

Ground Movements Caused by Trenchless Pipe Installation Techniques

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The ground movements caused by trenchless pipe installation techniques can have a significant effect on adjacent services and road structures. A fundamental understanding of how these techniques affect the ground is lacking. This can result in the stipulation of an overly conservative distance between trenchless pipelaying and other services, and a concomitant lack of confidence in the techniques. To rectify this, a series of laboratory simulation tests was conducted at Loughborough University of Technology, U.K. These tests simulated pipejacking or microtunneling (convergent) operations using different shield arrangements and pipebursting (expansive) operations, with the aim of determining the patterns and magnitudes of displacements in the surrounding soil. This in turn permits the prediction of movements in adjacent services and structures, as well as the development of techniques for their minimization. The tests were conducted in a rigid, glass-sided tank using semicircular shields and pipes buried in different dry sands. This arrangement allowed direct observation of the sand displacements on the centerline of the simulated operations. For the pipejacking tests, two face-support methods (open and closed faces) were used. The pipebursting operations used different sizes of existing plaster pipe, which was progressively broken out as the burster advanced, to simulate different bursting ratios. Various combinations of sand density and cover depth were used. Selected results from the three test programs are presented in terms of ground movement contour plots and vector displacement diagrams. The results confirmed that soil density strongly influences the magnitude and extent of the ground displacements. The denser soils produce a greater effect in compression situations, and looser soils have a greater effect when the soil is moving into cavities. Increasing cover depth creates a confining effect and restricts the extent of the soil movements. The open shield behaves differently than the closed shield, which displaces more soil and produces broadly similar results to those of the angled pipebursting unit. The results presented herein are essentially visual, thus permitting a full appreciation of the ground movements under various boundary conditions.

Trenchless technology has become firmly established as an alternative method of pipeline construction to compete with trenching, or open-cut, methods and traditional tunneling. Several techniques are available (1), all of which have their own particular applications; these have considerable advantages over open-cut techniques where they can be used. Due to the location of many services beneath road pavements, particularly in urban areas, trenching is necessarily slow, causing considerable traffic congestion and incurring the large social, or indirect, costs associated with such congestion (2). In addition, open-cut methods result in damage to road pavement structures and adjacent buried services, with consequent loss of structural life. This is due to displacements that occur within the soil that are caused by changes to the stress field, and hence loss of support to the structure or service, in addition to any direct damage to the structure or service caused by the excavation (3).

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Many of the trenchless pipelaying techniques have been developed with the goal of reducing such damage to a minimum. Nevertheless there will be ground displacements associated with these techniques that will necessarily affect road pavement structures and buried services. It is often quoted in the extensive and growing literature on the subject that trenchless techniques are far better than other techniques in this respect, although these quotes are made on the basis of minimal data. The project reported herein is aimed at quantifying the movements that can be expected from the use of such construction operations.

A comprehensive program of research has been carried out at Loughborough University of Technology, U.K., to study the ground displacements caused by pipejacking (excavation) and pipebursting (expansion) operations by simulation in physical model tests. In microtunneling, which is a fully automated development of pipejacking that is used for smaller diameter tunnels and pipelines, sophisticated slurry and earth pressure balance techniques have been adopted to deal with the problems of ground loss and ground-water ingress. In certain cases the perceived need to ensure the avoidance of soil or water ingress has resulted in overcompensation for soil or water pressure (4). This overcompensation has resulted in a lack of excavation and in soil being forced away from the shield. Such a situation has also been simulated, in the extreme condition, in the test program by the use of a shield with a closed face.

Extremes of behavior were examined using loose and dense dry sands, which also facilitated development of a simple theoretical model for ground displacement prediction. Data are presented from all three types of test in order to establish patterns of movement. This is achieved by a series of vector displacement diagrams in the plane of longitudinal cross section. A method of interpretation, by interpolation and extrapolation, is presented to allow the results to be extended to practical situations.

PLANE STRAIN TEST FACILITY

The plane strain test facility in which the tests were conducted consists of a 1.5-m long \times 1.5-m high \times 1.0-m wide steel tank with two perpendicular glass sides. A water bag arrangement in the lid of the tank is able to supply a vertical stress to the surface of the soil placed within the tank, allowing simulation of different cover depths. The steelwork supporting the sides of the tank is designed to maintain plane strain conditions at the viewing faces throughout each test. The tank allows complete observation of the soil movements while simulated trenchless technology operations are carried out within it. Quantification of the ground movements was achieved by analyzing a series of photographs of the sand taken through the glass faces at different stages of the operation.

The ground movements were measured in two different types of dry sand, a uniform Leighton Buzzard sand ($C_u = 1.36$, $C_c = 1.04$, $D_{10} = 1.18$ mm) and a well-graded gravelly sand ($C_u = 2.84$, $C_c = 0.66$, $D_{10} = 0.67$ mm, where C_u = coefficient of uniformity, C_c = coefficient of curvature, and D_{10} = diameter below which 10 percent of soil particles fall). These sands were placed in both loose and dense states in the tank prior to testing, using a sand-raining technique to ensure consistency. The sands were chosen to provide materials that had sufficiently large particles to be readily identified from photographs while having different shearing (frictional and volume change) behavior. Dry sands were used to remove the effects caused by time-dependent equilibration of both positive and negative porewater pressures.

A semicircular pipe arrangement was jacked behind the appropriate head (shield or pipeburster) and adjacent to the glass front of the tank to simulate the jacking operation. Thus the observations of movement made were those taking place along the centerline of the installed pipe. The pipe was kept tight against the glass using a guide rail system. The jacking force was supplied by a single 30-t hydraulic jack that bore onto a steel thrust plate. The pipes were jacked forward, forcing the shield or head into the tank in 10-mm increments over a total distance of 1 m. This procedure enabled the effect of the sides of the tank on the measured displacements to be gauged. It also permitted a comprehensive series of observations to be made, establishing that the results were consistent. Several of the tests were duplicated to ensure repeatability of the results. Further details of the equipment are given elsewhere (5).

The external diameter of the installed pipes in all tests was 200 mm. For the pipejacking tests the front of the lead pipe was attached to a 100-mm-long semicircular shield with a diameter of either 220 or 240 mm, depending on the degree of overcut being investigated. It was considered important for the tests to have an overcut dimension (t) that matched the overcut dimension used in practice, rather than to scale down the overcut dimension by the same factor as that used to scale down the size of the pipe and shield. This would allow for a more realistic representation of the movements at the overcut while causing no significant influence at the front of the shield. For the pipebursting test a 12° steel cone was attached to the lead pipe. The existing pipe (i.e., the pipe to be renewed) was simulated by using semicircular plaster pipe sections fixed to the inside of the glass. Two sizes of existing pipe were used to provide two different bursting ratios (external diameter of burster divided by internal diameter of existing pipe). The maximum diameter of the steel cone was designed to be larger than the installed pipe sections, to allow the effect of overbursting to be investigated.

It should be stressed that the pipebursting tests represented full-scale models of these operations, albeit on the lower bound of sizes found in practice. The pipejacking tests, however, are scaled versions of field operations, with the scaling factor typically being 5 to 10.

