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INFLUENCE OF GROUND SUBSIDENCE IN THE DAMAGE TO MEXICO CITY'S PRIMARY WATER SYSTEM DUE TO THE 1985 EARTHQUAKE

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SUMMARY

The main objective of this paper is to analyze the influence of ground subsidence, typical in the Valley of Mexico, in the observed damage to Mexico City's primary water system during the 1985 Michoacan earthquake.

According to the observed damage, it is believed that seismic wave propagation was the main cause for the failures. However, the accumulated subsidence in the Valley of Mexico could have increased the destructive action of the earthquake.

We analyze damage data to the primary water system during the 1985 earthquake and try to explain them using two variables: peak ground velocity –a parameter related to the earthquake– and accumulated ground subsidence –a parameter related only to the ground–.

The main conclusion of this paper is that ground subsidence, along with peak ground velocity, are better predictors of damage than peak ground velocity alone, which clearly indicates that ground subsidence is an important vulnerability factor. Finally, according to the results, the seismic damage to buried pipeline water systems could be increased by the effect of ground subsidence. This effect was identified only for weak ground motions. For strong ground motion, it was not possible to quantify the effect of ground subsidence.

INTRODUCTION

After the occurrence of the 1985 Michoacan earthquake, it is believed that the main cause for the failures in the Mexico City's Water System (MCWS) was the seismic wave propagation. However, the ground subsidence could have increased the damage (Ayala [1]).

In order to analyze the pipeline failures due to the influence of seismic wave propagation, the damage has been associated to peak ground acceleration (PGA) and peak ground velocity (PGV). Theoretically, PGV

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is better related to buried pipeline seismic damage. Pineda [2] demonstrated that PGV has better correlation with damage than PGA, for the observed damage in the MCWS after the occurrence of the 1985 Michoacan earthquake. Some authors have proposed several damage functions in order to estimate the damage in the water system, using PGV as a seismic parameter (O'Rourke [3] and Pineda [4]); however, there is not a function which includes the effect of ground subsidence and takes into consideration the pipeline diameter. This paper intends to propose damage functions considering two variables: peak ground velocity PGV, which is a parameter related to the earthquake, and ground subsidence, a parameter related only to the ground. These functions were associated to 3 important pipeline diameters in the system.

DAMAGE FUNCTIONS USING PEAK GROUND VELOCITY AND SUBSIDENCE AS PARAMETERS

Figure 1 shows the spatial distribution of the mean annual ground subsidence values for Mexico City between 1983 and 1992 (DGCOH [5]). In the same picture the Mexico City's water system and the observed damage sites after the occurrence of the 1985 earthquake are shown.

