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# Static and Dynamic Effects of the Pipe Insertion Machine Technique

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A new method of in-place sewer reconstruction called the Pipe Insertion Machine was field tested by the U.S. Army Construction Engineering Research Laboratory. The technology uses an impact mole to break up the existing pipe and force it into the surrounding soil as the new pipe is pushed into the space created by the impact mole. The field test monitored stress induced in an adjacent pipe, soil displacement, and vibrations. The results indicate that, under the site conditions of this test, the reconstruction method was successful and induced very little stress on the surrounding utilities. Vibrations may be a problem for certain structures in the immediate vicinity of the impact mole, but vibrations damp out quickly a short distance away.

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A new method of in-place sewer reconstruction called the Pipe Insertion Machine was field tested by the U.S. Army Construction Engineering Research Laboratory. The technology uses an impact mole to break up the existing pipe and force it into the surrounding soil as the new pipe is pushed into the space created by the impact mole. The field test monitored stress induced in an adjacent pipe, soil displacement, and vibrations. The results indicate that, under the site conditions of this test, the reconstruction method was successful and induced very little stress on the surrounding utilities. Vibrations may be a problem for certain structures in the immediate vicinity of the impact mole, but vibrations damp out quickly a short distance away.

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# STATIC AND DYNAMIC EFFECTS OF THE PIPE INSERTION MACHINE TECHNIQUE

Demetres Briassoulis, Stephen W. Maloney, and Steve Sweeney

## INTRODUCTION

Repair, renovation, and renewal are the major options in sewer rehabilitation. Many communities face serious problems with a large percentage of sewers being either collapsed or in need of urgent attention. Severely damaged, fractured, or deformed sewers require complete replacement or a systematic program of renovation [1,2].

A relatively new technique of renovation is the so called on-line replacement. This is a method for replacement of the existing pipe without excavation, by utilizing the "hole" which already exists in the form of the old pipe. Thus, on-line replacement does not require excavation nor does it rely on the uncertain structural condition of existing sewers. It can be designed for a long period (i.e., 50 years) by utilizing new technology and materials. Safety concerns associated with working in trenches are also eliminated.

The most recent development in the area of on-line replacement concerns microtunneling and similar techniques. Microtunneling is primarily intended for relatively large diameter pipes (diameters above 0.9 meters [3]). Mechanized pipe jacking is another on-line replacement scheme which is basically designed for thick walled reinforced concrete pipes. The most rapidly developing method of on-line replacement of utility pipelines, however, is the Pipe Insertion Machine technique (PIM) [3-6].

The PIM technique consists of physically breaking up an existing pipe by an advancing impact mole. The mole is followed by a new pipe jacked through the void. One of the most important advantages of this technique is that it can increase hydraulic capacity by placing a larger pipe in the place of a smaller one, without a trench along the entire route [6]. Insertion and reception pits are required as in sliplining, but unlike lining, the PIM technique does not reduce internal diameter.

Pneumatically operated moles have been used most often, but hydraulically operated moles also exist. A pneumatic mole consists of a reciprocating hammer contained within an enclosed cylinder and powered by compressed air. The mole moves horizontally by the striking action of the hammer on a fixed head. Simultaneously, a radial force is exerted by the expanding tapered mole on the existing pipe and the surrounding soil. The expander, as the shield around the hammer cylinder is called, breaks up the existing pipe and pushes the broken pieces into the surrounding soil which is locally consolidated [6]. In this way, the PIM technique can be used to replace an existing pipe by a similar one or by a pipe of a larger diameter.

The PIM technique has been used to replace pipes of cast iron, vitrified clay, unreinforced concrete, pitch fiber, asbestos cement, and UPVC. It cannot, however, be used for pipes of ductile materials, such as reinforced concrete, ductile iron, steel, or some plastic pipe [6].

The pipe insertion machine technique is rather new and there is no long term data available regarding its overall performance. Potential damage of adjacent utilities and the surrounding soil due to induced strains and deformation, potential damage to adjacent structures due to vibration and potential long term deflection of the new pipe are the most serious considerations. Experimental studies to assess the effects of the impact mole technique on adjacent pipes and the surrounding soil have been initiated in England, and the first results are rather encouraging [7-9]. An experimental study, similar to the ones conducted in [7-9], was undertaken to confirm the generality of the results obtained from the earlier studies.

This paper concerns the experimental study (see also [10]) conducted at Fort Belvoir, Virginia, in the summer of 1987. The PIM technique was used to replace a 152 mm (6 in.) clay sewer pipe by a 203 mm (8 in.) diameter flexible pipe. The study focused on the strains induced on an adjacent instrumented pipeline, the deformation experienced in the surrounding soil, the peak particle velocity measured on the ground surface and the long term deflection of the installed flexible pipe.

## TEST CONDITIONS AND PROCEDURE

### Soil

Based on results of laboratory tests (performed by ATEC Associates, VA), the soil at the site where the test was conducted may be classified as fine sandy Clay (CL) with some silt. Moisture content was found to vary from 16.5 to 22.2 percent. Atterburg limits were found to vary as: Liquid Limit = 32 to 40 percent, Plastic Limit = 16 to 22 percent and Plasticity Index 10 to 22 percent. Dry density was 1600 to 1760 kg/m$^3$ (100 to 110 pcf). Field penetrometer tests indicated that the majority of insitu fill and natural soils exhibit unconfined compressive strength between 120 and 431 kN/m$^2$ (1.25 and 4.5 tsf). Sand pockets might be responsible for the variation in strength found with the penetrometer tests. Due to the high percentage of sand, all but one Shelby tube sample broke apart. The unconfined compression test of the single intact sample indicated unconfined compressive strength of 138 kN/m$^2$ (1.44 tsf). The corresponding undrained shear strength of 69 kN/m$^2$ (0.72 tsf) is considered indicative, but not representative, of the strength in the test site.

The undrained Young's modulus is in the range of (100 to 200 tsf) [ATEC Associates; personal communication]. A lower bound of the undrained Young's modulus at the test site was estimated from a laboratory test of a remolded sample to be 14.4 MN/m$^2$ (150 tsf).

### Test Setup

The existing sewer pipe consisted of two sections 30.5 and 40.7 m (100.5 and 133.5 ft), from manhole to manhole, respectively. The test was monitored within the first 30.5 m (100.5 ft) section. The layout of the site is shown in Figure 1. A "dummy" iron pipe was placed perpendicular to the sewer pipe to monitor strains. Three holes were bored in the soil above the sewer pipe to monitor soil displacements and geophones were placed in the same area to monitor vibrations. Details about the test set-up are given in [10].