EXPERIMENTAL PROCEDURE

Pipejacking Tests

Simulation of the pipejacking operation (i.e., forward jacking and insertion of new pipe sections) is relatively straightforward, whereas simulation of face excavation and support characteristics with the necessary repeatability and consistency is very difficult. The complex nature of many of the face support systems in use today, such as slurry pressure balance systems, means that accurate modeling is impossible. In order to overcome this problem in the

model tests, the two extremes of face support were considered, a completely open face and a completely closed face, and interpolation between the two was made.

Due to the nature of dry sand, the open-face shield allowed the sand to form a stable natural slope within the shield, and had angled cutting edges designed to maintain this stability. During the jacking stage of the model tests, more sand was forced into the shield, which would rapidly create a plug of sand if the additional sand were not removed. The jacking process was therefore stopped after 10-mm forward movement to allow excavation of the excess sand. The excavation was performed using a carefully controlled suction technique, taking care not to overexcavate the face and cause instability. Further details of this technique are reported elsewhere (6). Forward jacking, again in 10-mm increments, of the closed shield caused the sand necessarily to move away from the face and thus to simulate excessive overpressurization of the face support provided by a slurry pressure balance machine. The pipejacking model tests described in this paper concentrated on the jacking part of the pipejacking operation, rather than on the excavation process, which had no influence on the surrounding soil.

Photographs were taken at every stage (before and after every jacking operation), and pairs of photographs were viewed in stereoprojection to obtain the pattern of sand displacements. Measurements of the displacements were then made directly from the photographs to enable the patterns, in the form of horizontal and vertical movement contours, to be quantified and vector diagrams to be produced.

Pipebursting Tests

The steel cone section, attached to the front of the pipe train being installed, was advanced into the tank by a static force (7). This closely models the expansion process that occurs during a hydraulic pipebursting operation. The burster ran along the invert of the existing pipe because of the shallow nature of the bursting operations simulated. The existing pipe was progressively broken out as the burster advanced, forcing the pieces of existing pipe into the surrounding sand.

The test proceeded in 20-mm forward jacking stages; photographs were taken before and after each stage. The sand displacements were obtained in a manner similar to the pipejacking tests.

EXPERIMENTAL RESULTS

A comprehensive program of tests was carried out to vary test parameters such as cover depth, type and density of sand, overcut ratio (pipejacking) or overburst ratio (pipebursting), and surface confinement for the three techniques (8). In this paper comparisons are made between the results of selected tests (Table 1) that illustrate differences in shield arrangements, soil density, and cover depth. The results of tests using the uniform sand are quoted because the well-graded sand produced broadly comparable results, although they were somewhat more random and less repeatable. More importantly, these results were less extreme in both extent and magnitude. Thus the uniform sand produced the upper-bound displacements for the dense (heave) and loose (settlement) sand tests.

An example of the contour plots produced from the photographs is given in Figure 1, in which the general pattern of forward and

TABLE 1 List of Laboratory Tests Referred to in this Paper

Test ^a	Operation	Sand Type ^b	Sand Density ^c	Cover Depth (m)	Overcut/Overburst Ratio ^d	Bursting Ratio ^e
OPJ1	Pipejacking	uniform	dense	0.9	0.1	-
OPJ2	Pipejacking	uniform	loose	0.9	0.1	-
OPJ3	Pipejacking	uniform	dense	4.0	0.1	-
CPJ4	Pipejacking	uniform	dense	0.9	0.1	-
CPJ5	Pipejacking	uniform	loose	0.9	0.1	-
CPJ6	Pipejacking	uniform	dense	0.4	0.1	-
CPJ7	Pipejacking	uniform	loose	0.4	0.1	-
PB8	Pipebursting	uniform	dense	0.9	0.05	1.7
PB9	Pipebursting	uniform	loose	0.9	0.05	1.7
PB10	Pipebursting	uniform	loose	0.4	0.05	1.7
PB11	Pipebursting	uniform	dense	0.9	0.05	1.2

^aOPJ refers to open shield pipejacking, CPJ refers to closed shield pipejacking.

^bThe uniform sand is Leighton Buzzard sand ($C_u = 1.36$, $C_c = 1.04$, $D_{10} = 1.18\text{mm}$).

^cDense sand = 2.07 Mg/m^3 and loose sand = 1.94 Mg/m^3 .

^dThe overcut ratio is the ratio of external diameter of the shield to the external diameter of the following pipe. The overburst ratio is the ratio of the maximum external diameter of the bursting head to the external diameter of the following pipe.

^eThe bursting ratio is the ratio of the external diameter of the burster to the internal diameter of the existing pipe.

upward movements in front of a closed shield in dense, uniform sand can be seen clearly. The downward movements at the overcut, which were limited by dilation within the dense sand, are equally apparent. The dashed contour lines represent areas of movements that were not well defined, due to either the random nature of the movements or their small magnitude.

Comparison Between Open- and Closed-Shield Pipejacking Tests

Figures 2 through 5 show the vector displacement plots for four tests (OPJ1 and CPJ4 in dense sand, and OPJ2 and CPJ5 in loose sand, respectively) to illustrate the effects of volume of excavation, the only difference between the pairs being the (open or closed) shield type. Figures 2 and 4 illustrate the general pattern of sand movements in the longitudinal plane as one of a circular motion around, and particularly over, the shield. There were outward (forward) and upward movements in front of the shield, which above the shield crown altered progressively to backward and upward movements. In addition there were downward movements of the sand lying above the shield into the void created by the overcut of the shield, and forward movements into this void by sand lying behind the shield. It should be noted that, for the reasons given in an earlier section, the movements at the overcut were exaggerated and that this influenced the overall pattern to a degree, although the influence can be easily allowed for from visual interpretation.

The main observation when comparing the open- and closed-shield tests concerned the extents and magnitudes of the resulting movements. For the open-shield test in dense sand (OPJ1) the maximum extent of the sand movements in front of the shield was only approximately three diameters from the shield, whereas the movements for the equivalent closed-shield test (CPJ4) extended to the surface. This difference was expected, because the sand in front of the closed shield cannot move into the shield and consequently must move forward during jacking, causing much more sand to be displaced. The extents for the equivalent loose sand tests (OPJ2 and CPJ5) were similar in many respects, with neither test producing movements in front of the shield that reached the ground surface, because of sand compression. The closed-shield test movements did, however, extend further in front of the shield.

Over the shield and at the overcut, the observed movements for the open- and closed-shield tests were very similar, once allowance was made for the greater upward and resultant spreading (hence soil disturbance) effects in front of the closed-shield tests. This caused the plane separating the horizontal forward movements and the horizontal backward movements at the shield crown to have a much greater angle to the horizontal for the closed-shield tests. Sand behavior at the overcut was largely influenced by the relative density of the sand. The movements in dense sand diminished and extended only a small distance above the pipe. In loose sand, the movements extended much further and in the shallower (0.9-m deep) tests reached the surface, giving rise to a funneling effect caused by sand compression.

