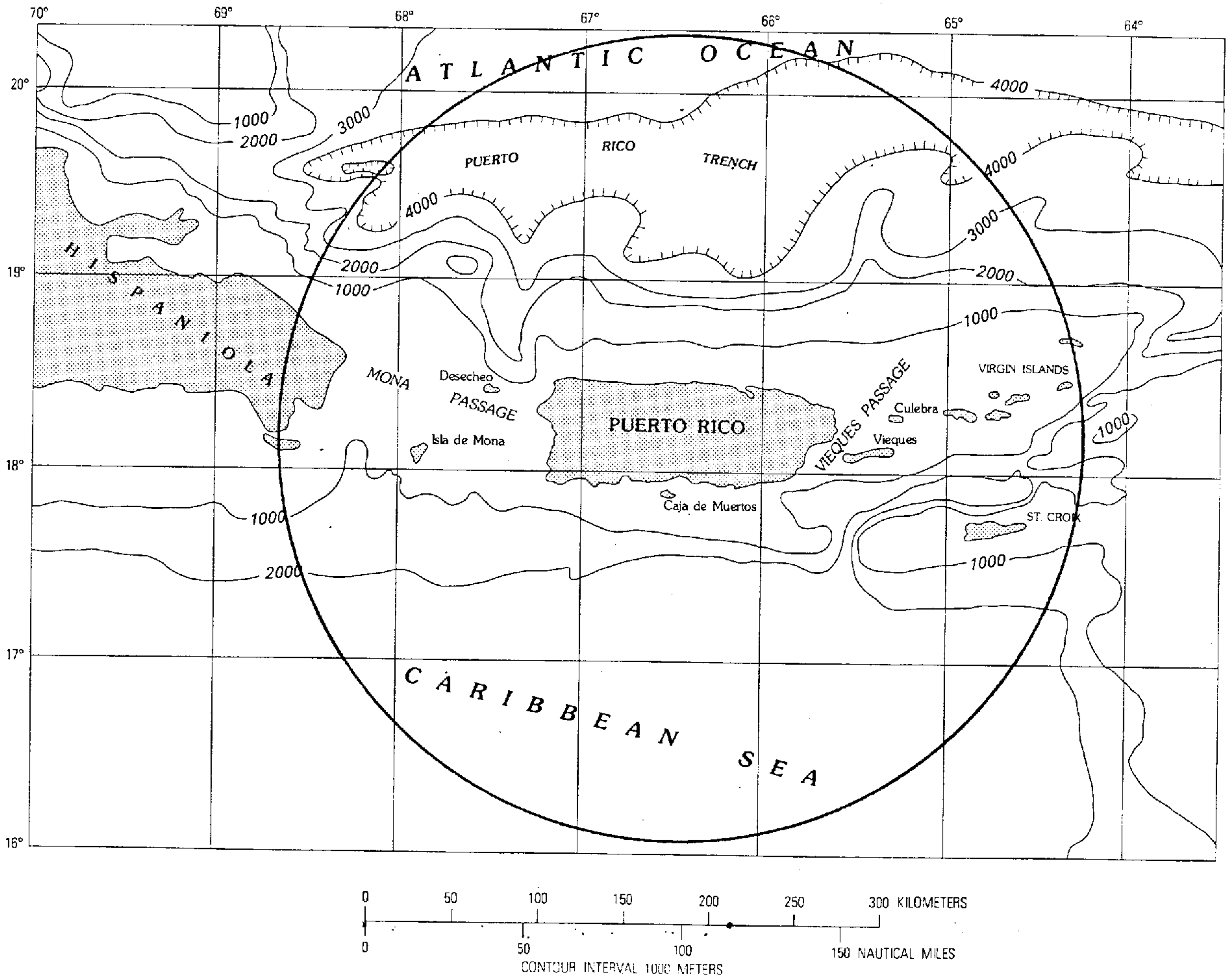

FIGURE 1: Earthquake Activity in Puerto Rico

