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LABORATORY MEASUREMENTS OF PULLING FORCE AND GROUND MOVEMENT DURING A PIPE BURSTING TEST

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ABSTRACT: Measurements of pulling forces and ground movements obtained from a pipe bursting experiment are reported. Results are given for the specific case where an existing intact clay pipe with an external diameter of 184 mm backfilled with a poorly-graded dense sand was replaced with a polyethylene pipe with an outside diameter of 165 mm using a commercially available burst head with a diameter of 202 mm. An average pulling force of 17.7 kN was required to break the clay pipe. Ground loss through cracks in the clay pipe in advance of the burst head occurred and at some locations led to the development of sink holes that progressed to the ground surface. The three-dimensional pattern of surface deflections induced by pipe bursting was quantified. For the specific conditions tested, a maximum surface heave of 27 mm was measured when the burst head was located directly beneath that point. Once the burst head passed beyond a certain point, the ground heave was reduced to a residual value of about 8 mm.

1. INTRODUCTION

Pipe bursting is one available trenchless construction technique that may be used to replace existing buried pipes with minimal disturbance at the ground surface. The process of pipe bursting involves a cable or rod placed within an existing pipeline of brittle material (e.g., clay, concrete, iron) that is used to pull through a "bursting head" which breaks the original pipe. The original pipe is broken (or burst) as the diameter of the bursting head exceeds that of the original pipe. A replacement pipe is then pulled into place behind the bursting head. The new pipe may be of the same size or may be larger than the original, since the bursting operation pushes the fragments of the original pipe radially outwards to make room.

Two issues that need to be considered in the planning of pipe bursting operations are the magnitude of: (a) pulling forces that must be applied to break the existing pipe and pull the new pipe into place, and (b) ground displacements induced by pipe bursting, which if excessive may have detrimental effects on surface structures and adjacent utilities. Current selection of required pulling force is often based on experience and there is no available technique to estimate the pulling force. Ground deformations are also difficult to quantify. Chapman and Rogers (1991) have conducted laboratory tests simulating the bursting of shallow buried pipe in sand by inflating a rubber bladder to expand an existing cavity. Fernando and Moore (2002) have used the theoretical solution of Yu and Houlsby (1991) to infer that the strength characteristics rather than the stiffness of the soil that controls the radial soil stresses that press onto the fragments of existing pipe as the new pipe is dragged into position. Two dimensional finite element analysis was then used to examine the influence of the ground surface above the pipe being

replaced, and pre-existing ground stresses that are non-uniform and anisotropic (Fernando, 2002). These analyses have the potential to provide predictions of ground disturbance in the vicinity of the bursting head, and estimates of earth pressures applied to the pulled-in-place pipe, so that axial force and axial stress can be estimated. However, there is little high-quality data available to verify the ability of these approaches to correctly quantify the pipe response and ground displacements. Such data is required before these techniques can be used to develop design methods.

The objective of this paper is to present measurements of pulling force and ground displacements from a laboratory pipe bursting experiment. The experiment was intended to simulate the specific case where an existing clay pipe with outside diameter (OD) of 184 mm backfilled with poorly-graded dense sand is replaced with a new polyethylene pipe with an OD of 165 mm by pipe bursting. The size of the polyethylene pipe was selected to have the same internal diameter as the clay pipe. The laboratory apparatus, boundary conditions of the experiment and instrumentation used to record the pipe and ground response are described. Measured values of pulling force are reported. Surface displacements are presented for various stages of the pipe bursting process providing data to quantify the three-dimensional distribution of ground displacements.

2. EXPERIMENTAL DETAILS

The experiment was conducted in an existing 2 m wide by 2 m long by 1.6 m deep apparatus developed by Brachman et al. (2001). A photograph of the apparatus is provided in Figure 1 and a cross-section is given in Figure 2. A new clay pipe with an outside diameter of 184 mm and thickness of 19 mm was placed near the centre of the apparatus and backfilled with a poorly-graded sand (synthetic olivine with a mean grain size of 0.5 mm). The clay pipe was positioned such that the enlarged bell ends of the pipe were placed against the walls of the apparatus. The sand was placed in 200 mm thick lifts and each lift was compacted by dropping a 250 mm square plate with mass of 6.8 kg a distance of 0.3-0.4 m. This resulted in an average dry density of the sand of 1.49 g/cm^3 at a water content of 3%, as measured with a nuclear density meter. This density is close to the maximum dry density reported for this material by Lapos and Moore (2002), and at this density the sand has an internal angle of friction of 44° .