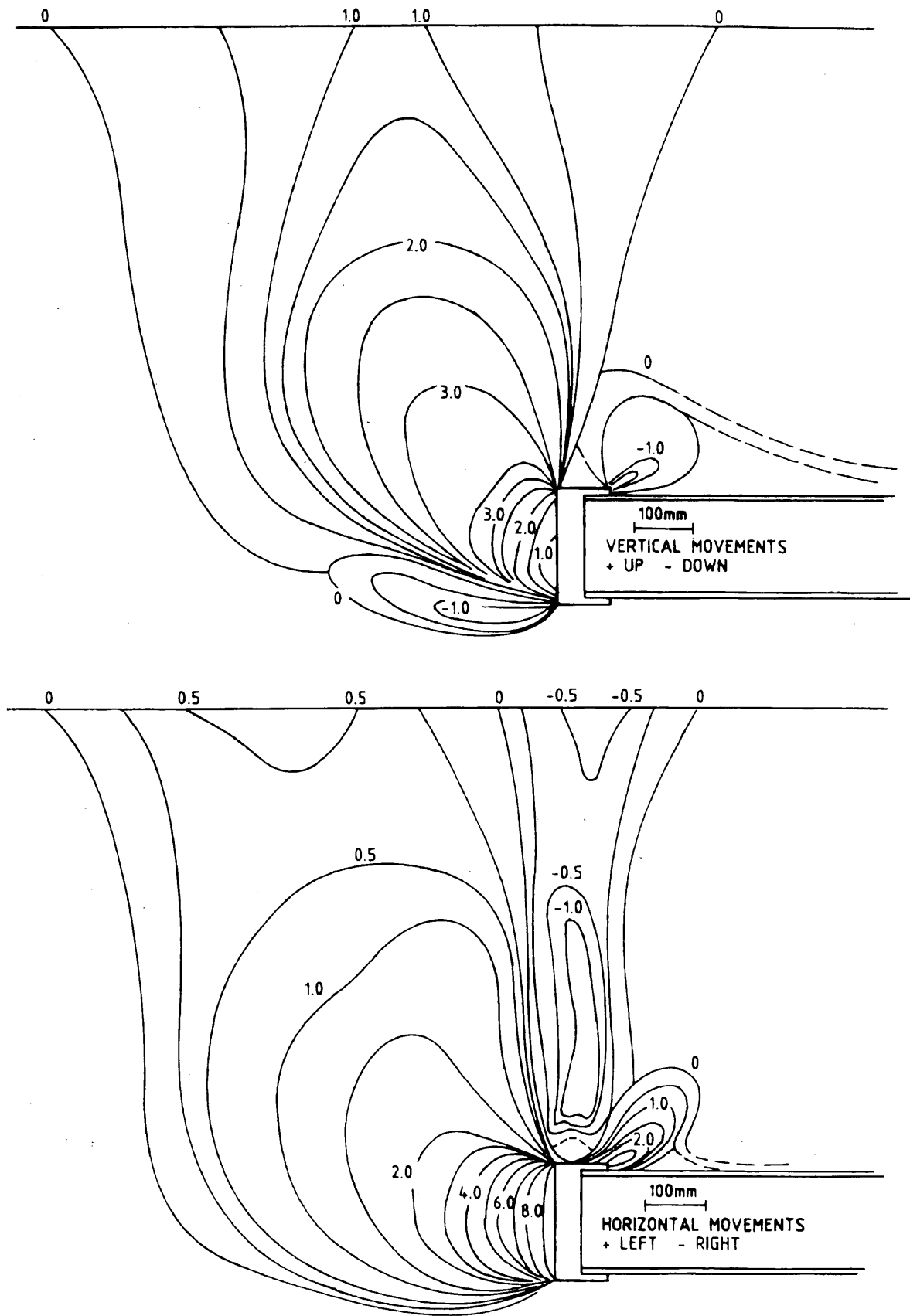


FIGURE 1 Typical example of displacement contour plots (Test CPJ4) from analysis of laboratory test data (10-mm jacking distance, contours in mm).

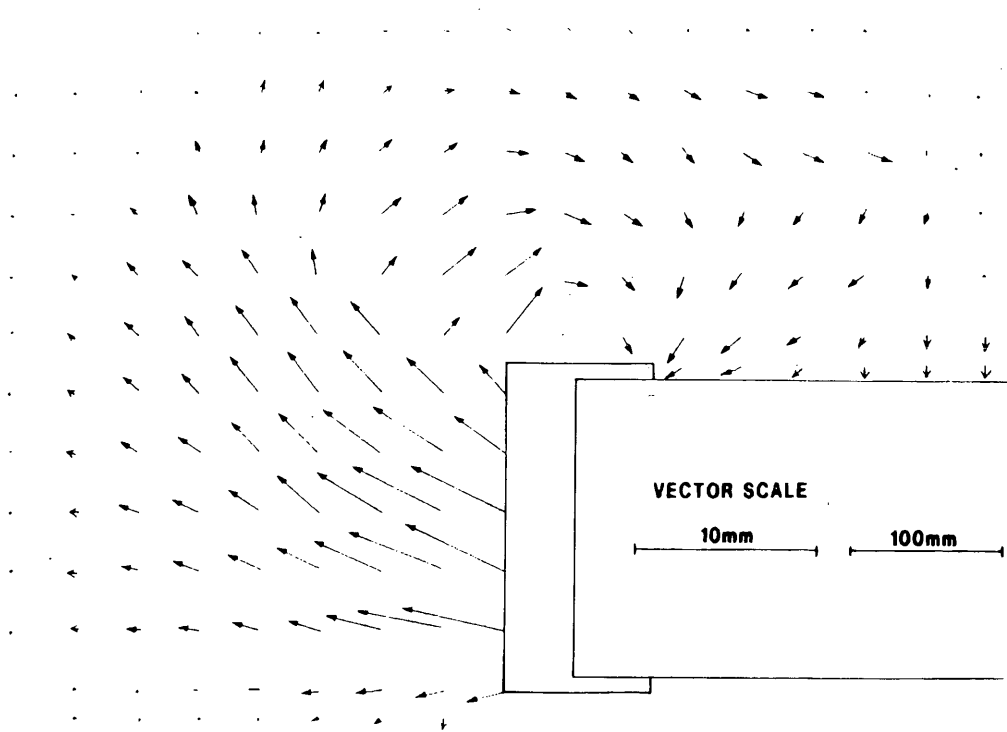


FIGURE 2 Vector displacement plot for Test OPJ1 (0.9 m deep in dense sand, 10-mm jacking distance).