## Instrumentation

Strains were measured on the crown and springer line of the instrumented pipe with 14 general-purpose strain gages. All gages were applied in the field and were protected for the underground application using a special protective coating (F-coating; by Microstrain). A four wire full bridge circuit was used to balance lead wire resistance and increase the accuracy of the measurements. Displacements of the soil above the sewer pipe were measured by position transducers. These same transducers were used to measure deflection of the new polyethylene pipe after installation. Two transducers were connected to telescopic spring loaded pistons. The pistons were attached perpendicular to each other in a flexible cylinder of diameter equal to the inside diameter of the polyethylene pipe. The cylinder was then pulled through the installed pipe. All strain and deflection measurements were recorded using a measurement and control system, with instantaneous measurements taken at 5 second intervals and dumped to final storage on magnetic tape.

Vibrations were monitored by geophones. A triaxial array of vertical and horizontal geophones was used to monitor peak particle velocity (PPV) on the pavement above the sewer line, and a vertical geophone was used at a distance 2.8 m from the sewer line. The natural frequency of these geophones is 4.5 Hz and, for vibration frequencies above 20 Hz, they have a sensitivity of 0.97 v/in/sec (verified through calibration). Amplifiers were used, one for each geophone, due to expected vibration of low intensity.

## RESULTS

The results of this test are discussed in detail in reference 10. They are also briefly summarized here to make the paper as self-contained as possible.

## Mole Speed

The average speed of the mole was found to be 0.82 m/min (2.7 ft/min). No friction was developed on the new pipe during insertion.
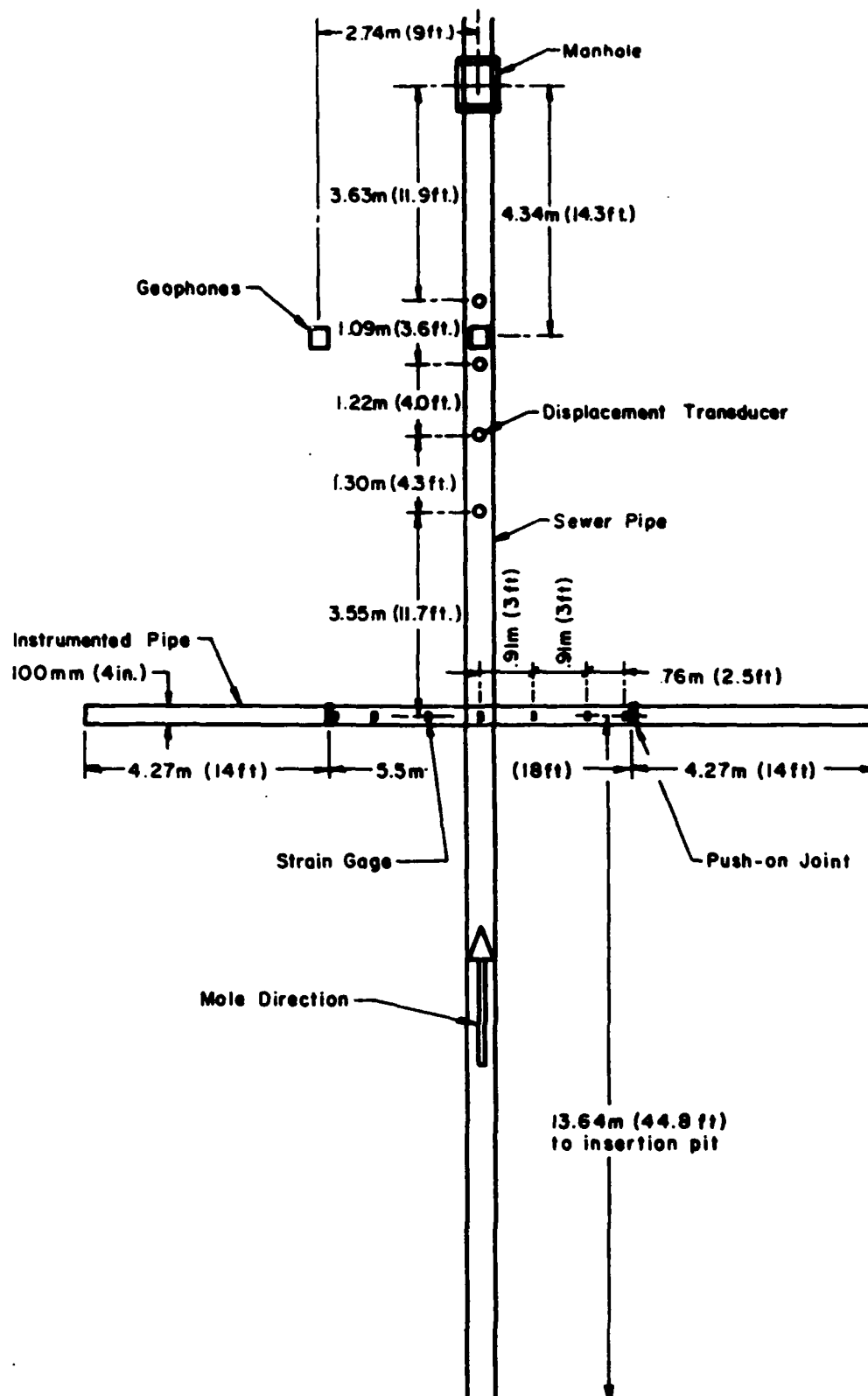
Figure 1. Schematic Diagram of Test Site.

## Strain

The longitudinal strains introduced in the instrumented pipe were not found to be, in general, significant (at least compared to those obtained in similar tests in England [10]). The maximum strain (200 $\mu\varepsilon$) was developed at the crown of the instrumented pipe just above the sewer pipe. The distribution of strain along the crown line is shown in Figure 2. This is a classic strain (stress) distribution for a beam on elastic foundation.

## Soil Displacement

The soil displacements measured at different elevations above the sewer pipe are shown in Figure 3. Maximum displacement is 15 mm (0.60 in.), measured at 410 mm (16 in.) above sewer pipe. This compares to an increase of pipe radius by 25 mm (1 in.), associated with an even larger expansion of the surrounding soil by the 260 mm (10 in.) diameter mole.