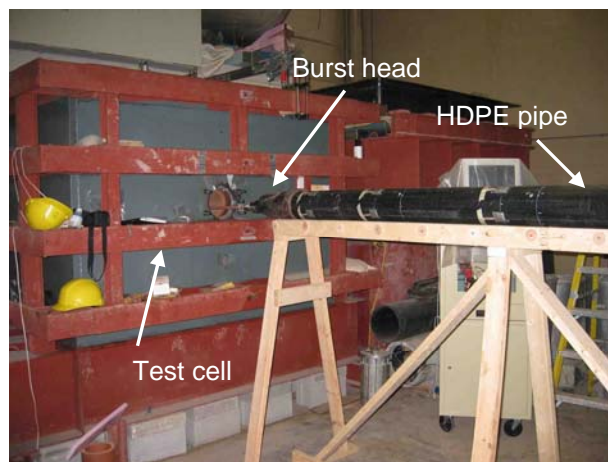


Figure 1. Photograph showing the test apparatus, burst head and HDPE prior to the experiment.

The effect of friction mobilized along the walls of the apparatus was minimized using multiple layers of plastic film lubricated with grease (Tognon et al. 1999). It is acknowledged that the proximity of the stiff walls of the apparatus to the pipe will influence the ground response relative to the field case with no lateral restraint. Preliminary analysis suggests that pulling forces will not be influenced by the lateral boundaries but that ground deflections will be larger than those without lateral boundaries. Consequently, any attempt to calibrate numerical analysis based on the measured results needs to model the presence of the lateral boundaries.

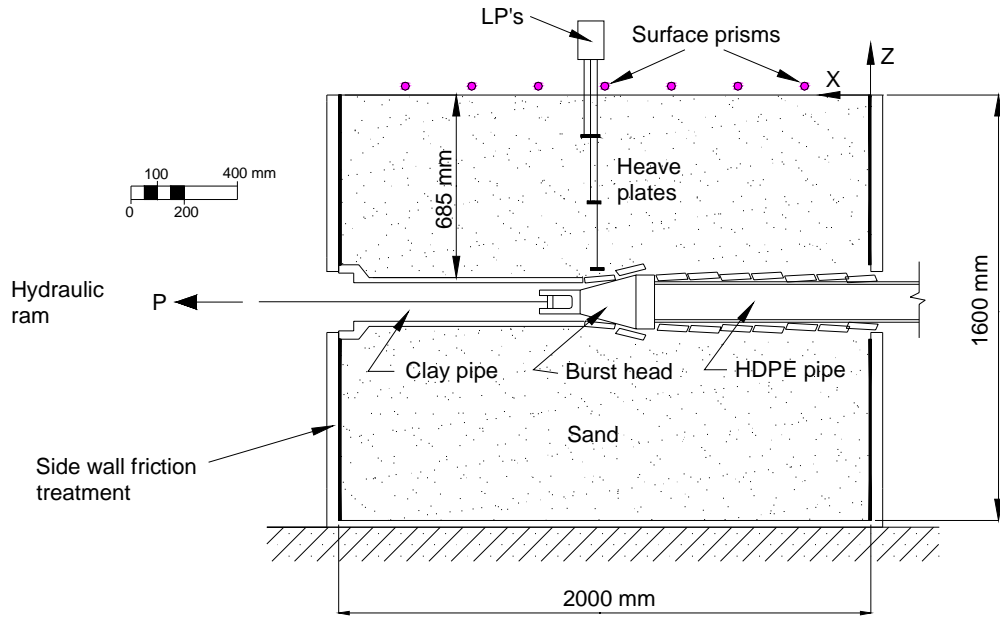


Figure 2. Cross-section through test apparatus showing the set up for the pipe burst experiment.