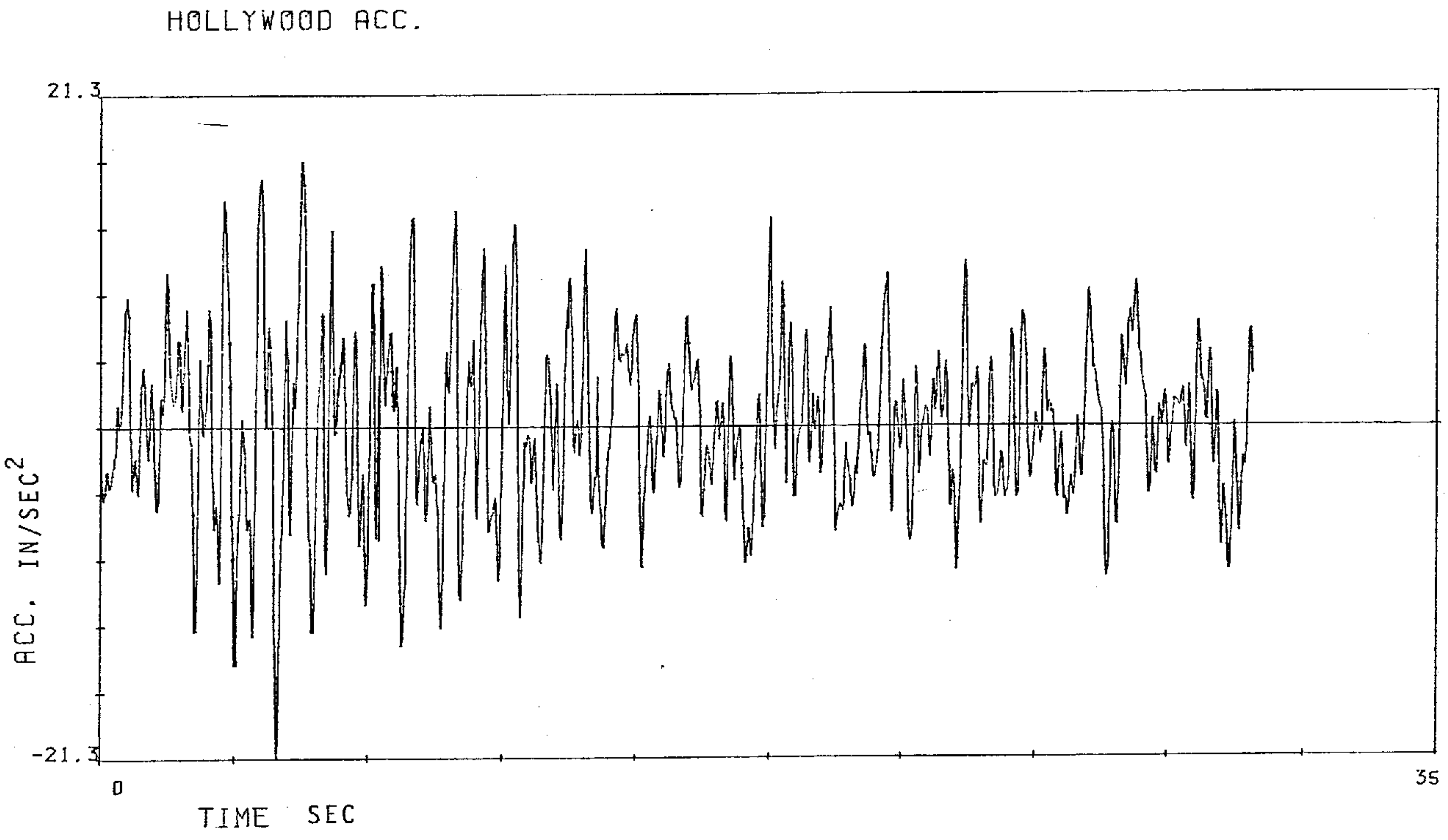

FIGURE 2: Hollywood Storage Basement

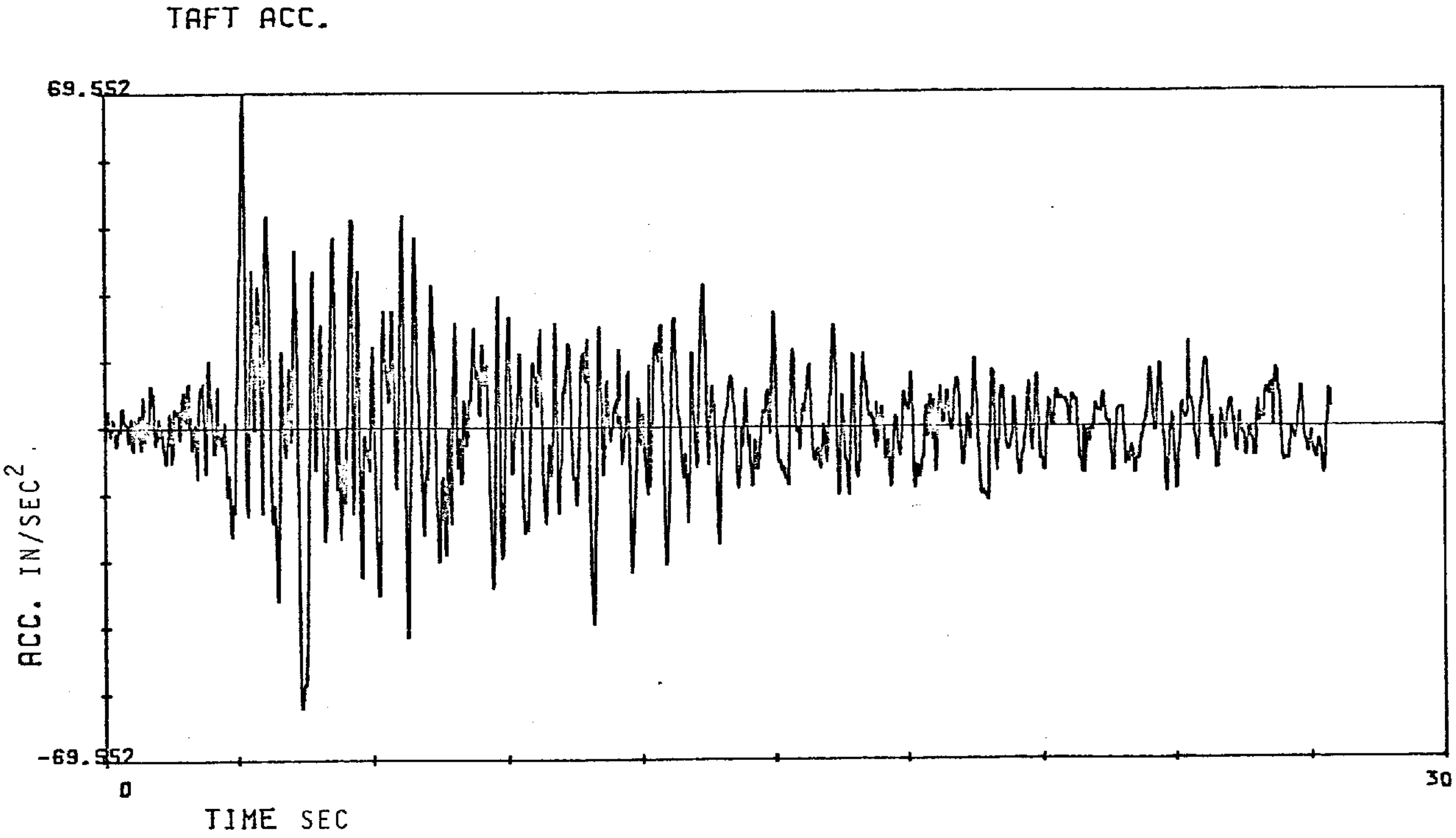