The general tendency observed in Figure 3 is that soil deformation experienced in this test is substantially plastic. This is a basic difference from the corresponding results obtained in England and may explain why the overall strains and displacements are lower in this case.

## Deformation of New Pipe

The deformation of the new polyethylene pipe, after it was inserted in place, is shown in Figure 4. Pipe deformation is described in terms of relative changes of the horizontal and vertical diameters. As the device entered into the free end of the pipe, in the reception pit, it showed no deformation until it entered the buried pipe. A gradual increase of deformation of the pipe is shown in that region (Figure 4). The deformation pattern is elliptical, as expected, remaining almost constant as the device was pulled through the buried new pipe. The maximum deformation is shown to be equal to 2.5 percent change of the pipe diameter. At the region of the joint, however, located approximately 12 m (38 ft.) from the free end, the device was stuck (and pulled back). An inner circumferential rib, left by the butt fusion procedure used to form the joints, did not allow the device to go through the rest of the pipe.
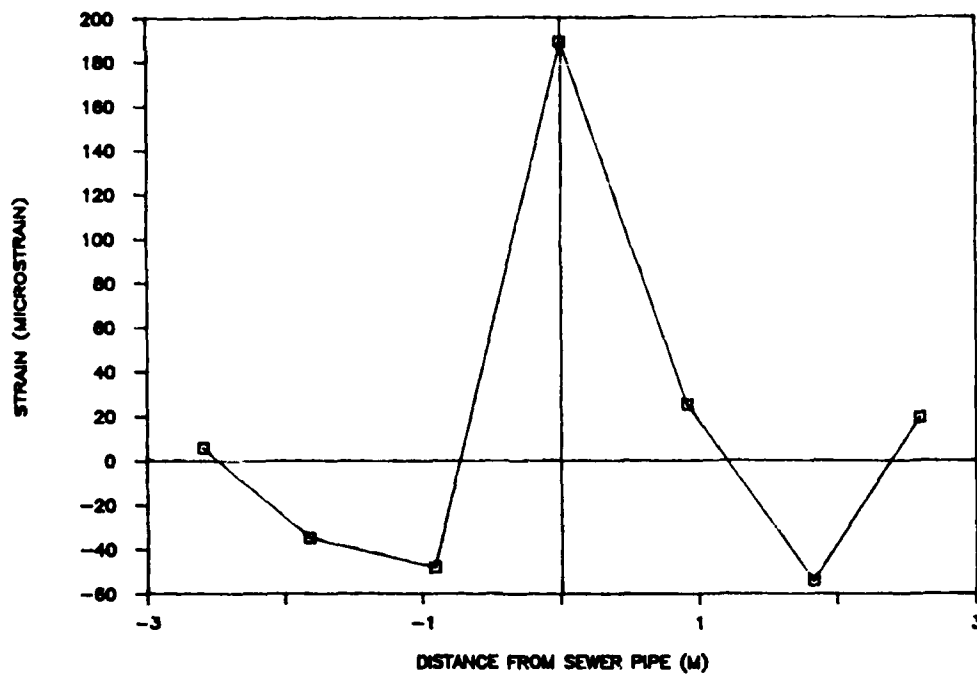
**Figure 2.** Longitudinal Strain Distribution Along the Crown Line of the Instrumented Pipe When Mole Was Passing By (mole beneath instrumented pipe).
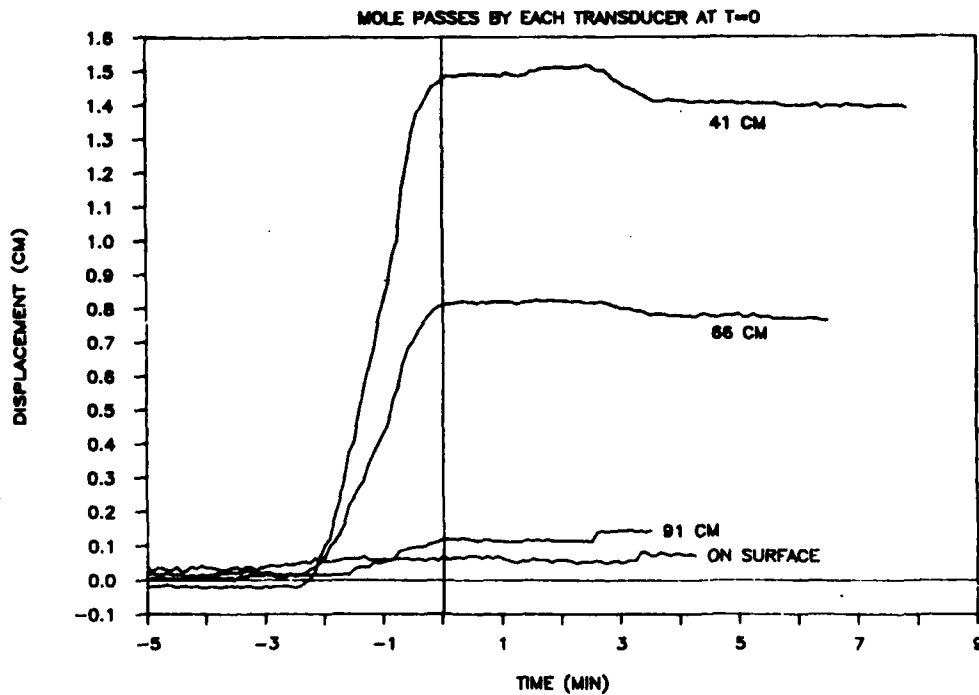
**Figure 3.** Soil Displacement as Different Depths Above Sewer Pipe as Mole Was Passing By. (Results are normalized so that time zero corresponds to the time when mole was beneath each displacement transducer).
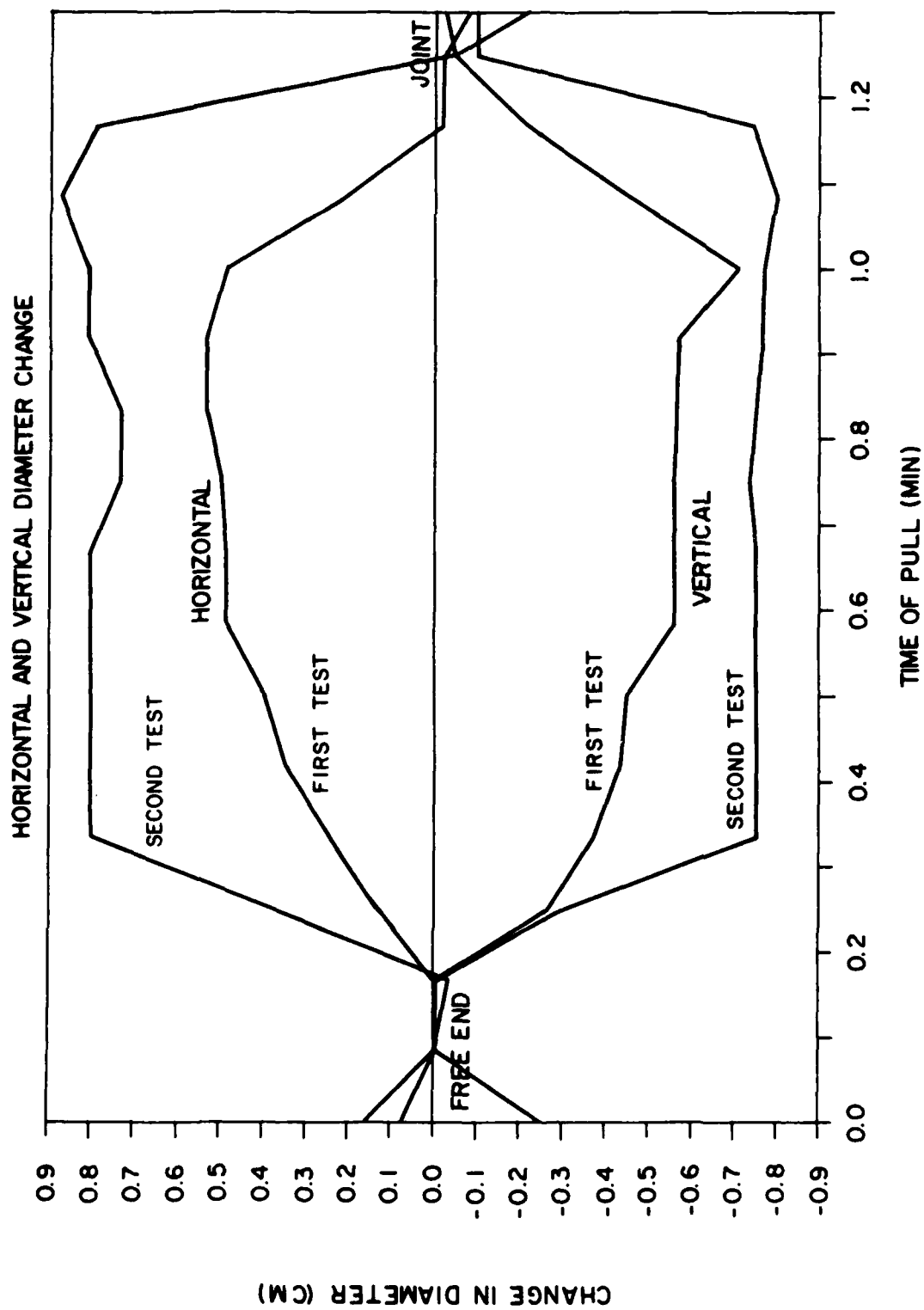
Figure 4. Deformation of Inserted Polyethylene Pipe After Installation (Deformation is elliptical described by relative changes in horizontal and vertical diameter of pipe).