A commercially available burst head with a maximum outside diameter of 202 mm was used to break the clay pipe. The burst head had a sharp fin to help fracture the clay pipe. The initial orientation of the burst head had the fin located at the crown of the clay pipe. The burst head was free to rotate during the experiment. A steel rod was attached to one end of the burst head to pull the burst head through the clay pipe. Attached to the other end of the burst head was a high-density polyethylene (HDPE) pipe with an outside diameter of 165 mm and average wall thickness of 10 mm. Figure 1 shows a photograph of the burst head immediately before entering the cell with the HDPE pipe following along behind.

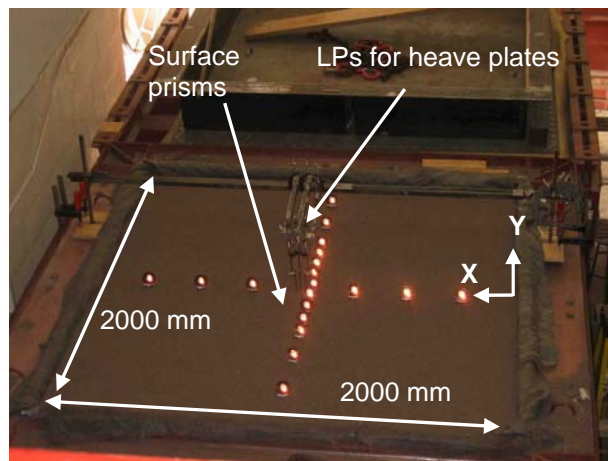


Figure 3. Photograph of a top view of the test apparatus showing the location of reflective prisms on ground surface.

The experiment proceeded in stages by pulling the burst head a distance of 250 mm with a hydraulic ram. For reference, the pull preceded in the x direction as defined in Figures 2 and 3. The pulling force was continuously recorded during each stage with a load cell attached to the steel rod. Also during each pull

stage, the ground displacements above the pipe were continuously monitored by three heave plates located at the centre of the apparatus ($x=1000$ mm, $y=0$). The heave plates were placed 500 mm, 250 mm and directly above the clay pipe. The lower heave plates consisted of steel rods attached to 50 mm square plates. A steel casing was used to separate the rod from the sand and the inside of the casing was lubricated to limit friction. Linear potentiometers (LP) were used to measure the vertical movement of the heave plates (to an accuracy of ± 0.01 mm). Following the completion of each pulling stage, surface deflections were measured using 19 reflective prisms placed on the ground surface and a total station. The prisms were located along two lines oriented parallel and perpendicular to the direction of pull. The location of the prisms is shown in Figure 3. The surface deflections were measured within ± 0.5 mm.

3. RESULTS

3.1. Pull forces

Pull forces recorded for stages 2-6 of the experiment are plotted in Figure 4. As expected, the pull force varies through each stage as the burst head breaks through the clay pipe. The average and maximum pulling forces for the 13 stages of the experiment are reported in Table 1. The largest forces were measured during stages 8 and 9 corresponding to locations where the burst head had to break the enlarged bell end of the clay pipe and the burst head pulled through the access hole in the apparatus. Since there were no differences in geometry for stages 2-6, similar pulling forces were expected for these stages. Statistical testing (using a t-test distribution) showed that the differences between the average pull forces for stages 2-6 are statistically insignificant at a 95% confidence level. This permits obtaining an average pull force of 17.7 ± 0.4 kN (where ± 0.4 is the 95% confidence level of the mean) for pull stages 2-6. The maximum force measured in stages 2-6 was 25.5 kN.