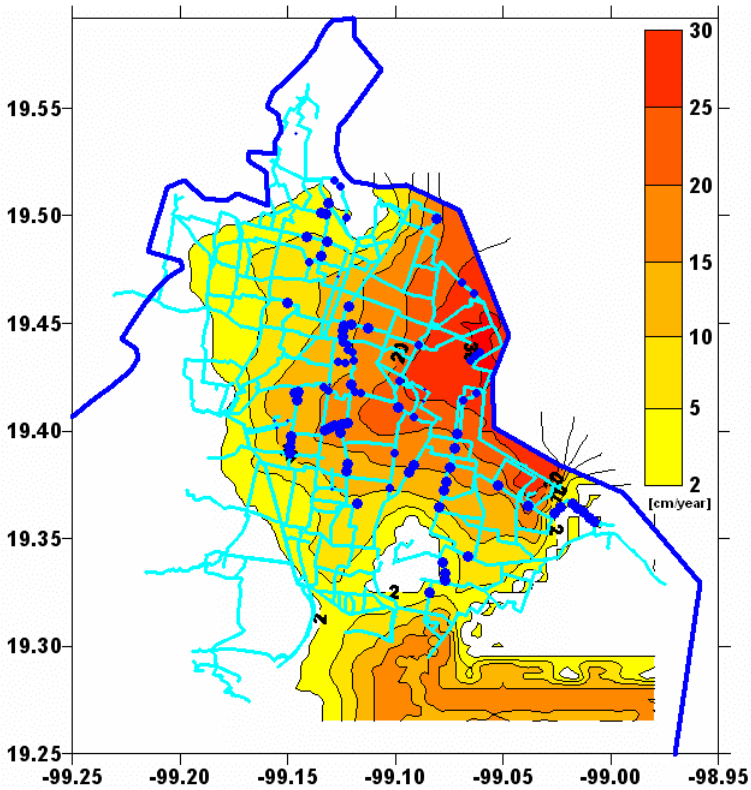

Figure 1. Mean Annual Ground Subsidence Map (1983-1992), Mexico City's Primary Water System and Repair Sites after the Occurrence of the 1985 Earthquake

It is considered that the ground subsidence has influence in the buried pipelines damage because the joints could be partially affected; and, as a consequence, a higher number of failures due to ground motion could be expected than the number expected without the influence of ground subsidence.

Figure 2 shows the estimated peak ground velocity map for the 1985 Michoacan earthquake (Pineda [2]). There, the dashed zone, which includes the well-known transition and lake zones, is composed mainly by

clay sediments which produce dynamic amplification of seismic waves. For this reason the PGV levels in the dashed zone are higher than the PGV values in the hill zone (located outside of the dashed region).

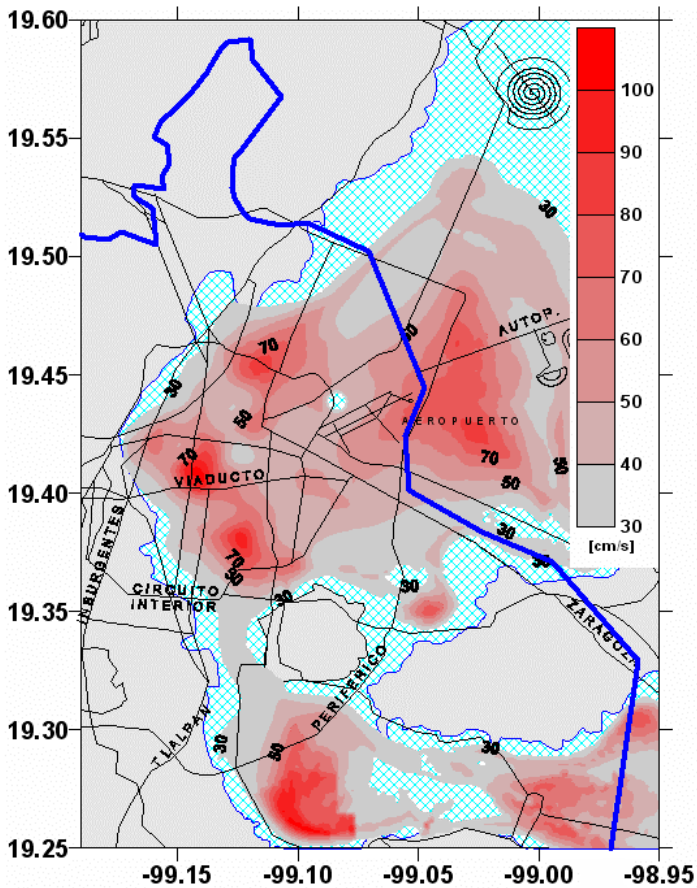

Figure 2. Peak Ground Velocity Map for the 1985 Earthquake

Comparing the spatial distributions of ground subsidence (fig. 1) and PGV (fig. 2) it is important to notice that there is a close relation between these two factors. This is a problem in the damage estimation, because a function which uses correlated parameters could produce ambiguous results.

However, the pipeline damage is not necessarily related to the absolute ground subsidence values; we believe damage is better correlated with the relative ground subsidence in the direction of each pipeline segment. In other words, the important parameter is the deflection angle γ of the pipe segment caused by the ground subsidence, which can be estimated with equation 1.

$$\gamma = \frac{|H_f - H_i|}{L} \quad (1)$$

Where *Hi* and *Hf* are the ground subsidence values associated to the initial and final end of each segment pipe with length *L*. γ is the mean annual deflection angle, caused by the relative ground subsidence in the segments. Since the authors do not have reliable information about the age of each pipeline segment, age has been considered uniform for the whole water system.