FIGURE 3: Taft Accelerogram

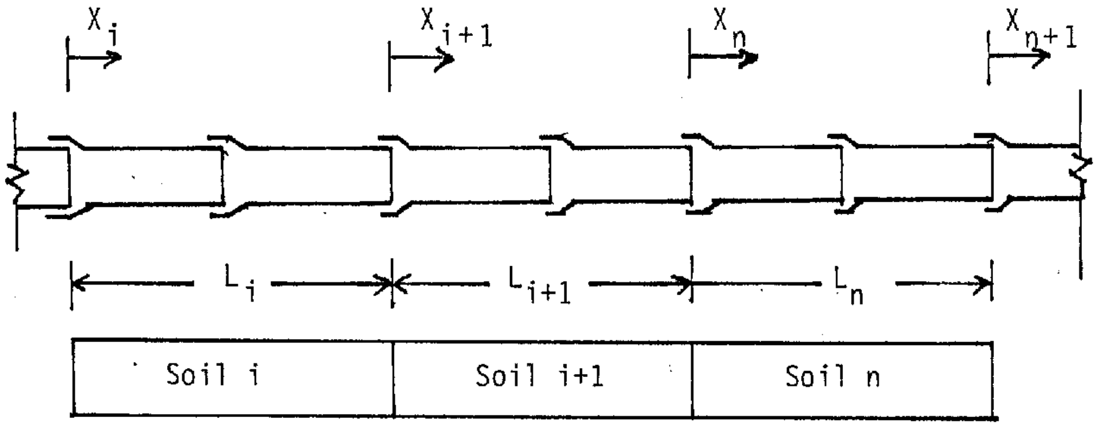

FIGURE 4: Pipeline Idealization