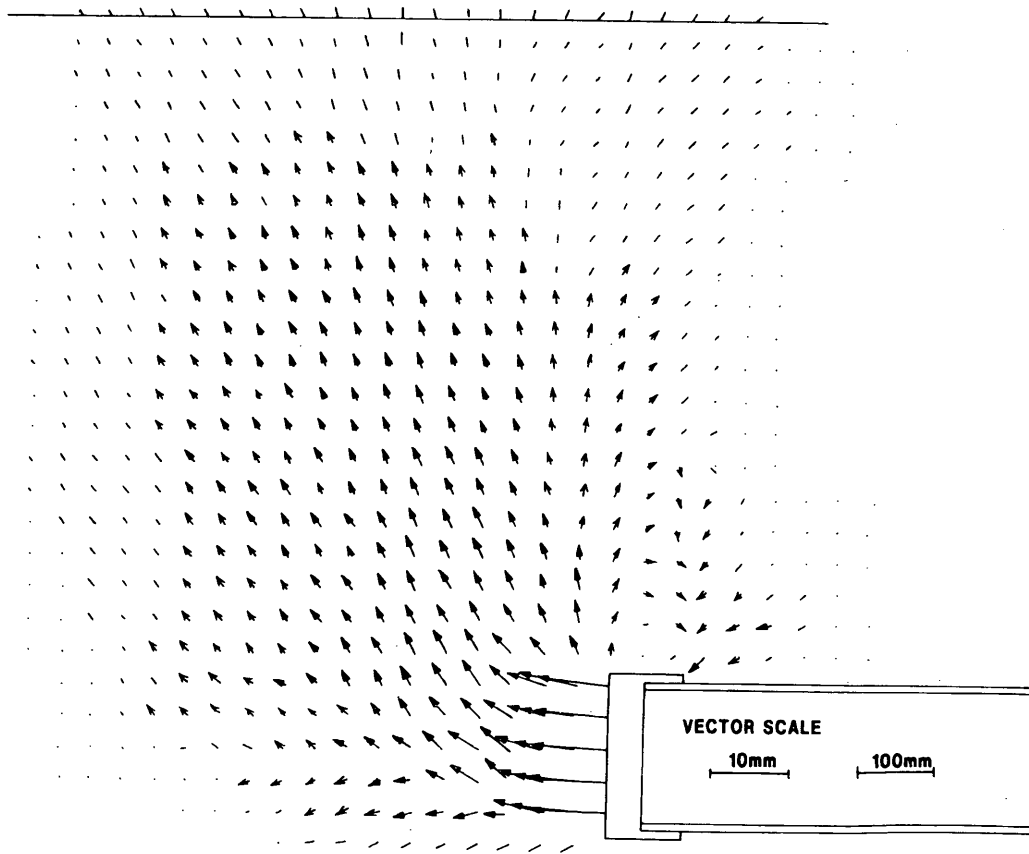


FIGURE 3 Vector displacement plot for Test CPJ4 (0.9 m deep in dense sand, 10-mm jacking distance).

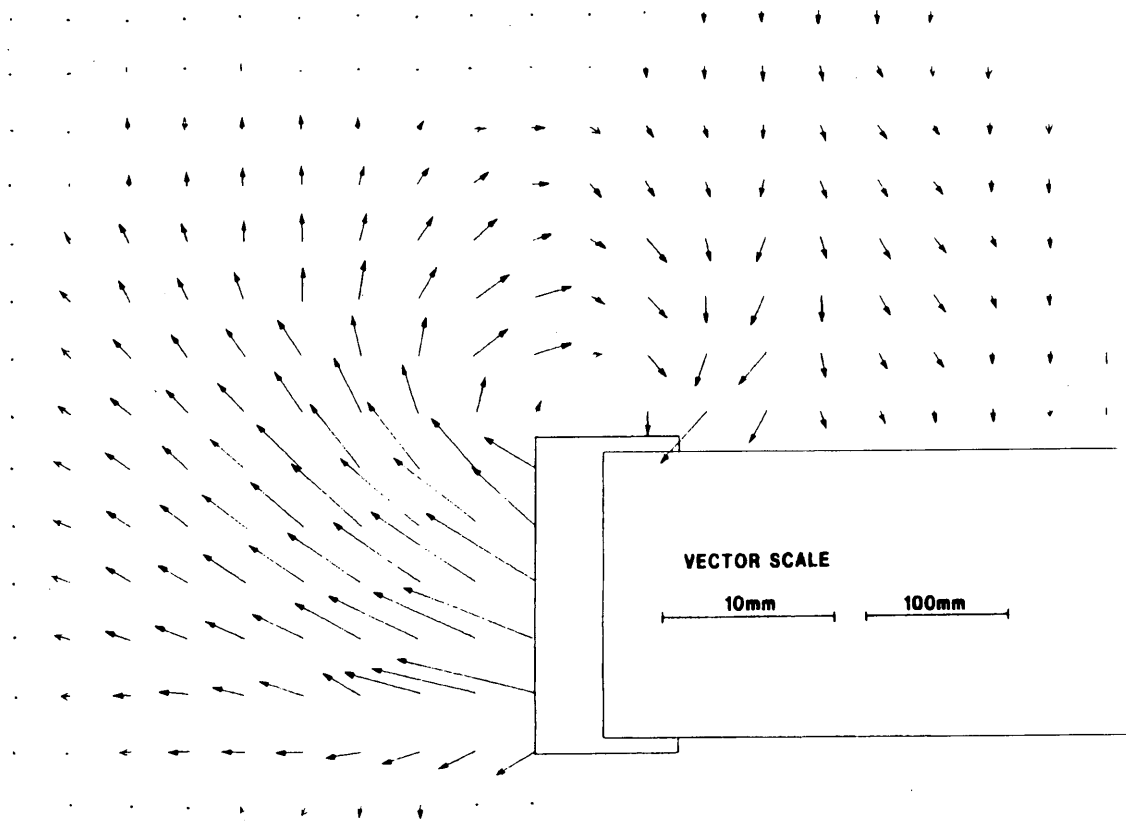


FIGURE 4 Vector displacement plot for Test OPJ2 (0.9 m deep in loose sand, 10-mm jacking distance).