A second test of pipe deformation was conducted 6 months after installation. Those results are also shown in Figure 4. The mode of deformation remained the same, but the magnitude increased to 4.5 percent of the initial diameter. This is close to the limit of maximum safe deflection of 5 percent for 8-inch SDR-17 HDPE pipe.

## Vibrations

Vibrations monitored on the pavement above sewer pipe were shown to be significant. The maximum vertical peak particle velocity reached 13.6 mm/sec (0.54 in./sec) when the mole was beneath the triaxial array of geophones, as shown in Figure 5. After the mole passed by, the PPV dropped. However, the vertical PPV, as well as the horizontal velocity in the direction of the mole movement, are shown to increase again as the mole approaches the manhole (Fig. 1). A similar observation was made in England [9]. The manhole may have acted to transmit the vibrations to the surrounding macadam, as the mole struck the side of the manhole.

The vertical PPV measured at a distance 2.74 m (9 ft.) from the projection of the sewer pipe line on the pavement, is shown to decrease just before the mole reaches the triaxial array of geophones. The vertical PPV measured by the distant geophone was only 1.55 mm/sec (0.61 in/sec) when the maximum vertical PPV was reached above the mole (Figure 5). This might be attributed to the presence of some underground obstacle resulting in a quick damping out of vibration with distance. The attenuation of vibration with distance at the time when the maximum vertical PPV is reached above the mole and at the time when the maximum vertical PPV is obtained at the distant geophone are plotted in Figure 6. The corresponding lines of attenuation of vertical PPV are found to be given by $v=107D^{-3.57}$ and $v=35D^{-2.35}$, respectively (where D is the distance between mole and geophones, and the exponent is the pseudo-attenuation factor; see reference [11]). Given that, in most cases, the pseudo-attenuation factor varies between 1 and 2 [11], whereas the factors obtained in this test are high and vary significantly within a small distance, it is believed that