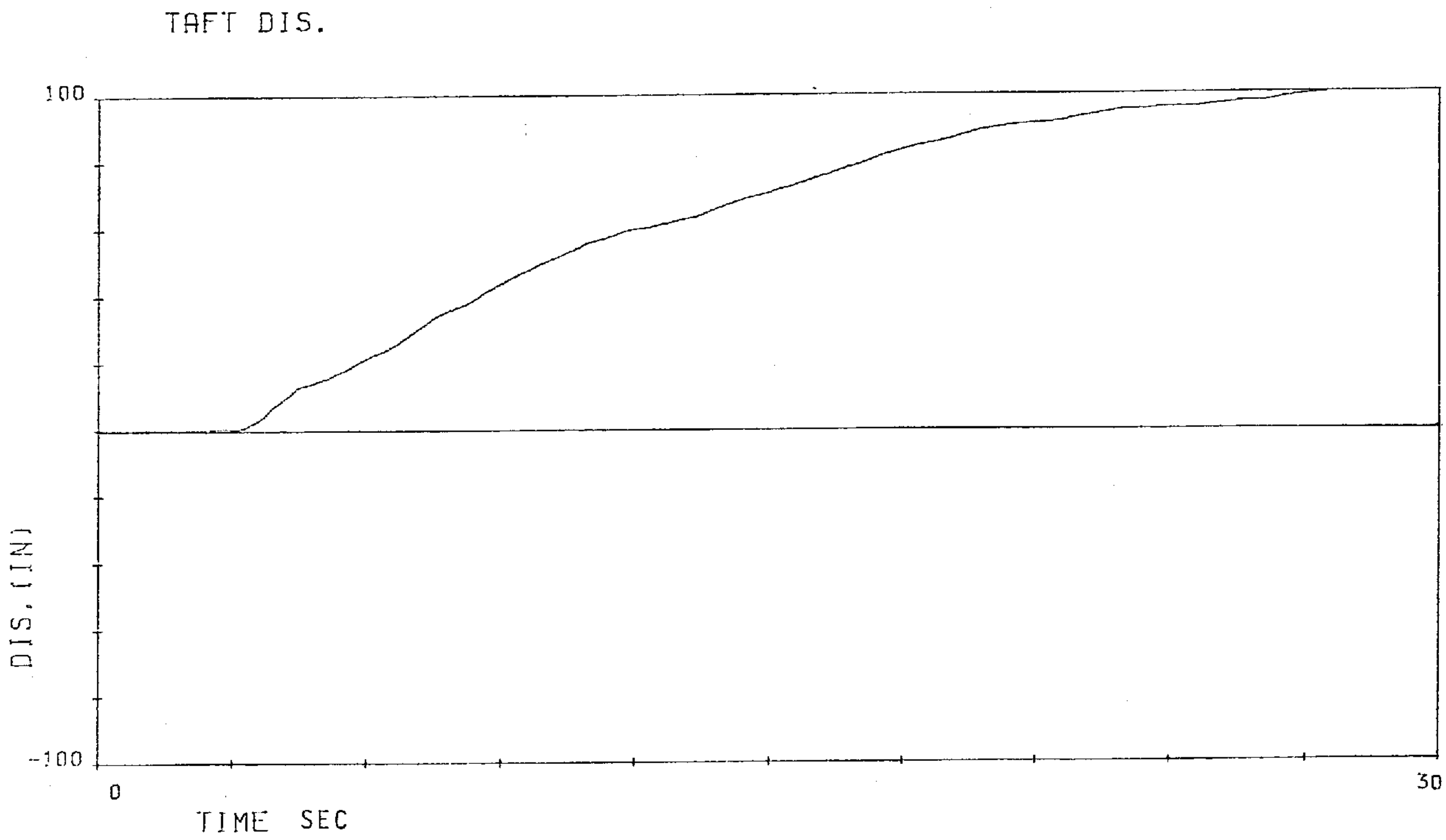

FIGURE 5: Ground Displacement vs. Time for Taft Record