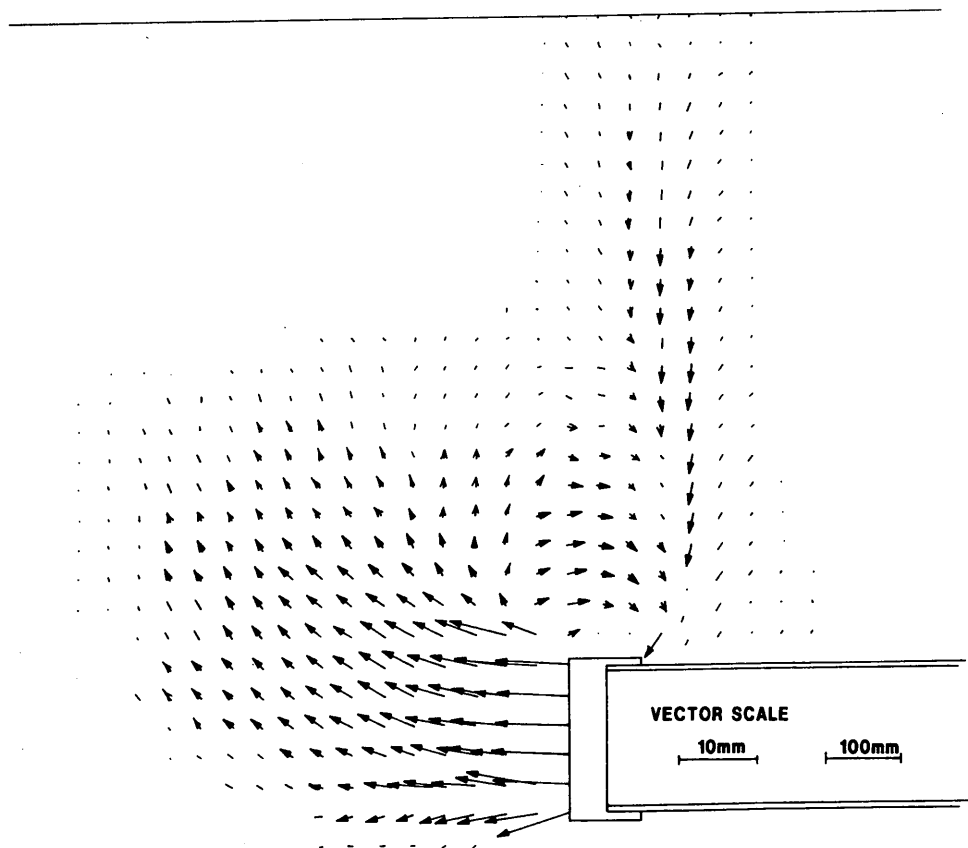


FIGURE 5 Vector displacement plot for Test CPJ5 (0.9 m deep in loose sand, 10-mm jacking distance).

The effect of increasing the cover depth from 0.9 m to 4.0 m in the open-shield pipejacking tests in dense sand can be seen in a comparison of Figures 2 and 6. It is clear that the higher vertical (hence mean normal) effective stress forced more sand into the shield, thus reducing the magnitude of the outward movements and preventing the spread of movements away from the operation. The closed-shield pipejacking tests were conducted only at relatively shallow depths. The results for cover depths of 0.4 m and 0.9 m in dense sand are presented in Figures 7 and 3, respectively. The increase in cover depth caused the movements immediately in front of the shield to become more horizontal before moving upward and, because of the greater mean normal effective stress, to reduce significantly in magnitude. The greater lateral spreading was also seen in a reduction in movements at the overcut.

Comparison Between Closed-Shield Pipejacking and Pipebursting Tests

In this section the results from pipebursting tests PB8 and PB9 (Figures 8 and 9) are compared with those from closed-shield pipejacking tests CPJ4 and CPJ5 (Figures 3 and 5). Although trenchless pipelaying techniques are superficially very different, the measured ground displacements were surprisingly similar. Indeed, if the plaster pipe in the pipebursting tests is ignored, the movements above the bursting head were very similar, in terms of both extent and magnitude, to those obtained in the closed-shield tests for both dense and loose sand. It should be remembered, however, that the

pipebursting movements were obtained from a 20-mm forward jacking distance, as opposed to 10 mm for the pipejacking tests.

For the dense-sand tests (Figures 3 and 8), the vector displacement plots show a large area of upward and forward movement in front of (or above) the particular operation, with some backward movement due to spreading effects. A smaller, localized area of rapidly diminishing downward movement was observed at the overcut/overburst due to sand moving into the cavity created by the forward jacking operation. These observations are typical of a dilatant material and result in surface heave effects.

For the loose-sand tests (Figures 5 and 9), the outward and upward movements did not reach the surface, dissipating 0.5 m above the operation, whereas the settlement caused by the overcut/overburst did reach the ground surface and became the dominant feature of these tests. These observations are typical of a soil with a very small dilation angle. At shallower depths (PB10 and CPJ7, Figures 10 and 11, respectively) in loose sand the movements did extend to the surface in front of (or above) the operation, although the high compressibility of the sand was evident and the settlement trough again dominated. The plots generally show a greater proportion of forward movement and more concentrated rotational movements in the pipebursting tests, the latter being due to the length of the shield separating the heave and settlement effects.

These results indicate that a pipeburster with a 12° cone, determined from the comparisons with pipebursters used in practice, that was pushed twice the distance of a vertical closed shield of similar size would cause similar soil movements. This allows interpretation

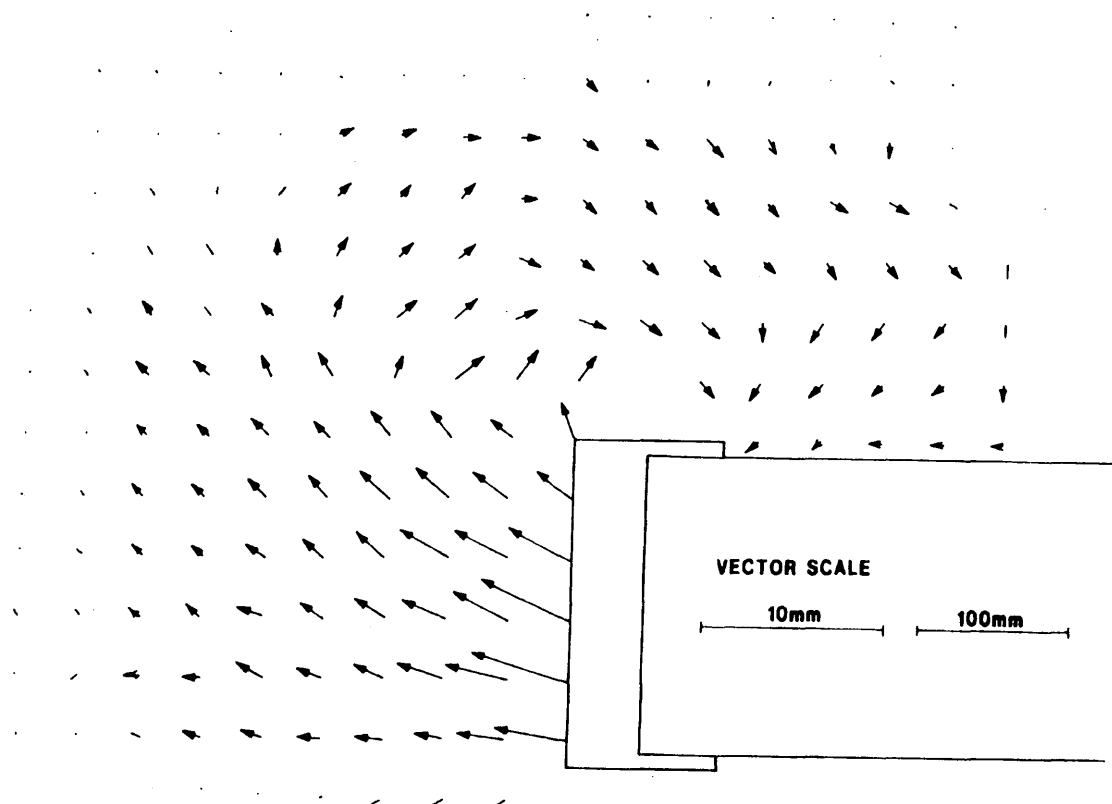


FIGURE 6 Vector displacement plot for Test OPJ3 (4.0 m deep in dense sand, 10-mm jacking distance).