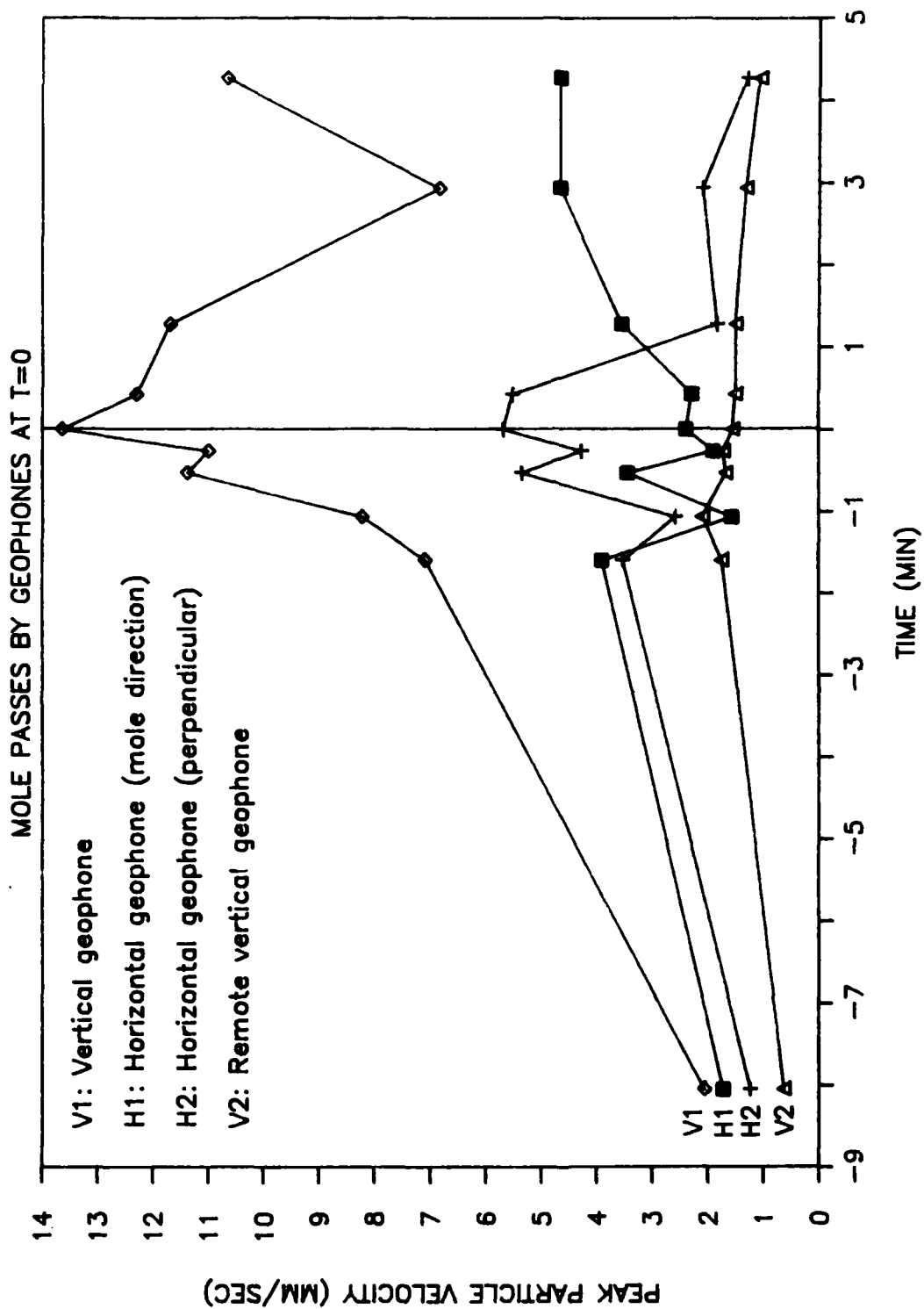Figure 5.   Peak Particle Velocities Above Operating Mole (V1, H1, H2: vertical, horizontal perpendicular and horizontal along the mole, respectively) and at a Distance of 2.74 m from the Projection of the Pipe on the Pavement (V2: vertical).
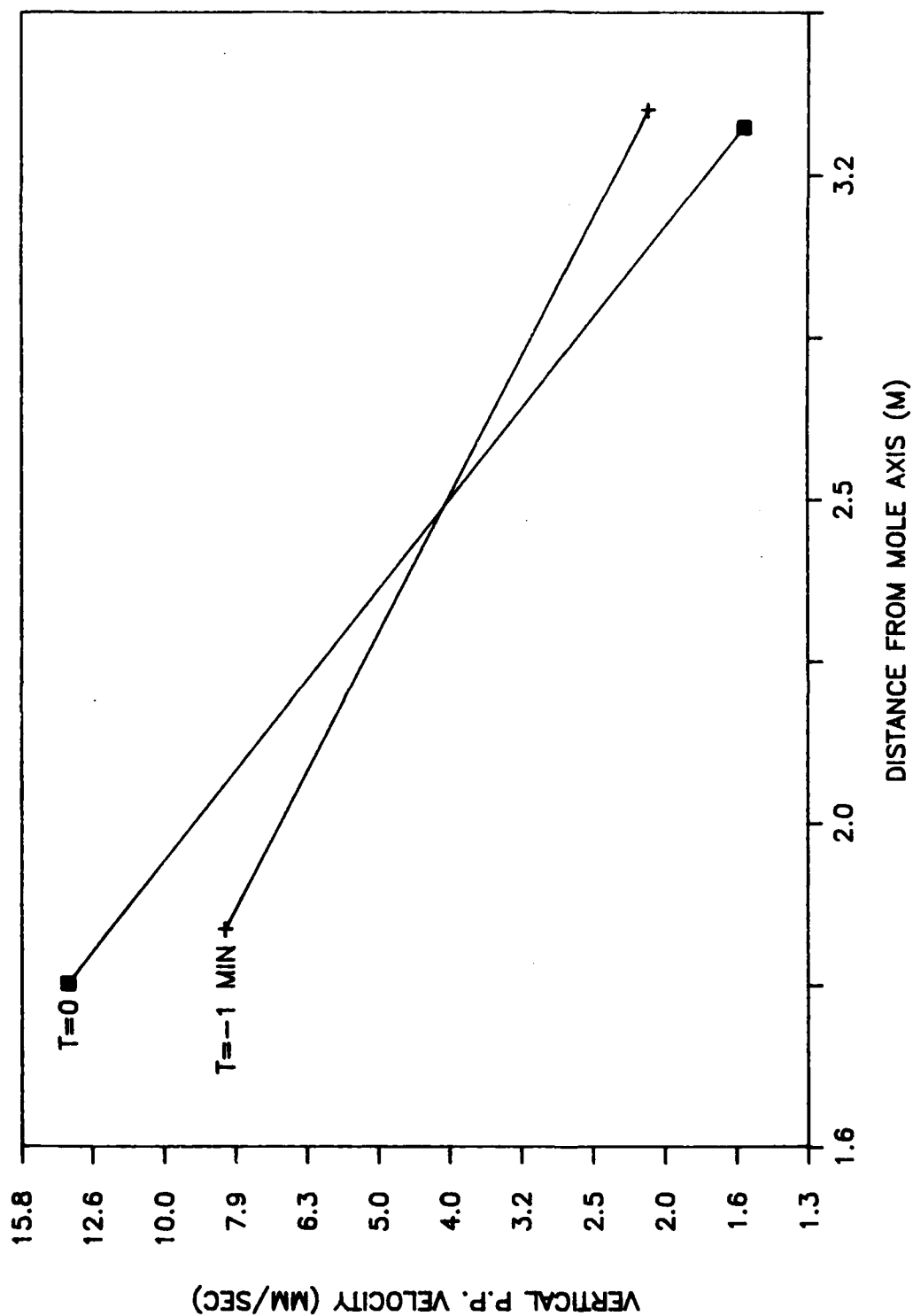
Figure 6. Attenuation of Vertical Peak Particle Velocity with Time. (Corresponding to data recorded when maximum velocity was reached above mole; time 0, and at the distant geophone; time -1).

transmission of vibrations was not uniform in this case, probably due to nonuniform underground conditions.