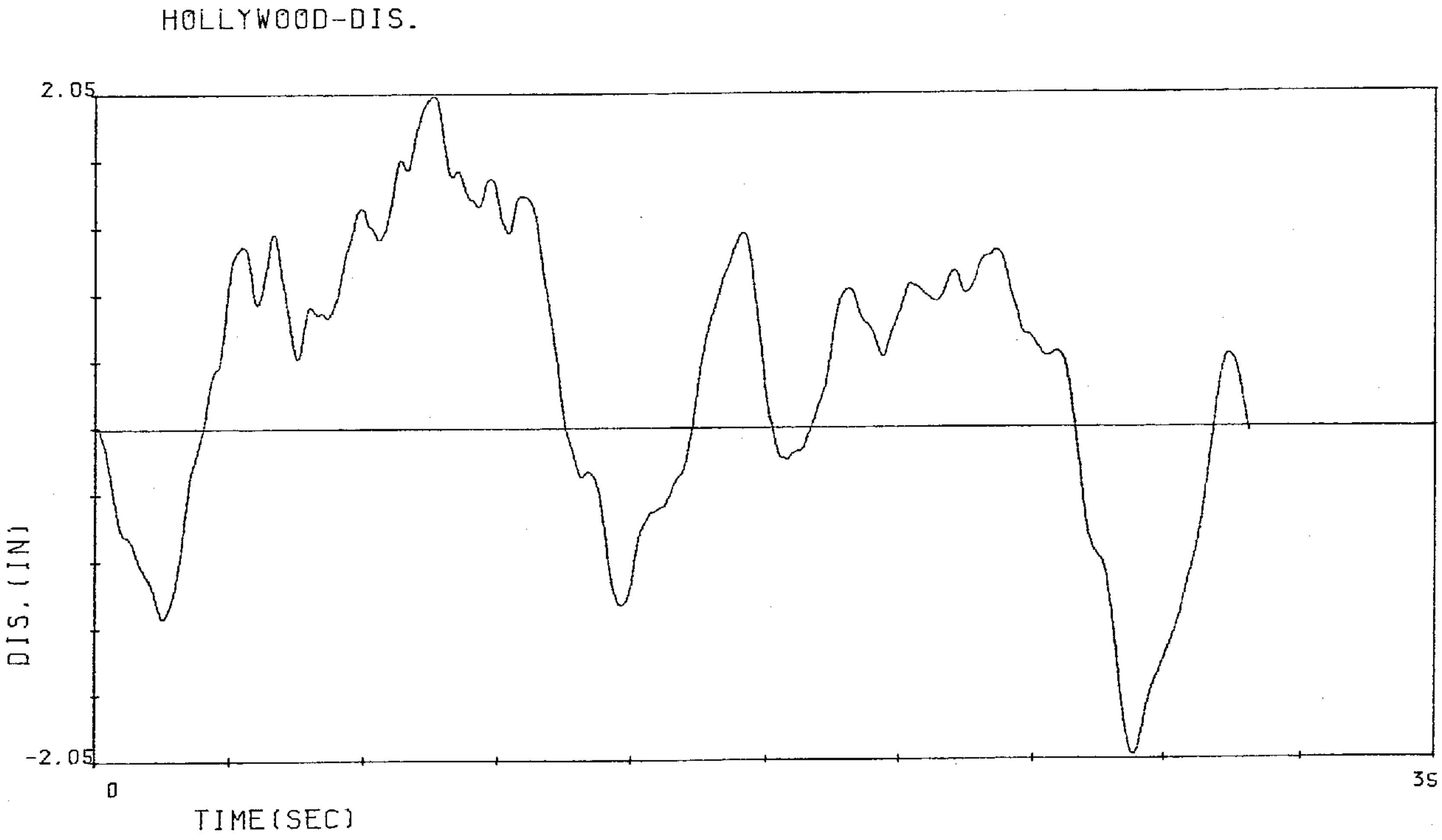

FIGURE 6: Ground Displacement vs. Time for Hollywood Record