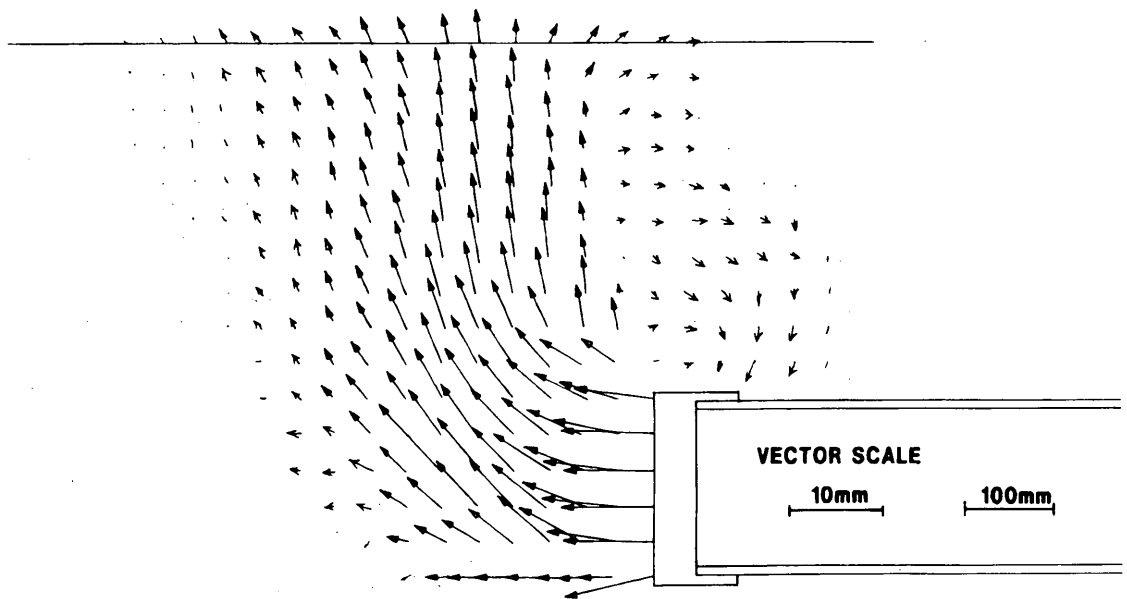


FIGURE 7 Vector displacement plot for Test CPJ6 (0.4 m deep in dense sand, 10-mm jacking distance).

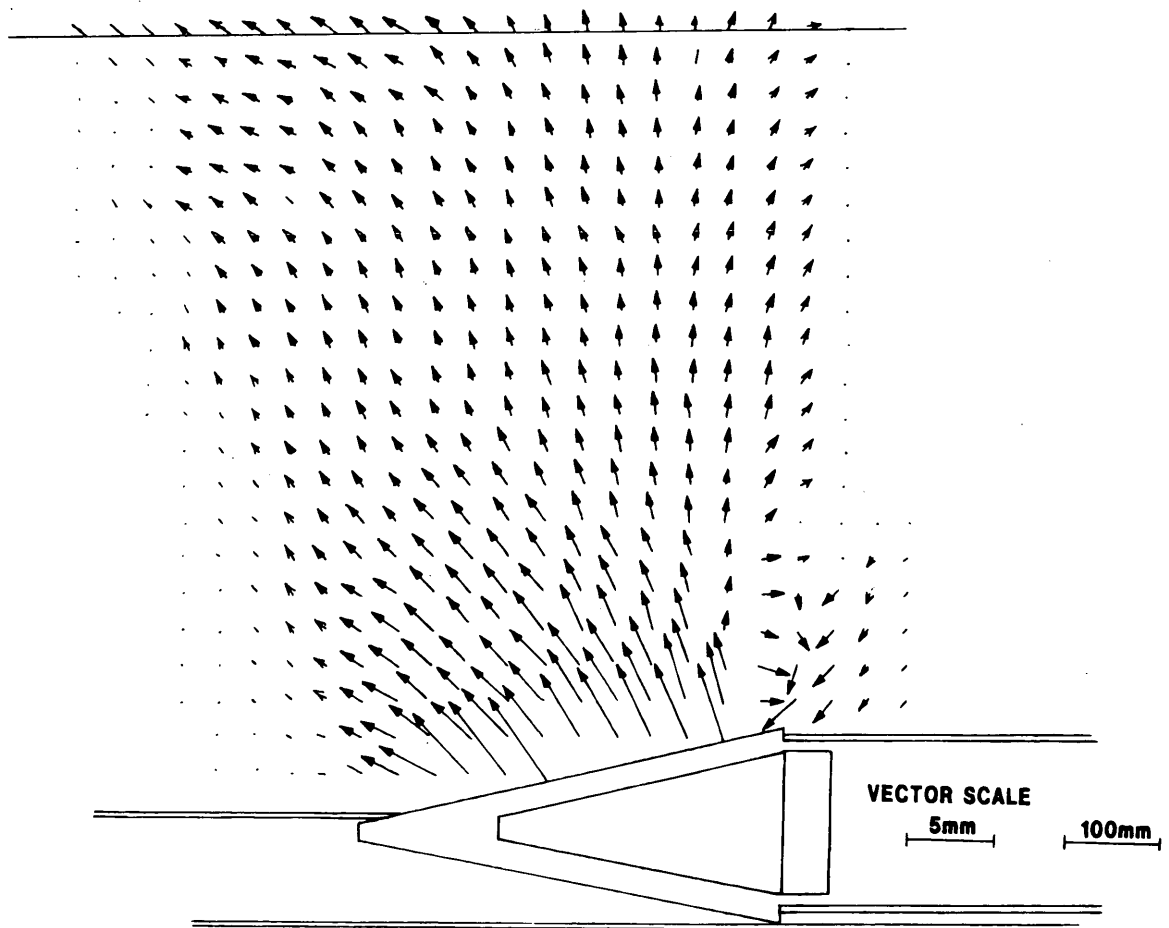


FIGURE 8 Vector displacement plot for Test PB8 (0.9 m deep in dense sand, 20-mm jacking distance).