## ANALYSIS OF STRAIN AND DEFORMATION

### Test Procedures

A comparative analysis between the results obtained from a series of tests performed in England [7-9] and the results obtained from the present test can be found in [10]. The results of the analysis of [10] can be summarized as follows:

Higher strains were induced in adjacent instrumented pipes in the tests in England, compared to the present test. It was shown that this is a result of the direct relationship existing between mole power, size of pipe to be replaced and pipe oversizing on the one hand, and bending strains induced in adjacent pipelines on the other. This relationship, however, is very much affected by the soil type, and it is inversely dependent on the stiffness of the adjacent pipeline under consideration.

### Analytical Procedures

The strains/displacements induced on adjacent pipelines by the PIM technique and to the surrounding soil can also be analyzed by utilizing appropriate theoretical models. Such a model was developed by O'Rourke [12]. Application of this, or any other model, to the present test case, however, should be done with major reservations because of the inadequate determination of soil properties. Therefore, utilization of the model of O'Rourke [12], in this case, is only intended to investigate some general trends rather than to compare numerical results.

O'Rourke's model [12] studies the ground movement patterns associated with expanding methods of trenchless pipe laying techniques in undrained clay. The PIM technique is modeled as an expanding cylindrical cavity in a perfectly elastoplastic material (Figure 7). The basic assumptions of the analytical model are that the cylindrical cavity expands under plane strain, the
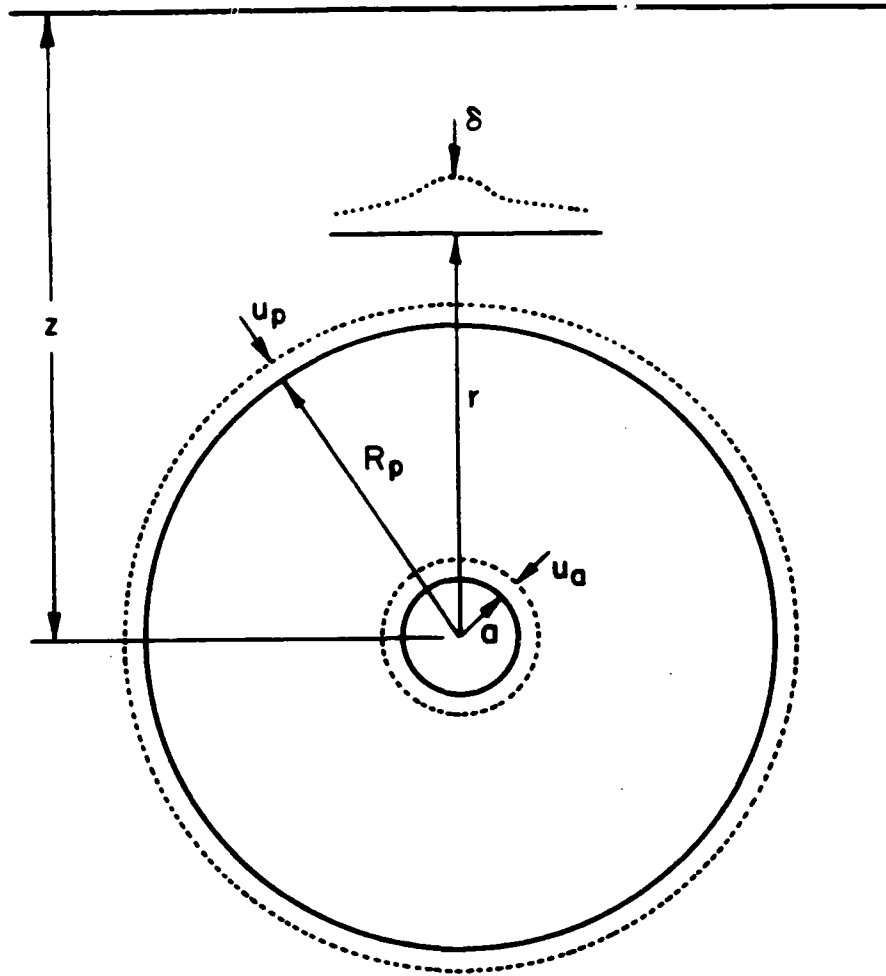
Figure 7. Analytical Model of the Expanding Cylindrical Cavity [12].

perfectly elastoplastic undrained clay is homogeneous and isotropic, the depth

of the cavity is larger than twice the radius of the plastic deformation

around it $(z>2R_p)$ and that the radius of plastic deformation $R_p$ is much larger

than the expansion $(u_p)$ of the initial radius of the cavity (a).

Soil displacement can be determined as a function of the plastic zone

radius and the ratio of the undrained Young's modulus over the undrained shear

strength $(E/Su)$. The radius of the plastic deformation zone is a function of

$u_a/a$ and $E/Su$. In this case oversizing was $u_a/a=0.70$. A ratio of $E/Su=280$

was assumed (based on E=200 tsf, Su=0.72 tsf; according to the limited data available and taking into account that for clay E/Su is usually between 200 and 1000 [12]) such that the radius $R_p$ is estimated to be 102 cm. This indicates that the soil would deform plastically up to the ground surface, as confirmed from the soil displacement data shown in Figure 3.