In order to get better results in this study, the water system was divided in pipe segments with length equal to 50 m or less.

Relation Between γ and the observed damage

In order to get a better appreciation of the influence of γ in the observed damage, damage index values were calculated taking into consideration the relative ground subsidence as a unique parameter. These values are shown in figure 3. By omitting other parameters (e.g. PGV) it was possible to verify that, as a general tendency, the damage index increases as γ does, for most values of γ. However, for γ larger than 0.0041E-04 there is a discontinuity, which could be explained by the scarce pipeline length associated to these levels of γ. For this reason, these data points were discarded in further analyses.

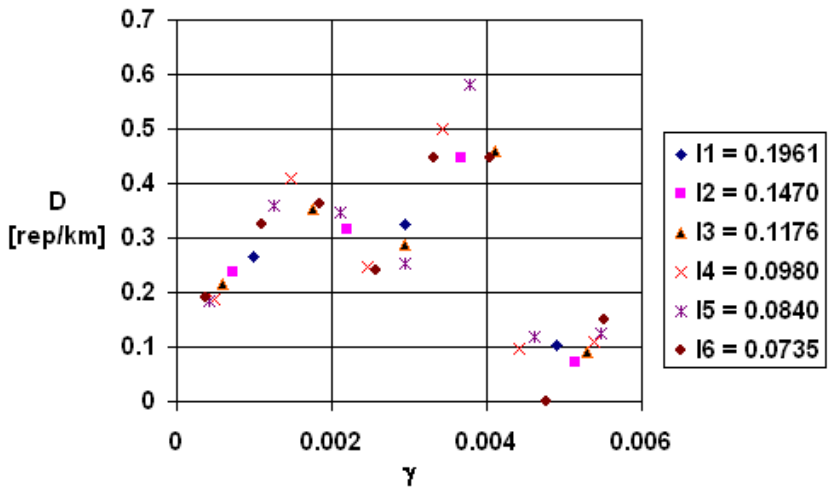

Figure 3. Damage indexes associated to different relative subsidence values

Damage functions using γ and PGV as parameters

Here, we determine damage functions that relate *D* with PGV and γ. Since *D* is a sort of "damage density" parameter, there is not a unique way of relating damage with γ and PGV, because the procedure to calculate the damage data points is the following: 1) divide the water system in zones associated to intervals of γ and PGV; 2) count the number of repairs; 3) measure the pipeline length in that zone; and 4) calculate the average damage *D* in the zone as the ratio between the number of observed repairs and the pipeline length. This average damage, then, would be related with the PGV and γ values associated to the zone. We discarded the data points with damage index equal to zero.

Following the procedure described, the damage functions, for pipelines with 3 different diameters (figures 4, 5 and 6), were calculated. Pipelines with 20" and 48" were selected because they have the greatest length proportion in the water system (23.22% and 53.57%, respectively). The damage function for *D* = 32", although associated to a small pipeline length (only 3.77% of the total length), shows the effect of ground subsidence.

In view of the procedure to calculate the mean damage indexes *D*, it is difficult to reduce dispersion, and as a consequence, to adjust equations. Equations 2 to 10 are proposed in order to estimate the number of pipeline repairs taking into consideration the effect of ground subsidence and the ground motion intensity (measured as PGV), for 3 different pipeline diameters.