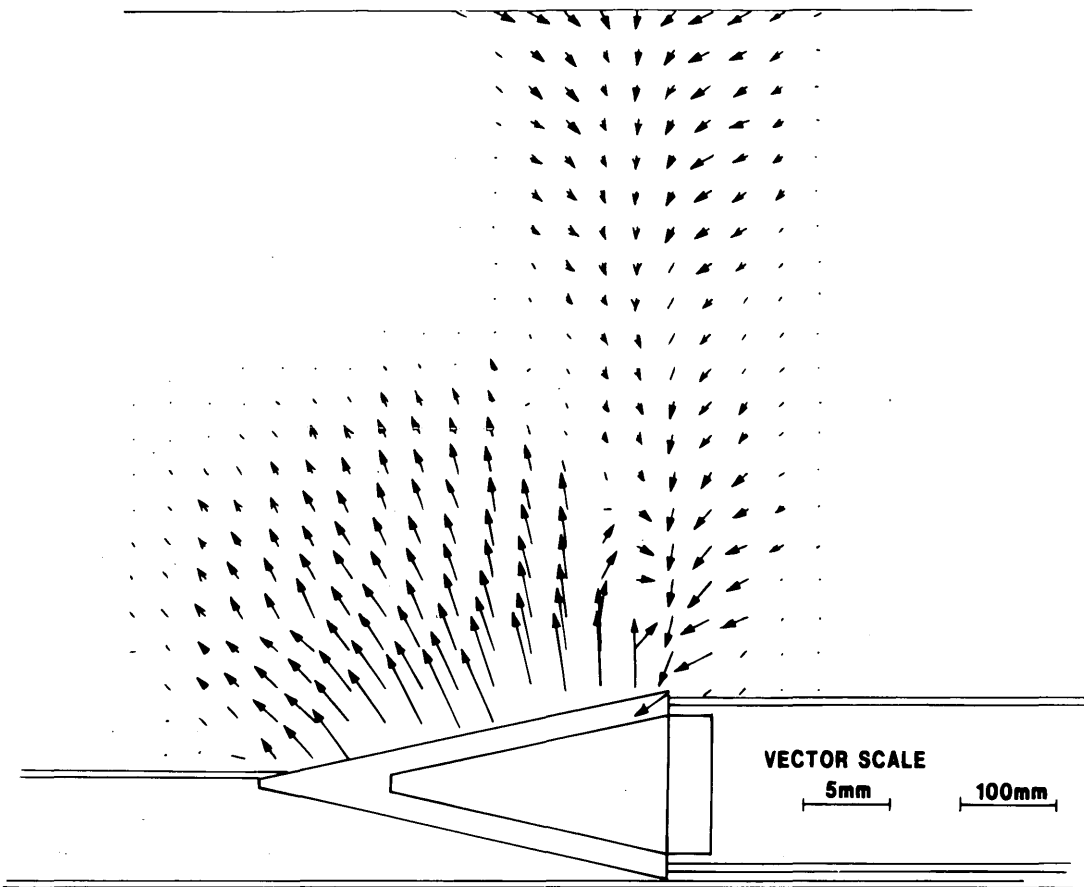


FIGURE 9 Vector displacement plot for Test PB9 (0.9 m deep in loose sand, 20-mm jacking distance).

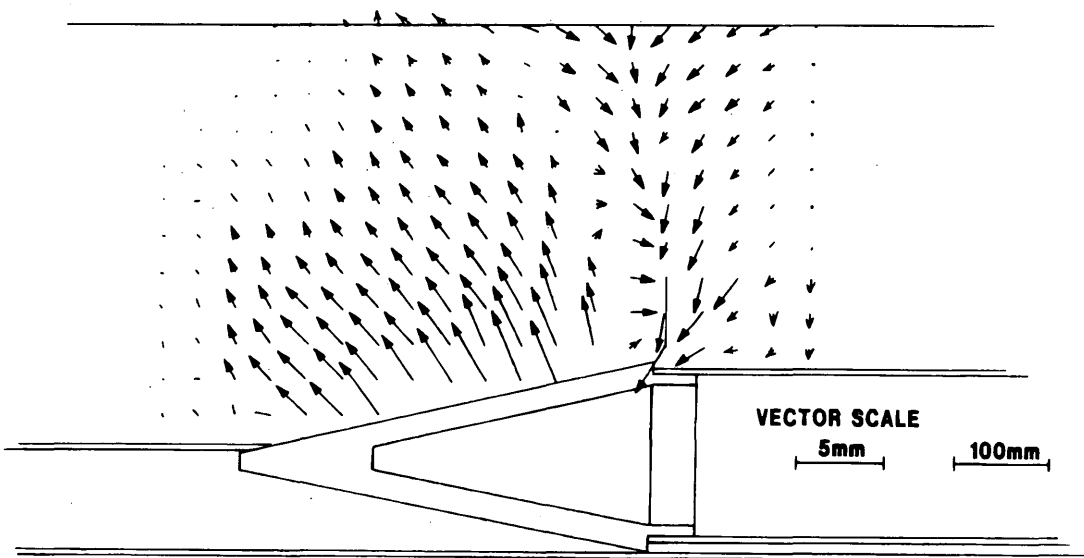


FIGURE 10 Vector displacement plot for Test PB10 (0.4 m deep in loose sand, 20-mm jacking distance).

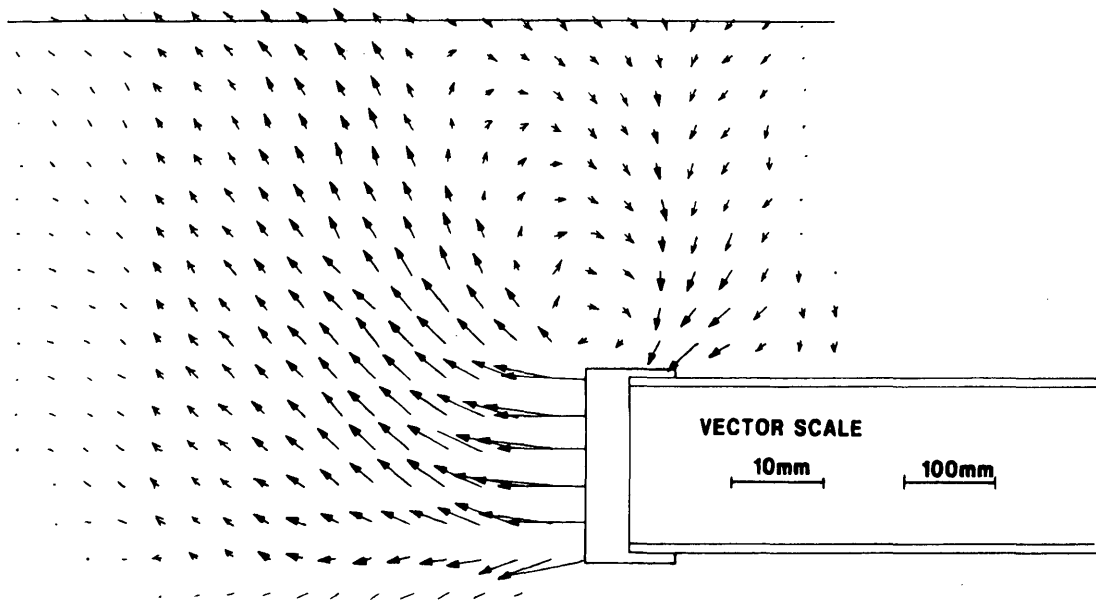


FIGURE 11 Vector displacement plot for Test CPJ7 (0.4 m deep in loose sand, 10-mm jacking distance).

of the likely ground movements caused by variations in the bursting head angle. If the whole passage of these operations is considered, the closed-shield pipejacking tests produced twice the magnitude of movements of the pipebursting tests. It should be noted that the overburst for the pipebursting tests (5 mm) was smaller than the overcut for the pipejacking tests (10 mm). However, the cavity is twice as long due to the 20-mm forward jacking distance, so the volume loss is similar.

