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AN EXPERIMENTAL STUDY OF SOIL EROSION AROUND LEAKING PIPES

Sherif Kamel[1] and Mohamed A. Meguid[2]

[1] Graduate Student, Department of Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke St. West, Montreal, Quebec H3A 2K6.Email: cherif.kamel@mail.mcgill.ca
[2]Assistant Professor, Department of Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke St. West, Montreal, Quebec H3A 2K6. Email: mohamed.meguid@mcgill.ca

ABSTRACT: Infiltration into leaking pipes is a problem of growing concern to geotechnical and environmental engineers. Adverse effects of pipe leaking include groundwater contamination and soil erosion into cracks, holes and joints. It has been reported that soil erosion can lead to significant stress changes around pipes. The resulting stress concentration can leads to further deterioration and possibly failure. In this study, experimental investigations have been conducted to examine the effects of different parameters (e.g. hole size, location and soil type) on the contact pressure against a rigid pipe and the associated soil movements. Significant increase in radial pressure was measured when a hole is introduced at the pipe crown. The experimental results presented in this study provided an insight into understanding this important soil-structure interaction problem.

1. INTRODUCTION

Buried pipes are important infrastructure for modern cities. They are being used for water supply, wastewater transfer and storm water management. A Challenging task facing most municipalities is not only the expansion of the pipeline systems to keep up with the constant population growth, but also the replacement and rehabilitation of deteriorated systems. One of the most critical aspects of aging pipe networks is leakage. Pipe joints, breaks and cracks are essential factors contributing to leakage, which causes a tremendous loss in the distribution and disposal systems. Losses due to leaks mean that more water is required by the distribution systems; hence increased costs to comply with the population needs. Leakage from defected sewer pipe can lead to the contamination of the groundwater table.

The adverse effects of leaking pipes are not only limited to the subsurface environment, but also propagates to ground surface. Defects located along the circumference of pipes can lead to subsurface soil erosion. This is particularly true when the backfill material contains significant percentage of fine material. For gravity pipes, these fines can erode under gravity or carried by the water flow into the pipe. Once subsurface soil erosion is initiated, fines continue to flow causing progressive volume loss that could reach the ground surface causing settlement and possibly failure.

Several cases have been reported (e.g. Carlson and Urquhart, 2006; Paggioli, 2005) where ground surface collapsed leading to sinkholes near aging pipes. Research, to date, has focused on the effect of pipe deterioration on the structural performance of the pipe in isolation from the surrounding ground. The above problem has not received enough research attention particularly the contact pressure distribution around leaking gravity pipes. A summary of selected relevant research is given below.

1.1 Distribution of contact pressure on buried pipes

Investigating the contact pressure distribution on buried pipes dates back to the 1960’s, where Marston and Spangler developed their popular theories. Marston theory (Spangler and Handy, 1973) allowed one to estimate the net vertical force acting on a buried conduit. The net force was evaluated as the weight of the soil column plus or minus the shear forces acting on the sides of the column. The direction of the shear forces is controlled by the arching phenomena. Spangler (Spangler and Handy, 1973) suggested

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that the vertical overburden pressure is uniformly distributed over the conduit's width, and the lateral earth pressure is parabolically distributed over a central arc with the peak pressure proportional to the product of the springline deflection. This approach led to the well established Iowa formula to calculate the deflection of flexible pipes. Hoeg (1968) conducted experimental and analytical studies to investigate the contact pressure on underground cylinders. Figure 1 shows the distribution of the experimental radial contact pressure against a typical rigid pipe. The pipe-soil interaction problem was also investigated analytically and a closed form solution was developed and expressed in terms of two stiffness ratios (the compressibility ratio and the flexibility ratio) and three constants derived for two different boundary conditions, namely, no slippage or free slippage condition. The radial pressure (σ_r) is expressed as follows:

$$\sigma_r = \frac{1}{2} p \left\{(1+K)\left[1 - a_1\left(\frac{R}{r}\right)^2\right] - (1-K)\left[1 - 3a_2\left(\frac{R}{r}\right)^4 - 4a_3\left(\frac{R}{r}\right)^2\right]\cos 2\theta\right\} \quad [1]$$