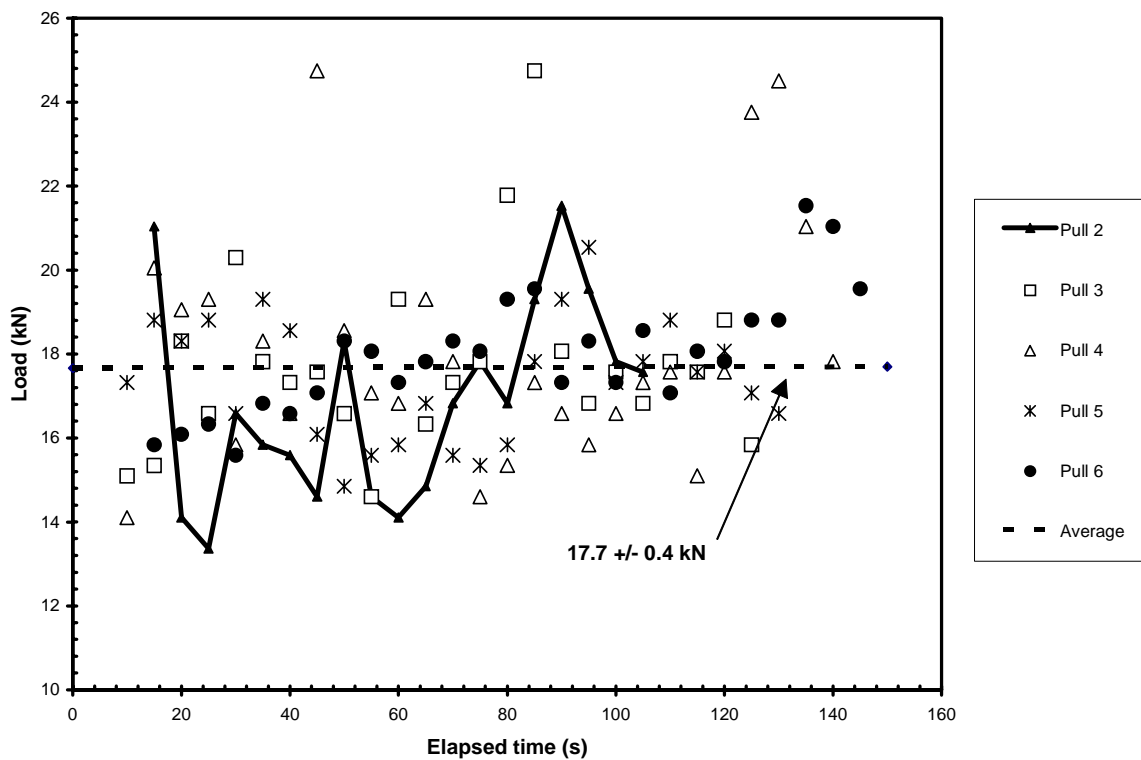


Figure 4. Measured pulling force for pull stages 2-6.

In pull stages 10 to 13 the burst head was outside the apparatus and consequently the force required to overcome only the friction force on the 2 m long portion of the HDPE pipe in the apparatus was measured. The average force to overcome friction on the 2 m long HDPE pipe was 1.6 ± 0.2 kN, with a maximum value of 2.7 kN.

Table 1. Summary of pull force data recorded for the 13 stages of the experiment.

Pull stage	Approx start and end position of each pull stage (x)	Average pull force (kN)	95% confidence interval of average (kN)	Maximum pull force (kN)
1	0 - 250	18.1	1.2	24.0
2	250 - 500	17.5	0.9	21.5
3	500 - 750	18.3	1.1	24.7
4	750 - 1000	17.7	1.0	24.5
5	1000 - 1250	17.1	0.5	20.5
6	1250 - 1500	19.6	0.9	25.5
7	1500 - 1750	19.3	0.6	23.0
8	1750 - 2000	21.9	0.7	26.2
9	2000 - 2250	14.8	5.1	27.2
10	2250 - 2500	2.3	0.2	2.7
11	2500 - 2750	1.1	0.1	1.2
12	2750 - 3000	2.2	0.1	2.2
13	3000 - 3250	1.4	0.2	2.0

3.2. Ground loss

Cracking of the clay pipe in advance of the burst head was observed during the experiment. For example, Figure 5 is a photograph taken from inside the clay pipe that shows a crack near the crown of the clay pipe. Since the opening of the crack exceeded the particle size of the surrounding backfill, sand was able to flow into the pipe. At two locations, the loss of ground into the pipe was sufficient to lead to the development of sink holes on the ground surface. At $x=1000$ and $x=1250$ both on the y axis ($y=0$) the sink holes were both 70 mm in diameter and 35 mm deep. Flow of sand stopped after the clay pipe in front of the burst head filled with sand.