For pipebursting operations the bursting ratio is clearly important in ground movement prediction. The smaller this ratio, the smaller the amount of burster exposed outside the old pipe, and hence the reduced extent of the observed movements in front of the operation. This is clearly illustrated by the results from tests PB11 and PB8 (Figures 12 and 8, respectively), which showed bursting ratios of 1.2 and 1.7, respectively. This means that the greater the bursting ratio, the more similar the movements were to the closed pipejacking tests in terms of extent. The bursting ratio has little effect on the *magnitudes* of the resulting movements for a 20-mm forward jacking distance, but because of the great *extent* of the displacements, the total magnitudes of the soil displacements will obviously be greater for greater bursting ratios after summation (the process of which is described later). This would be expected because of the greater volume of soil displaced.

PRACTICAL APPLICATION OF RESULTS

The results for the three types of operation, open-shield and closed-shield pipejacking and (angled-shield) pipebursting, indicate clearly that there are close relationships between the resulting ground movements. For the pipejacking tests it is the degree of face support and amount of overcut that dictate the extent and magnitude of the resulting soil movements, whereas for pipebursting tests it is the angle of the burster, the bursting ratio, and the degree of overburst that are important. The results presented herein thus provide a fundamental understanding of the effects of the operation on the sur-

rounding soil. In addition, because of their consistency, the results can be extrapolated and interpolated, using engineering judgement, to predict the effects of pipejacking operations (using various face support methods) and pipebursting operations in practice.

It will be apparent that this discussion is wholly dependent on the type of soil through which the operation is being carried out. Extreme cases of running sand, cohesionless soils below the water table, and very soft saturated alluvial soils would result in a continuous flow of soil into an open pipejacking shield. This would clearly be unacceptable and some degree of face support would be used, thus restricting the movements to levels that are much closer to those that have been modeled here. Whether they are closer to the closed-shield or open-shield movements would depend on the type and degree of face pressure used. For cases in which porewater pressures (both positive and negative) will be generated, due allowance for the time dependency of movements and subsequent consolidation of clay soils must be made.

The type of soil is similarly very important in predicting the movements that are caused by pipebursting. A stiff, dense soil will produce considerably greater outward displacements within the ground than a loose, compressible material, which will in turn produce greater settlement at the overburst. These movements have direct implications for other pipes, services or other structures within the vicinity of these operations as different movement regimes will be induced into them.

The vector displacement plots shown in this paper all refer to a "snapshot" of the respective operations, 10-mm forward jacking for the pipejacking tests and 20 mm in the case of the pipebursting tests. In order to determine the full effects of the movements on adjacent services and structures it is necessary to obtain the total ground movements for the passage of the whole operation. This is achieved by a summation process of the results obtained from the snapshot plots, whereby the movements at 10 mm (in the case of pipejacking) or 20 mm (for pipebursting) horizontal increments at the height of the service or structure under consideration are added together according to the principle of superposition (7). By considering the

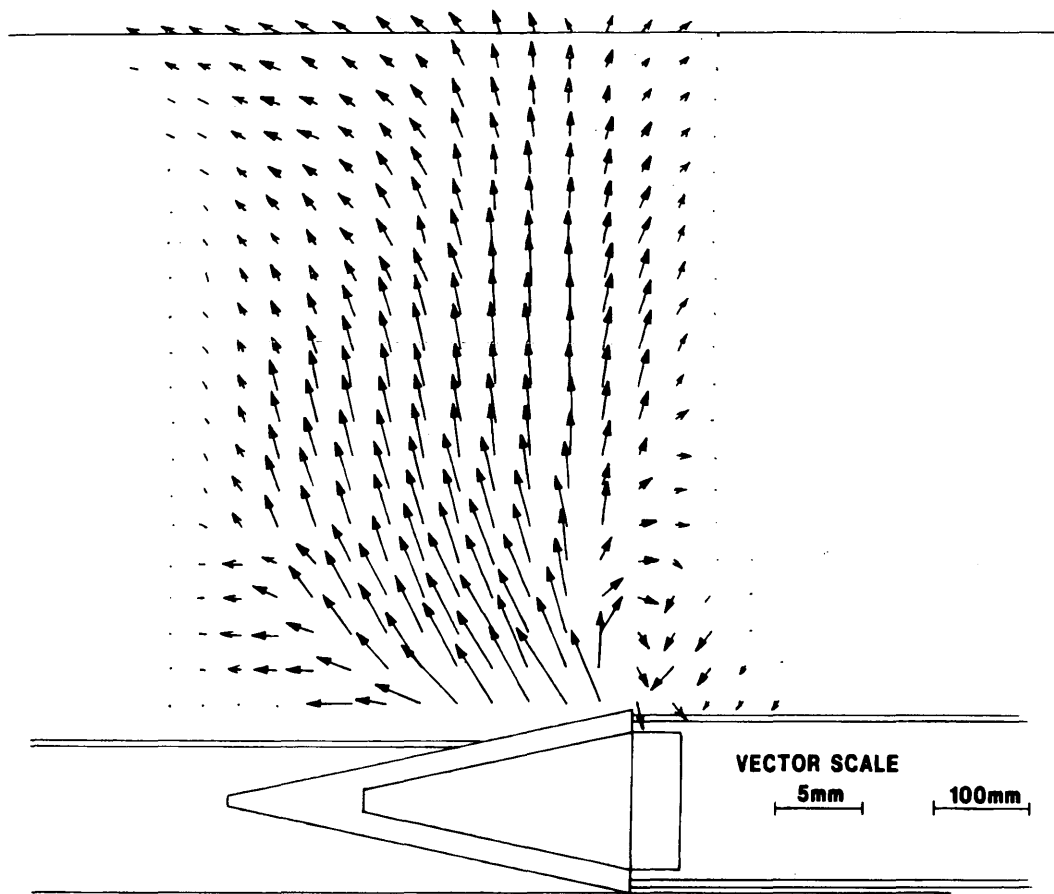


FIGURE 12 Vector displacement plot for Test PB11 (0.9 m deep in dense sand, 20-mm jacking distance).

relative stiffnesses of the soil and the service or structure, an estimation of the movements in the latter can then be made.

CONCLUSIONS

The results presented in this paper allow good visualization of the movements that occur in the ground during the jacking stage of various trenchless pipelaying operations. It is apparent from the results that there are many similarities between the patterns of movements observed, particularly between closed-shield pipejacking and pipebursting. The effects of variation of cover depth and, for pipebursting operations, the bursting ratio have also been demonstrated and conform broadly to expectations.

A knowledge of the ground movements caused by trenchless pipelaying operations and their effects on adjacent services and structures is of considerable importance if these operations are to be more widely accepted. This is particularly important in the congested urban environment, where the density of services is very high. A procedure for calculating the movements inducted in adjacent services or structures using the vector displacement plots has been described. It is intended, therefore, that the paper will provide a basis of understanding and data on which predictions of ground

movements in practice can be based. Ideally these can be refined further by field monitoring, resulting in greater confidence in the use of trenchless pipelaying operations.

ACKNOWLEDGMENTS

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