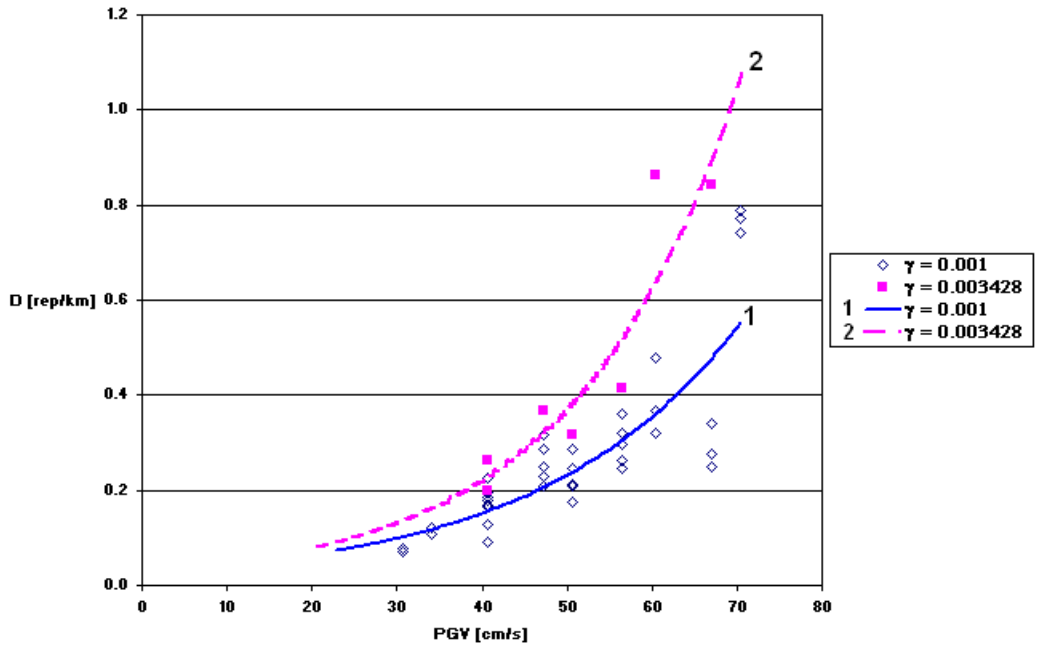

Figure 4. Damage Function for Pipelines with *D* = 20”

Damage functions for pipelines with $D = 20$” are:

For $\gamma = 0.001$ (fig 4, 1) $$D = 0.0273 \cdot e^{0.0521 \cdot PGV} \quad (2)$$

For $\gamma = 0.003428$ (fig 4, 2) $$D = 0.0277 \cdot e^{0.0425 \cdot PGV} \quad (3)$$

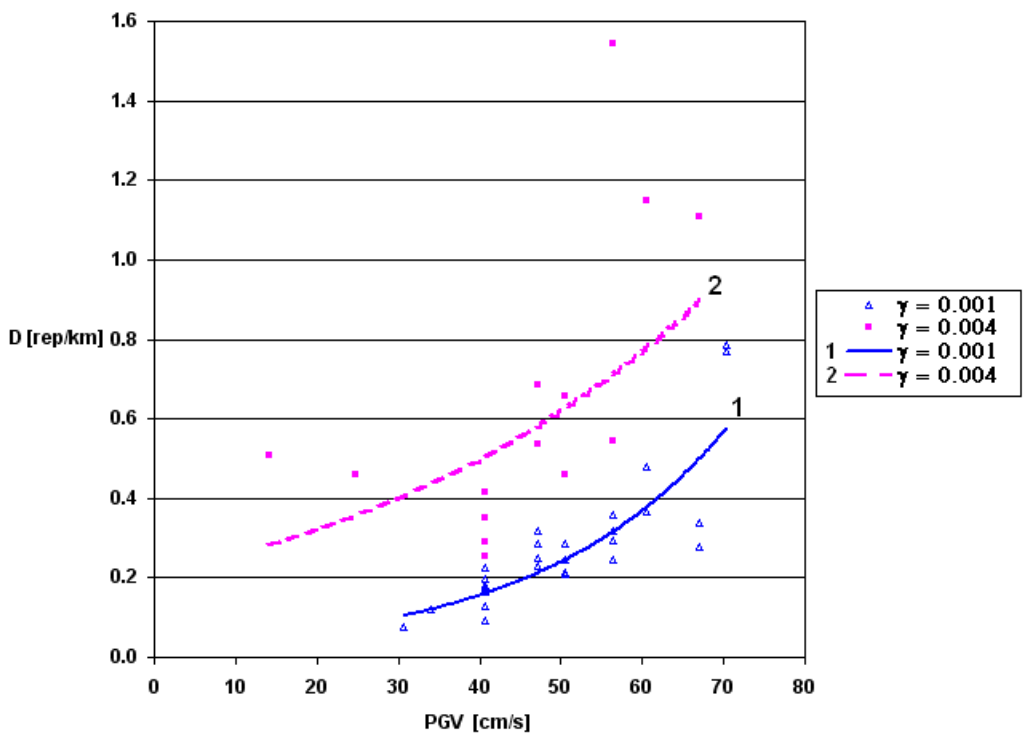

Figure 5. Damage Function to Pipelines with *D* = 32”