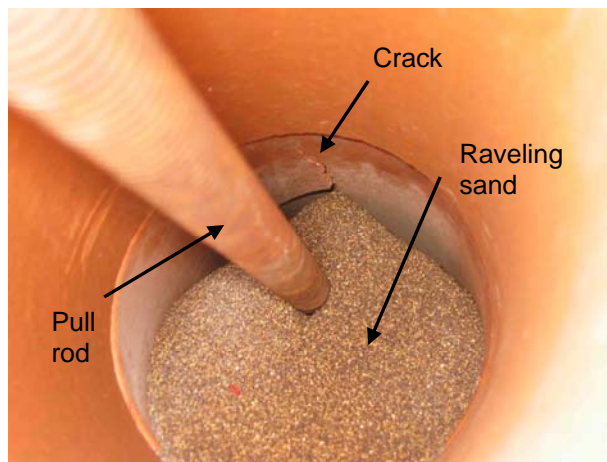


Figure 5. Photograph showing an internal view of the clay pipe with a crack near the pipe crown.

Ground loss also occurred where the clay pipe was in contact with the end walls of the apparatus. Sand was initially prevented from flowing through the access holes in the apparatus by placing the bells of the clay pipe up against the end walls. During pulls 1, 2, 8 and 9 the cracked clay pipe was no longer able to contain the sand because of cracking caused by the burst head. Figure 6 shows three sink holes that

developed during pulls 1 and 2. These holes were located at: $x=250$ mm, $y=0$ mm; $x=225$ mm, $y=50$ mm; and $x=0$ mm, $y=250$ mm. The largest of these holes was 100 mm in diameter and 50 mm in depth. The sand directly adjacent to the sink holes appeared to be unaffected by the development of the sink holes. A larger sink hole developed at the other end of the apparatus at location $x=2000$ mm, $y=0$ mm that was 350 mm in diameter and 200 mm deep during pulls 8 and 9. Preliminary analysis of the measured data suggests that the ground loss causing the sink holes appears to have only a local influence on ground deformations.

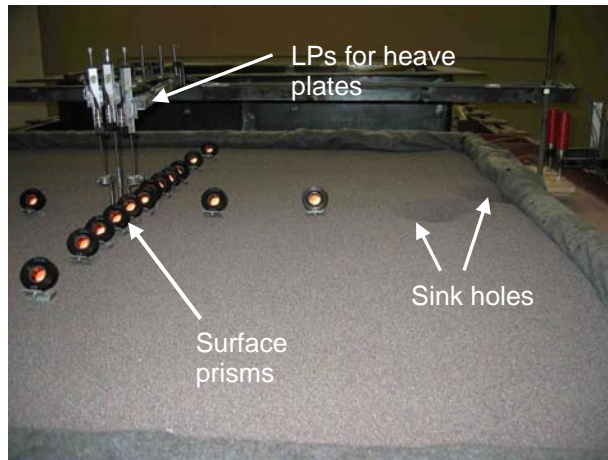


Figure 6. Photograph of ground surface showing location of sink holes in sand that occurred from pipe bursting.

3.3. Ground deformations

The vertical deflections of the ground surface measured by the prisms are plotted in Figure 7 following completion of each bursting stage. Positive values of vertical deflection correspond to upward movement (i.e. heave) of the ground. These results are plotted relative to the same position of the burst head for each stage, with the burst head drawn to scale in the inset to Figure 7. The resulting plot shows the variation of ground response in advance of, directly above and behind the burst head. Very similar results were obtained for the 13 stages of the experiment. This suggests that the sink holes have only a limited and local effect on the ground displacements. The largest surface heave was measured directly above the largest diameter of the burst head with an average value of about 21 mm and a maximum of 24 mm. The first ground response appeared once the burst head was within five times the burst head diameter. The vertical deflections decreased once the burst head had passed and approach a residual heave of 8 mm.