The soil displacement $\delta$ at a distance r above the mole, can be determined by using the equation of continuity for $R_p >> u_p$, which, in this case, yields [12]:

$$\delta = \frac{2\ a^*u_a + u_a^2}{2r} \tag{1}$$

The same equation was used [12] to derive the formula given by the analytical model for soil displacements in the elastic region. This is because, according to this model, the soil displacement is also calculated based on the equation of continuity (assuming Poisson's ratio for clay 0.5), making therefore the determination of soil displacement rather independent of soil parameters and primarily dependent on pipe oversizing. The soil displacements determined according to Equation (1) are shown in Table 1. A rather good agreement is found with the test results, except for the displacement nearest the surface (r = 91 cm [36 in.]) where the effect from the pavement is

Table 1. Soil Displacements Obtained Experimentally and Analytically (Fig. 11)

| Distance r (cm) | Displacement $\delta$ (cm) | |
| --- | --- | --- |
| | Test Results | Analytical* |
| 41 | 1.50 | 1.35 |
| 66 | 0.80 | 0.84 |
| 91 | 0.15 | 0.61 |

*Using Equation (1) ($u_a$=5.35 cm, a=7.65 cm)

greatest (test results indicate minimal displacement at pavement elevation).
Note that use of the formula given in [12] for soil displacements under the
assumptions of E/Su-280 and E/Su-53 resulted in the same results obtained by
Equation (1) and shown in Table 1. It is therefore, suggested that in cases
when the soil Poisson's ratio may be estimated to be 0.5 (clay), application
of Equation (1) will result in a good prediction of the expected soil
displacements under the PIM technique.

An upper bound of the strain induced on an adjacent pipeline can be es-
timated by using the analytical model, on the assumption that the pipeline is
located outside the plastic zone and it deforms in exactly the same pattern as
the soil displacements. Also, it is assumed by the model that the depth z is
at least twice the radius $R_p$. However, in the present test, the instrumented
pipe was located well within the plastic zone and the distance z is almost
equal to the plastic radius $R_p$. Flow of soil around the pipe should have con-
tributed, therefore, to the low strain measured on the pipe at Fort Belvoir.

## ANALYSIS OF VIBRATION EFFECTS

Vibrations monitored in the test of reference [9] were found to be rela-
tively low, with a maximum vertical PPV of 8 mm/s. The pseudo-attenuation
factor corresponding to this maximum velocity of vibration was shown to be
2.35 ($v=kD^{-n}$; v=peak particle velocity, D=distance from vibration source,
k=velocity at D=1 unit of distance, n=slope or pseudo-attenuation rate).
Vibration recorded in a different site during the same test was much lower,
being only 1.3. This confirms the sensitivity of the vibration effects to
soil conditions, also observed at Fort Belvoir.

The relatively low PPV recorded in the English test of [9] is due to the
larger depth at which the mole was operating compared to the test at Fort Bel-
voir. The maximum velocity of 8 mm/s, however, when normalized to the depth
of the test at Fort Belvoir becomes 36.7 mm/s, a rather significant velocity
compared to 13.6 mm/s recorded at Fort Belvoir. The difference between the
normalized maximum vertical PPV recorded in the two tests can be attributed to

the larger power required by the mole in the test of reference [9] for re-placement of a concrete 225 mm (9 in.) sewer pipe by a 400 mm (16 in.) poly-ethylene pipe (PPV is directly dependent on the energy of the source [11]). The energy delivered by the 460 mm mole used in that test would have been much higher than the one delivered by the 260 mm mole used at Fort Belvoir.

According to the Swiss standards for vibrations in Buildings [11], for vibration frequency in the range of 30-60 Hz, peak particle velocity higher than 12 to 18 mm/s exceeds the safety limits for buildings constructed of steel and concrete, such as factories, retaining walls, etc. However, attenuation of vibration is not expected to allow vibration from the operating mole to reach such critical levels at nearby buildings or structures. In addition, the maximum PPV at any given place will last only a few seconds as the mole moves through the pipe.

The observation of vibrations greater than the critical limits indicates a research need for the PIM technique. Data such as developed in this test should be gathered to establish a relationship between soil properties, impact mole and existing pipe characteristics, and vibration levels as a function of distance from the impact mole. These data could then be used to develop a formula which would indicate safe operating distances from sensitive structures for the impact mole.

One may be mostly concerned about "conduits in loose material" as they are described by the Swiss standards, for which the safety limits are set at 8 to 13 mm/s. Furthermore, for objects of historic interest, the corresponding safety limits are set at only 3 to 5 mm/s. Given the fact that both these categories may include objects at rather small distances from the operating mole, the use of the PIM technique should be carefully considered in such cases. Especially for places rich in archeological objects (e.g. Athens, Rome and others), application of this technique should be done only in close cooperation with the archeological authorities.

A comparison between the maximum PPV due to the impact mole and due to jack hammers and trucks is presented in Figure 8. The maximum vertical PPV

recorded at Fort Belvoir (FB) and in the English test (E) are shown by the marks. The lines of attenuation of vibration of these velocities, as depicted in Figure 8, are not the ones recorded in the tests. Instead, these lines were drawn assuming a pseudo-attenuation factor of 1.5, solely for comparison reasons (since all other data lines given in Figure 8 represent pseudo-attenuation factor of 1.5). That is, in the hypothetical case when soil conditions are the same as those for the trucks and jack hammers presented in Figure 8, the impact mole would have resulted in comparable vibration effects. Note that, for the same velocity at the source (mole), the assumption of the pseudo-attenuation factor of 1.5 would imply higher actual vertical PPV on the pavement above the sewer pipe than the ones recorded in the test and shown by marks in Figure 8. In other words, one may consider the lines of attenuation shown in Figure 8 for the PIM technique as conservative assumptions. However, it is considered that the simplified assumption allows one to get an idea of the general trend, since, vibration effects due to impact mole were shown to be rather sensitive to soil conditions even at the same site.