Damage functions for pipelines with D = 32" are:

For $\gamma = 0.001$ (fig 5, 1) $$D = 0.0283 \cdot e^{0.0429 \cdot PGV} \quad (4)$$

For $\gamma = 0.004$ (fig 5, 2) $$D = 0.207 \cdot e^{0.0218 \cdot PGV} \quad (5)$$

Most of the 20" and 32" pipelines are made of steel, concrete and asbestos cement.

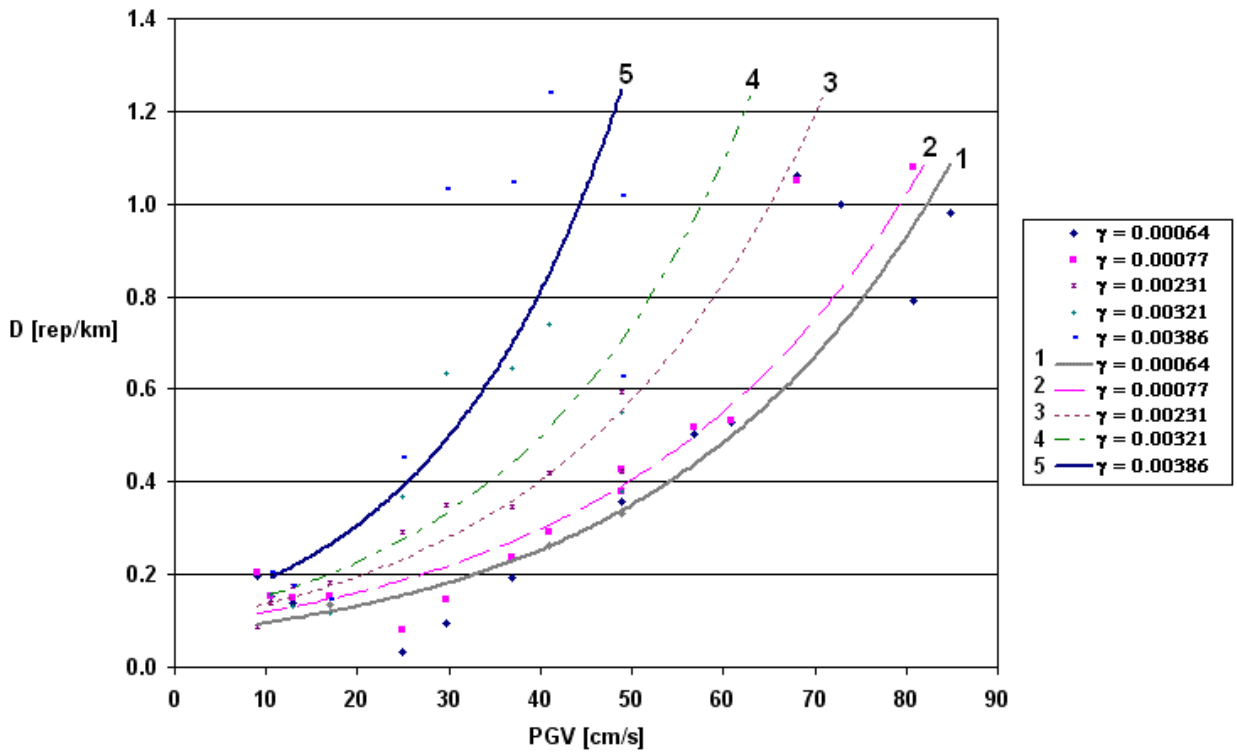

Figure 6. Damage Function to Pipelines with D = 48"

Damage functions for pipelines with D = 48", which are mainly made of prestressed concrete, are:

For $\gamma = 0.00064$ (fig 6,1) $$D = 0.0691 \cdot e^{0.0325 \cdot PGV} \quad (6)$$

For $\gamma = 0.00077$ (fig 6,2) $$D = 0.0874 \cdot e^{0.0307 \cdot PGV} \quad (7)$$

For $\gamma = 0.00231$ (fig 6,3) $$D = 0.0948 \cdot e^{0.0362 \cdot PGV} \quad (8)$$

For $\gamma = 0.00321$ (fig 6,4) $$D = 0.1033 \cdot e^{0.0394 \cdot PGV} \quad (9)$$

For $\gamma = 0.00386$ (fig 6,5) $$D = 0.1167 \cdot e^{0.0485 \cdot PGV} \quad (10)$$

QUANTIFYING THE EFFECT OF RELATIVE SUBSIDENCE IN THE SEISMIC DAMAGE

The objective of the following results is to quantify the effect of ground subsidence in the pipeline seismic damage. This was possible because some of the failures observed after the 1985 earthquake were related to γ values equal to zero. Then, seismic wave propagation must have been the only cause of failures. D values associated to $\gamma = 0$, were calculated and compared to other data points used to calculate a damage function (Pineda [4]) which considers only the effect of ground motion, measured with PGV (figure 7 and equation 11), but includes implicitly the effect of ground subsidence.

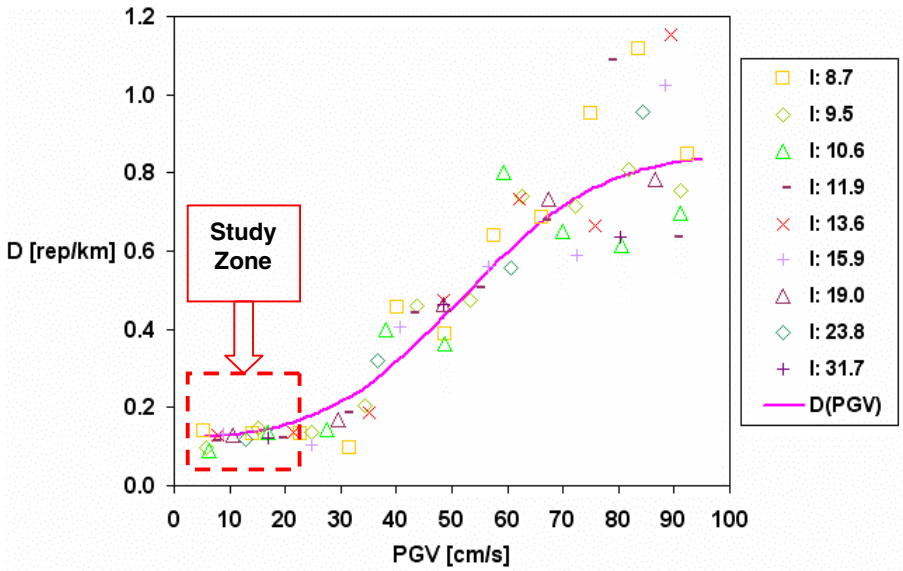

Figure 7. Damage Function to MCWS, Proposed by Pineda [4]

$$D(5.35 \le V < 95) = 0.1172 + 0.7281 \cdot \hat{n}(V; 51.8964, 19.7811) \qquad (11)$$

In equation 11, $\hat{n}$ is the cumulative normal function, defined by equation 12; and V is the peak ground velocity in cm/s.

$$\hat{n}(V; \mu, \sigma) = \int_{-\infty}^{V} \frac{1}{\sqrt{2\pi}\sigma} e^{-(1/2)[(v-\mu)/\sigma]^2} dv \qquad (12)$$

D was calculated dividing the PGV map in zones of equal PGV intervals (9 PGV intervals were used), and estimating the ratio between the number of repairs and the pipeline length. For the purpose of this study, we selected, from figure 7, only the data points associated to PGV smaller than 20 cm/s (fig 10, case 1), because the available damage data points associated to sites with $\gamma = 0$ are only found in this PGV interval (fig 8, case 2).