The surface deflections monitored along a section perpendicular to the direction of pull (located along $x=1000$ mm) are plotted in Figure 8 for pull stages 1-5. This plot represents ground response as the burst head approaches this section. Ground heaves are essentially symmetric about the centre line of the clay pipe. A maximum displacement of 27 mm was measured during stage 5 which corresponds to the stage when the largest part of the burst head past beneath this section. The results plotted in Figures 7 and 8 clearly show the three-dimensional nature of the ground response induced by pipe bursting.

Figure 9 is a plot of the measured vertical deflections of the soil obtained with the heave plates throughout the experiment. Results are shown for heave plates located directly above the clay pipe and at distances of 250 and 500 mm above the clay pipe. At all three elevations the peak response was measured during the sixth pull, which corresponds to when the largest diameter of the burst head passed beneath the heave plates. The maximum vertical deflection of roughly 50 mm was recorded at the clay pipe. The deflections measured at locations 250 mm and 500 mm above the pipe were nearly the same.

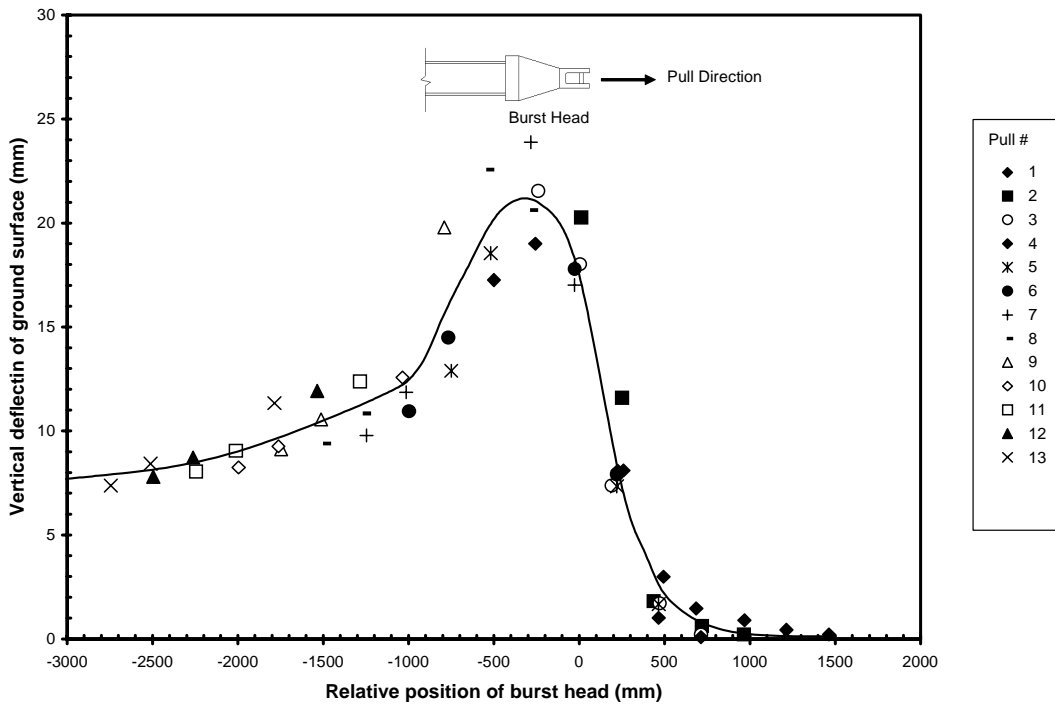


Figure 7. Measured vertical deflection of ground surface (along $y=0$) relative to position of the burst head for each stage of the experiment.