Where *R* is the pipe radius, *r* is the distance from the pipe center to the soil element under analysis, *K* is the lateral earth pressure coefficient; *p* is the soil vertical stress, *θ* is the angle of inclination from the springline and a_1, a_2 and a_3 are constants. These constants for the free slippage condition are given by:

$$a_1 = \frac{(1-2v)(C-1)}{(1-2v)C+1} \quad [2]$$

$$a_2 = \frac{2F+1-2v}{2F+5-6v} \quad [3]$$

$$a_3 = \frac{2F-1}{2F+5-6v} \quad [4]$$

The above constants are functions of the compressibility and the flexibility ratios that are defined as follows:

$$C = \frac{1}{2}\frac{1}{1-v}\frac{\frac{E_s}{E_p}}{1-v_p^2}\left(\frac{D}{t}\right) \quad [5]$$

$$F = \frac{1}{4}\frac{1-2v}{1-v}\frac{\frac{E_s}{E_p}}{1-v_p^2}\left(\frac{D}{t}\right)^3 \quad [6]$$

Where E_s , v are Elastic modulus and Poisson's ratio for the soil, E_p , v_p are Elastic modulus and Poisson's ratio for the pipe. *D* is the average diameter of the pipe and *t* is the wall thickness of the pipe.

1.2 Soil erosion around rigid pipe

The effect of subsurface erosion voids on the stress distribution in a rigid pipe was investigated numerically by (Zheng and Moore, 2007). The results indicated that the presence of erosion voids at the springline lead to an increase in the magnitude of bending moments. However, erosion voids located at the invert resulted in a decrease or sign inversion of bending moments depending on the void size. It was also found that an increase in voids size results in doubling the magnitude of bending moments, if the void contacts the pipe circumference over a 90 degree arc. It was concluded that location, shape, and size of erosion voids are considered to be important factors that control the changes in stresses in a rigid pipe subjected to subsurface erosion.

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Factors causing pipe deterioration and the effect of corrosion pits on the structural performance of pipes have been investigated by several researchers (e.g. Makar, 2000; Seica and Packer, 2004; Seica et al., 2002) with emphasis on cast iron pipes. It was concluded that corrosion was the main factor influencing pipe deterioration. Cracks initiates at corrosion pits lead to progressive circumferential and longitudinal cracks in addition to blown-out holes.

The above studies assume either defect-free pipes or defected pipe in isolation from the surrounding soil. The presence of defects in the pipe can lead to changes in the contact pressure distribution around the pipe. A better understanding of these changes is, therefore, needed. The objectives of this ongoing study are to investigate the soil movement and contact pressure distribution around a rigid pipe with a set of idealized circular holes introduced at different locations across the pipe section. The effects of different parameters (e.g. hole size, location, soil type, etc) are examined.

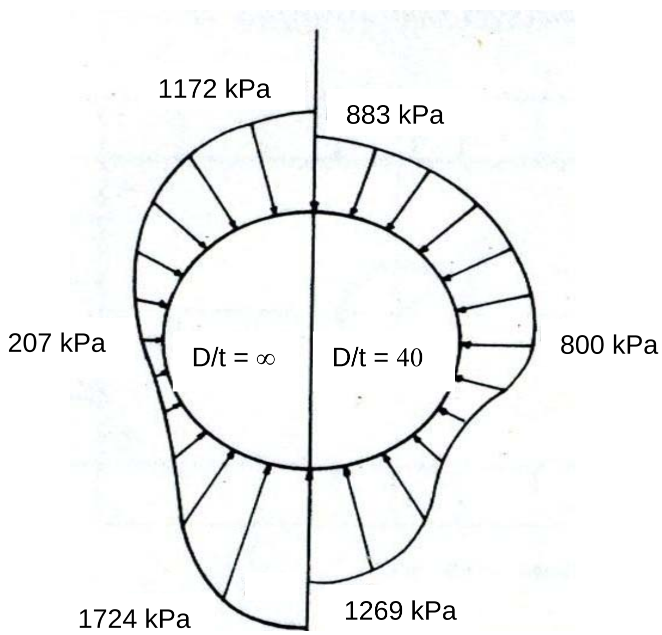

Figure 1. Distribution of Experimental Contact Pressure (Hoeg, 1968)