In figure 8 the effect of ground subsidence on damage index *D* is evident. Case 1 includes data points from figure 7, in which the effect of ground subsidence is implicitly accounted for; case 2 includes only data points associated to sites without relative ground subsidence.

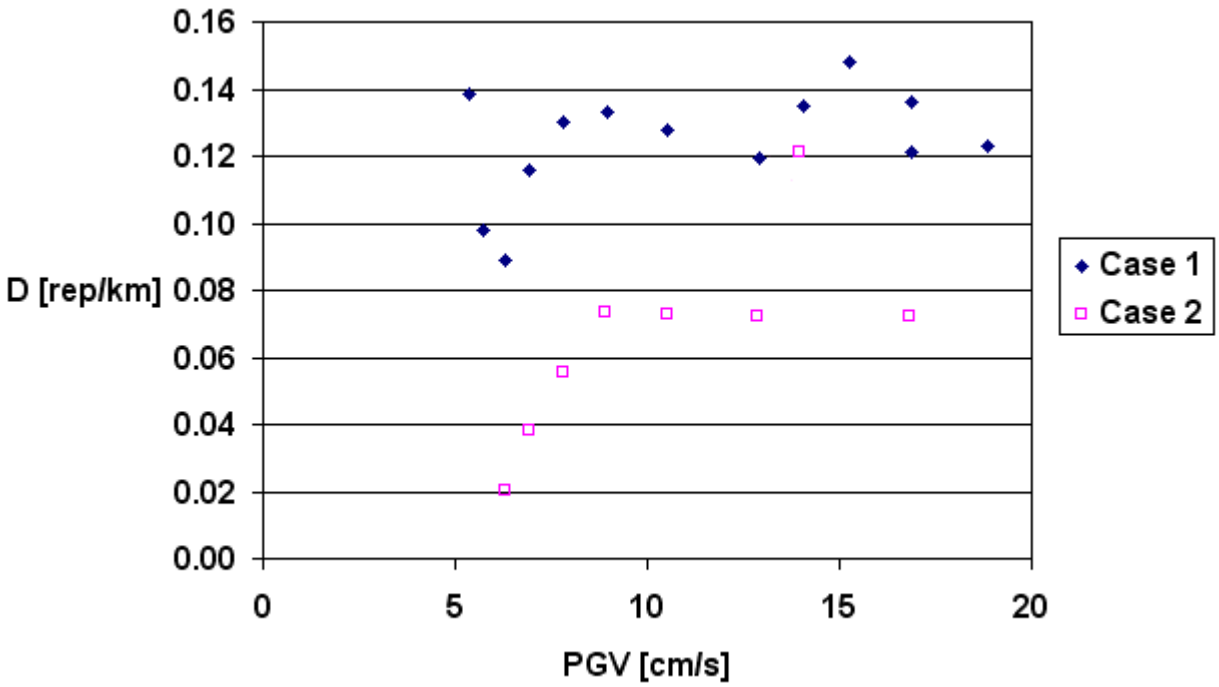

Figure 8. Damage indexes With and Without the Relative Subsidence Effect. (For PGV < 20cm/s)

CONCLUSIONS

We analyzed the effect of ground subsidence in the seismic damage to Mexico City's Primary Water System during the 1985 Michoacan earthquake. Using peak ground velocity and relative ground subsidence as parameters, three damage functions, for pipe diameters of 20", 32" and 48", were determined. These functions estimate the damage index, measured as the number of expected repairs per unit length, for different levels of ground motion and different relative ground subsidence levels. It was found that the damage index D increases with the ground motion intensity, and, additionally, with the relative ground subsidence γ. In other words, the effect of γ increases D for a specific ground motion intensity, which indicates that γ is an important parameter in the estimation of seismic damage to the water system studied and others systems located in sites affected by ground subsidence.

Finally, we compared damage indexes considering two cases: Case 1 includes data points in which the effect of ground subsidence is implicitly accounted for; case 2 includes only data points associated to sites without relative ground subsidence. It was found that, for PGV values less that 20 cm/s, the effect of ground subsidence could have increased the seismic damage to the water system, during the 1985 earthquake; for PGV values higher than 20 cm/s, this effect was not analyzed, because enough damage data were not available.

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