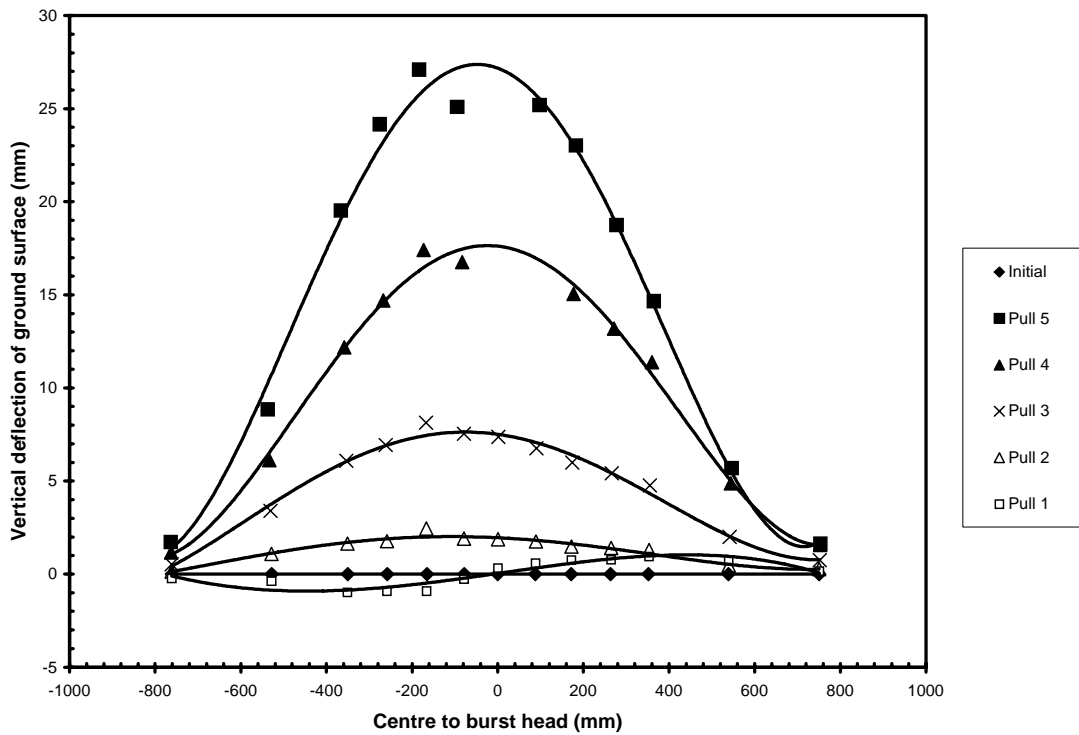


Figure 8. Measured vertical deflection of ground surface (along $x=1000$ mm) as the burst head advances towards the centre of the apparatus.