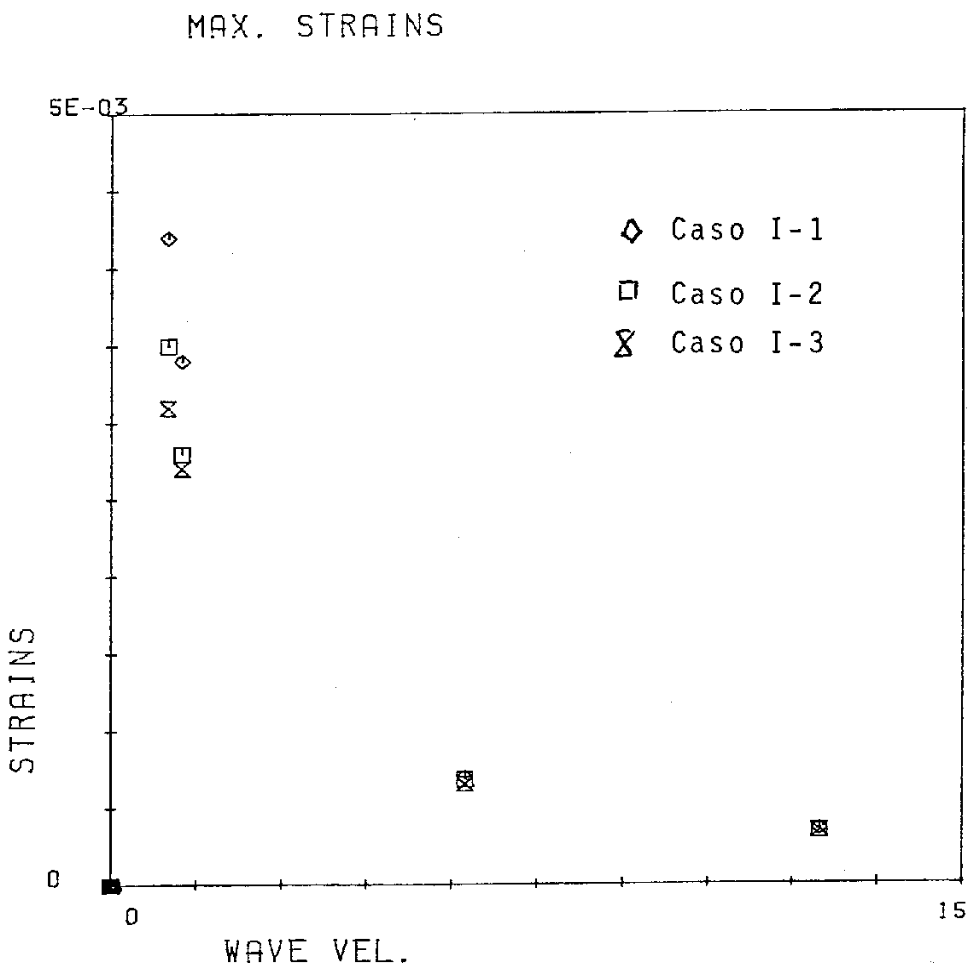

FIGURE 7: Maximum pipe axial strain for homogeneous soils