2. EXPERIMENTAL PROCEDURE

The experimental study included two different series of tests- the first aimed at measuring the changes in contact pressure on a rigid pipe before and after a circular opening is introduced at different locations in the pipe whereas the second set of tests was conducted to examine the surface failure mechanism above a leaking pipe installed in granular material and located above the groundwater table. The experimental set up is summarized below.

2.1 Test setup for contact pressure measurement

The first set of tests examined the pressure distribution on a rigid steel pipe (F = 0.08) under a uniform surface surcharge of 29.5 kPa which represent a burial depth of about 2 m below ground surface. A cubical Plexiglas box was designed and built to host the buried pipe and allow for the creation of different hole sizes at selected locations. The box is 500 mm wide x 500 mm deep reinforced using HSS sections and steel angles. The thickness of the Plexiglas wall is 127 mm. Two 152.4 mm openings were created across the box to allow for the pipe installation. The same tank was used throughout the experiments. A steel pipe (11.43 mm in diameter and 600 mm in length) was installed in the box and secured in place using two O-rings. Pipe deterioration was simulated by drilling different hole sizes along a circular cross

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section at the middle of the pipe. Three different hole-diameters were chosen based on the average particle size of the backfill material, namely, 3, 4 and 5 mm. Two single-point load cells each of a maximum capacity of 5 kg are installed at the crown and springline in the close vicinity of the holes were used to measure the contact pressure against the pipe. The cells are mounted inside the pipe with only the sensing area exposed to the soil. The surcharge required was applied using an MTS machine. A plywood block composed of seven single layers each of 465 mm x 465 mm was used to distribute the force over the soil surface. A picture of the experimental set up is shown in Figure 2.

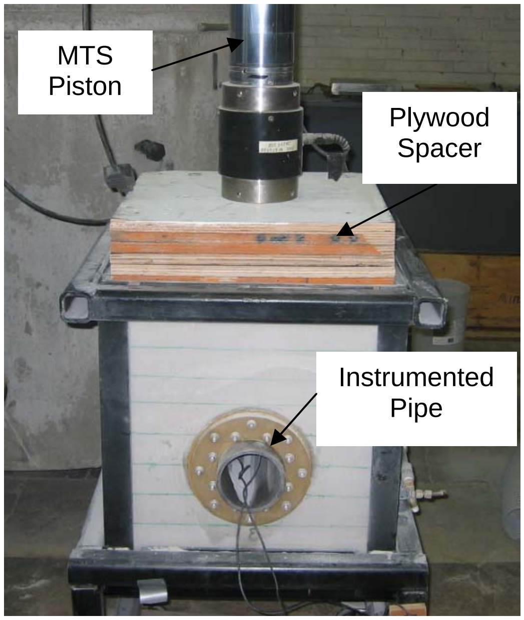

Figure 2. Experimental Set Up

Two different silica sands (grade 7030 and 2075) were used in preparing the backfill material. The first composed of silica-sand 7030 (with more fines compared to 2075). This type of backfill is referred to as soil type A (100% Fine). The second granular backfill was a mixture of the two sand materials in the following proportion: 90% silica-sand 7030 and 10% silica-sand 2075. This type of backfill is referred to as soil type B (90% Fine 10% Coarse). Soil type B was prepared in the laboratory by mixing specific amounts of sands in a mechanical mixer. The grain size distribution curves (Figure 3) indicated a uniform sand material with particle size ranging from 0.1 mm to 1 mm (D_{10} = 0.15 mm & D_{60} = 0.3 mm) for soil A and particle size ranging from 0.1 mm to 1.5 mm (D_{10} = 0.15 mm & D_{60} = 0.32 mm) for soil B.