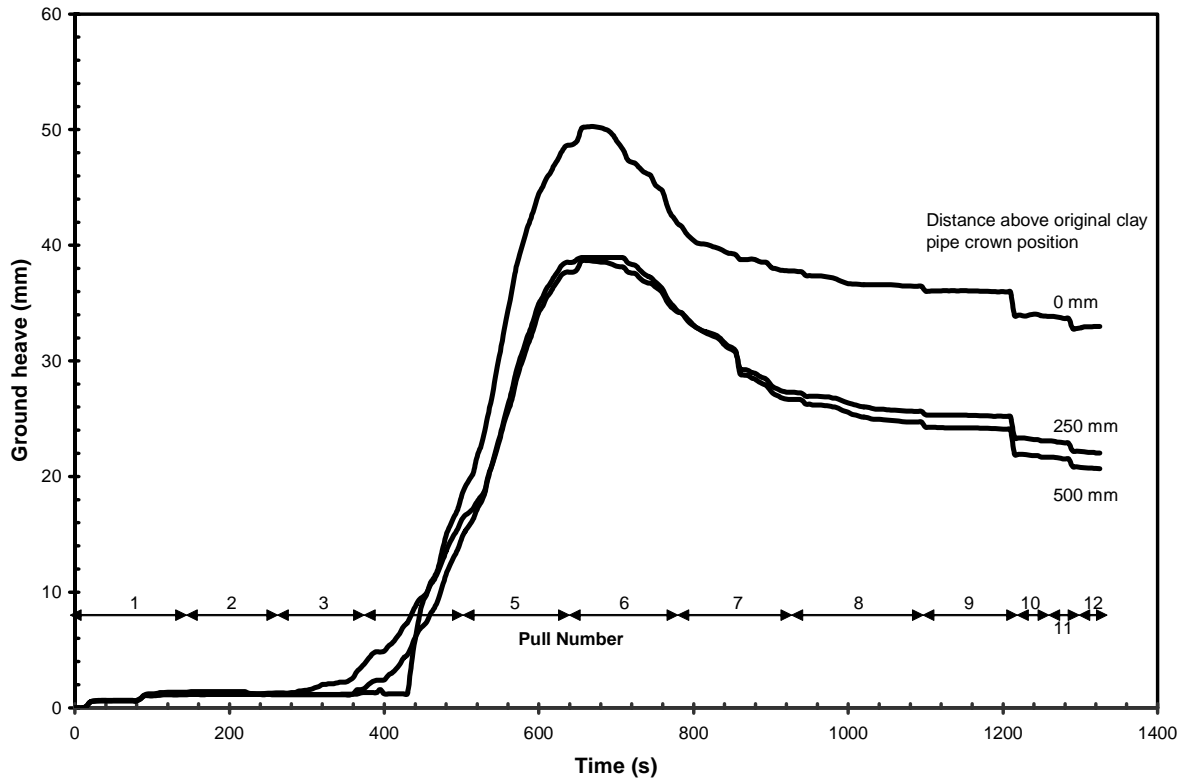


Figure 9. Measured vertical displacements of ground with heave plates for each stage of the experiment.

3.4. Observations following excavation

Following the experiment, careful excavation of the sand was conducted to provide visual examination of the nature of the clay pipe and HDPE pipe following pipe bursting. The clay pipe was visibly broken into many fragments with varying sizes around the entire circumference of the pipe. A photograph of the external surface of the clay pipe is provided in Figure 10. The fragments were not inclined to their original orientation but rather appeared to be outwardly translated away from their initial position in the radial direction. The average outside diameter of the broken clay pipe fragments was about 234 mm, which corresponds to an increase in diameter of 50 mm. Careful removal of fragments of the clay pipe revealed that sand almost entirely filled the space between the broken clay pipe and the HDPE pipe. This sand was able to flow through the gaps between clay pipe fragments. Thus the values of pull force measured in stages 10-13 (when the burst head was outside the apparatus) likely correspond to the friction generated along a sand-HDPE pipe interface, rather than that if the pipe was being dragged directly against the clay fragments.

4. SUMMARY AND CONCLUSIONS

Pulling forces and ground deformations were reported for the case where an existing intact clay pipe (OD=184 mm) was replaced with HDPE pipe (OD=165 mm) by pipe bursting. The back soil was a poorly-graded dense sand and a commercially available burst head (OD=202 mm) was used. An average pulling force of 17.7 ± 0.4 kN was recorded. The majority of this force is attributed to that required to break the clay pipe as much smaller forces were measured when the burst head was pulled through to the exterior of the apparatus.



Figure 10. Photograph showing fractured clay pipe following excavation after the burst test.

Ground loss through cracks in the clay pipe in advance of the burst head occurred and at some locations led to the development of sink holes that progressed to the ground surface. Provided that the grain size of the backfill is greater than the cracks generated in the clay pipe and/or the surrounding soil had sufficient resistance to flow when unconfined (i.e. possessed cohesion) such sink holes would not be expected in the field. However, for the specific conditions tested the sink holes were a real outcome of the bursting process. Preliminary analysis suggests that the influence of the sink holes is largely local.

Measurements of surface deflection demonstrate that ground deformations induced by pipe bursting show three-dimensional variations. A maximum surface heave of 27 mm was measured when the burst head was located directly beneath a given point. Once the burst head passed ahead, the ground heave reduced to a residual value of about 8 mm.

The results reported in this paper are applicable only for the specific conditions (e.g., pipe materials, sand backfill, geometry, and boundary conditions) examined in the experiment. Preliminary numerical analysis of the measured response suggests that the results from such experiments will be valuable to assess the applicability of available solutions to estimate ground deformations arising from pipe bursting, provided that the influence of the proximity of the lateral boundaries of the apparatus are modeled. Further testing is currently underway to quantify the ground response from pipe bursting for a wider range of burial depths and pipe sizes.

5. ACKNOWLEDGEMENTS

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