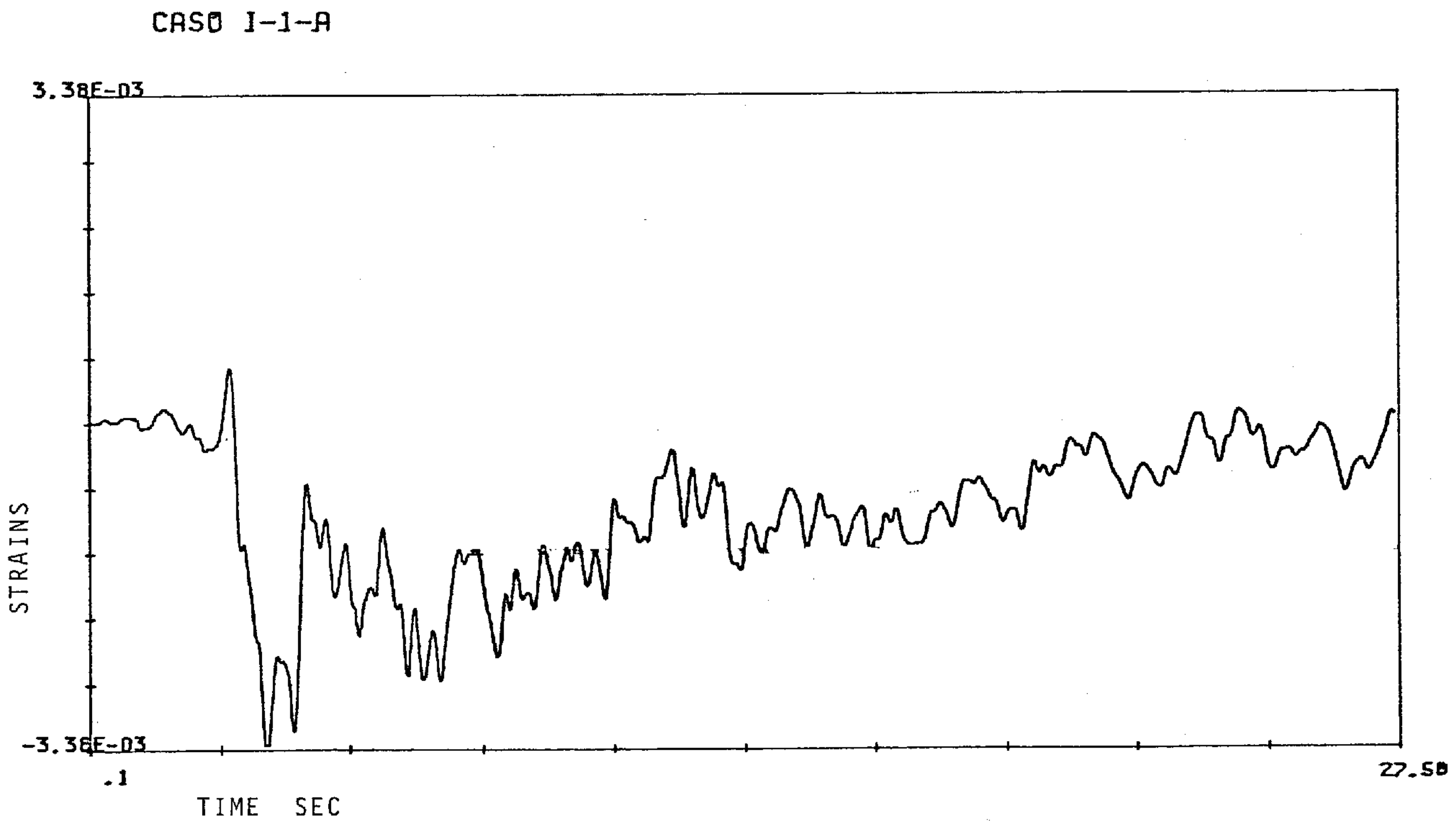

FIGURE 8: Typical Strains Time History of Pipeline for Homogeneous Soil