Based on the above results, it is believed that, with regard to vibration effects, the PIM technique should not be considered as more damaging compared to other alternatives (e.g. excavation using jack-hammers), or to usual sources of vibration (e.g. trucks), except for buried pipes and archeological objects located close to the operating mole.
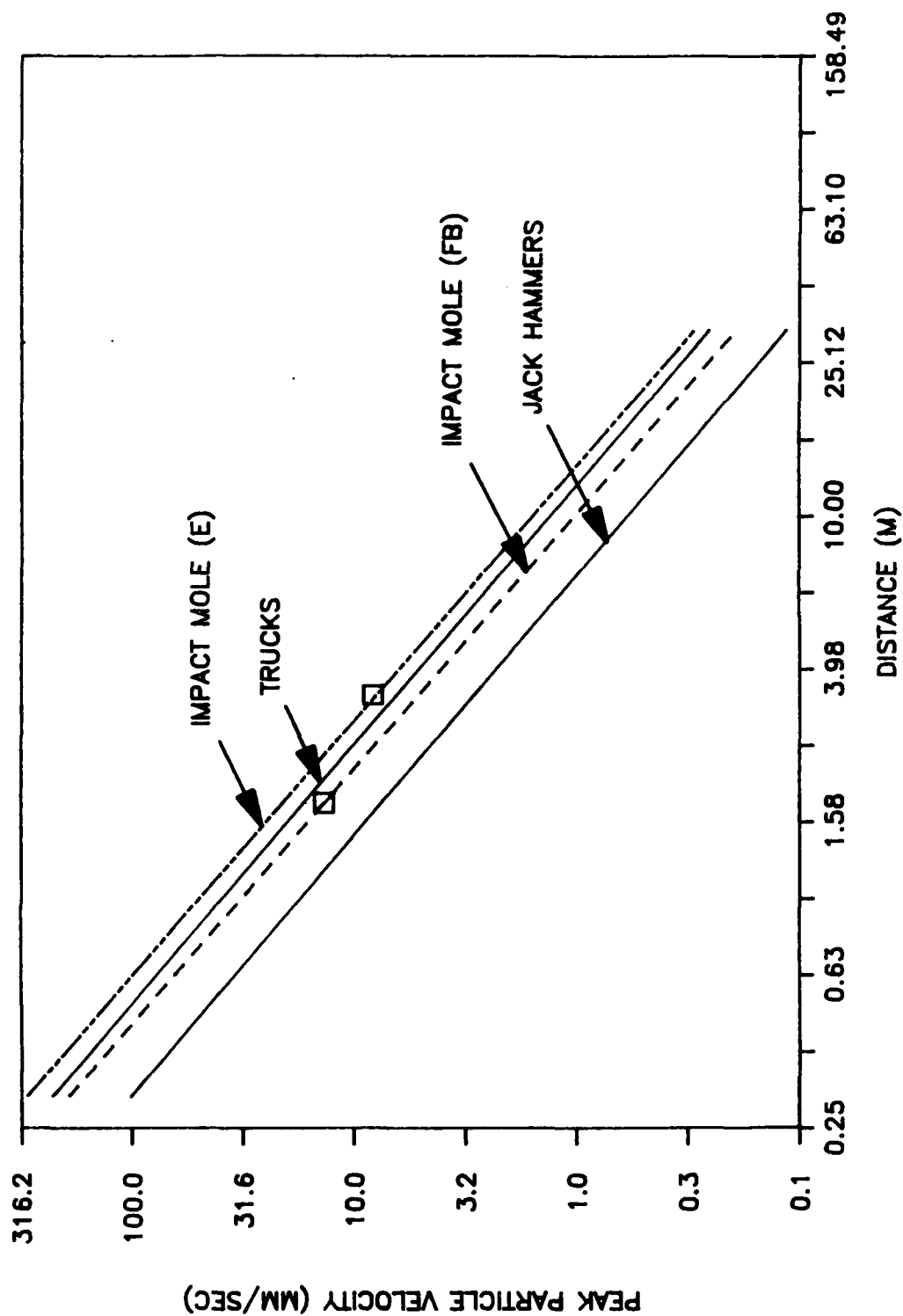
Figure 8.  Comparison of Attenuation Curves for Jack Hammer and Trucks
[11] and the PIM Technique Tests of [9] and the Recent One.
(Marks indicate recorded data from the tests while the curves
for the PIM technique were drawn on the assumption of a
pseudo-attenuation factor of 1.5; F.B. denotes the test at
Fort Belvoir and E denotes the test of [9] in England).

CONCLUSIONS

One of the most rapidly developing methods of on-line replacement of utility pipelines is the PIM technique. This technique consists of physically breaking up an existing pipe by an advancing impact mole. The mole is followed by a new pipe jacked through the void. One of the most important advantages of this technique is that it can replace an existing pipe with a new pipe of larger diameter, without digging a trench along the entire length of the pipe.

The pipe insertion machine technique is a rather new one and there is no long term data available regarding its overall performance. Experimental studies to assess the effects of the impact mole technique on adjacent pipes and the surrounding soil have been initiated in England and the first results are rather encouraging [1,2,3]. An experimental study, similar to the one conducted in England, was undertaken to confirm the generality of the results obtained from those earlier studies.

In this study, conducted at Fort Belvoir, Virginia, in the summer of 1987, the impact mole technique was used to replace a 152 mm (6 in.) clay sewer pipe by a 208 mm (8 in.) diameter flexible pipe. The study focused on the strains induced on an adjacent instrumented pipeline, the deformation and the vibration effects experienced in the surrounding soil, and the long term deflection of the installed flexible pipe.

The results obtained indicate consistency with overall trends reported in similar experiments performed in England. The differences found may be attributed to different soil type and different size of replacement. In general, the following observations were made.

The strains introduced in adjacent pipelines are strongly dependent on the amount of enlargement of the old pipe caused by the impact mole, but also on the soil behavior (i.e. characteristics). In this particular case, strains introduced in an instrumented ductile iron pipe placed perpendicular to the sewer pipe and 410 mm (16 in.) above it, were found to be relatively small.

The displacements within the soil were smaller compared to those obtained in England. In addition, the displacements measured in the present experiment indicate significant plastic deformation of the soil. A rather large plastic zone extending at least up to the pavement was confirmed analytically. The recorded soil displacements could also be estimated reasonably well by utilizing the equation of continuity within the plastic zone. Based on these results, it is believed that the soil around the instrumented pipe, located within the plastic zone, mostly flowed around the pipe. This behavior could have contributed substantially towards the relatively small strains measured on the instrumented pipe. In addition, this plastic deformation may be the reason for no apparent friction along the inserted new pipe.

Vibrations monitored on the pavement surface above the sewer pipe during the experiment were found to be rather significant. However, a short distance away from the pipeline, vibrations appear to dampen out quickly. The peak particle velocities reported in this test, as well as those reported in another test in England, are shown to be comparable to those produced by jack hammers and trucks. These velocities could be harmful, however, to pipes and archeological objects located close to the operating mole. This points to a research need in the PIM technique to establish a relationship between soil characteristics, impact mole and pipe characteristics, and vibrations, so that safe operating distances can be established for the impact mole.

Deformation of the inserted polyethylene pipe was monitored immediately after the pipe replacement. The deformation profile was shown to be elliptical. Maximum deflection was found to be 2.5 percent of the pipe diameter immediately after installation, and 4.5 percent 6 months after installation.

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