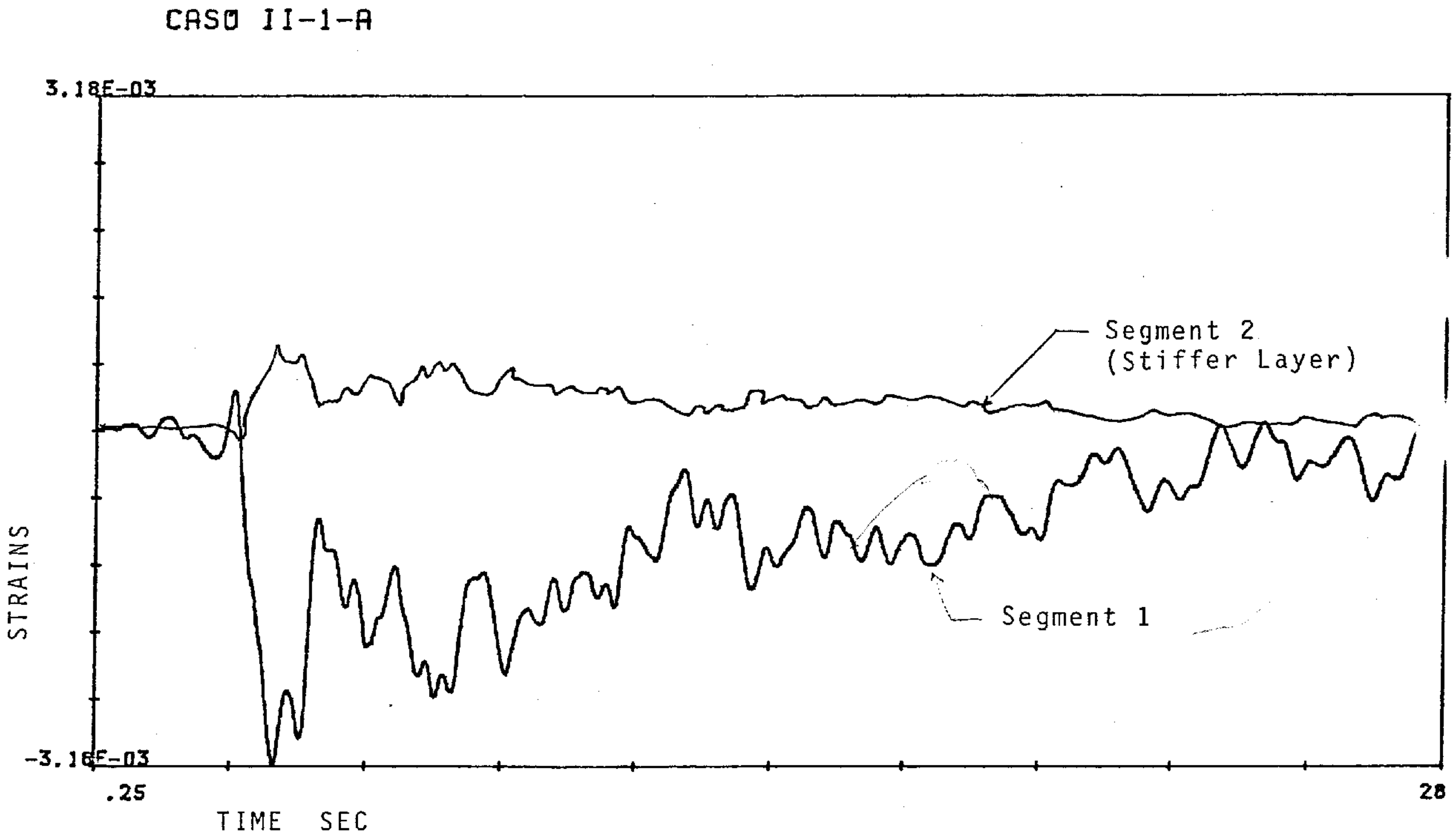

FIGURE 9: Strains Time History for Two Layers Conditions