In this set of tests, two load cells were mounted on the steel pipe at the crown and springline. The shim that is mounted on the sensitive area of the load cell was covered with a thin plastic sheet to ensure that no sand particles block the shim movement during the test. Before placing the sand for each test, the load cell readings were checked by applying dead loads of known mass on the shim. Then, the soil was rained to backfill the pipe up to twice the diameter (2D) above the crown. After leveling the sand surface the readings of the load cells were recorded using a data acquisition system. After the sand placement is completed, the plywood spacers were placed on top the sand surface and the MTS piston was lowered to touch the plywood surface. The MTS machine was programmed to run under a loading rate of 0.5 kN/min. After reaching the target force required for the test, the piston is kept in place to maintain a constant surface surcharge over the sand layer. At this stage, the initial contact pressure is recorded. Soon after, the hole representing the idealized pipe deterioration is unplugged and the contact pressure is re-recorded. The tests were repeated to examine the effect of the hole size (4 m vs. 5 mm diameter) and location (crown vs. springline) on the contact pressure against the pipe.

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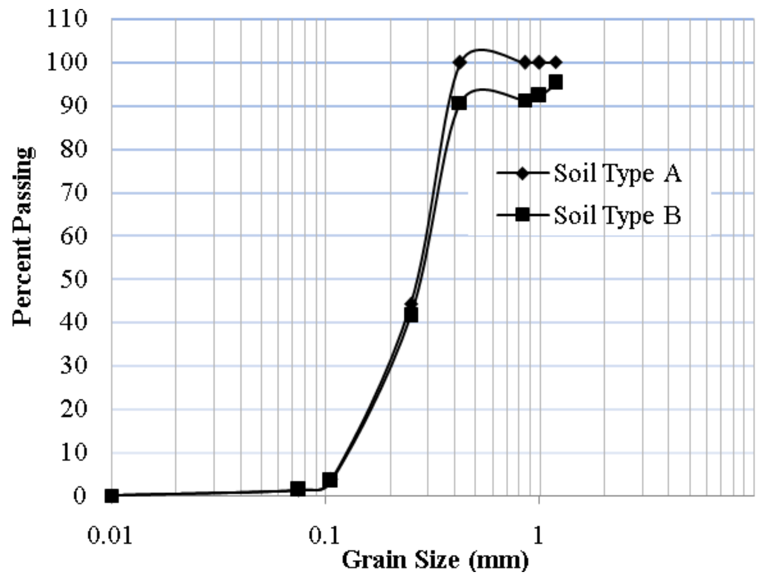

Figure 3. Grain Size Distribution

2.2 Test setup for investigating soil surface failure

Similar test setup was used to investigate the ground response to subsurface soil erosion. A circular hole is introduced in a rigid pipe buried in dry granular material and the resulting volume loss and surface settlement is measured. In these tests, a plexiglass pipe was used instead to allow for the erosion voids developing in the close vicinity of the pipe to be monitored. The three holes simulating the idealized pipe deterioration were drilled in the plexiglass pipe at the same location as the steel pipe used in previous investigations. The wall thickness of the plexiglass pipe was about 3 mm and no load cells were installed inside the pipe. A picture of this test setup is shown in Figure 4.

Three set of tests were conducted. The first set of tests examined the effect of the ratio between the particle size and hole diameter on the soil erosion process. The second set of tests investigated the effect of the induced hole location on the magnitude and location of the ground movement around the pipe as well as at the surface. The third set of tests considered the erosion caused by the 5 mm hole size when the ratio of fine to coarse grain size of the backfilling material changed (soil type B: 90% fine sand to 10 % coarse sand).

In each test about 135 kg of silica sand was used to backfill the pipe up to twice the diameter (2D) above the crown. For the first two set of tests, three hole-sizes (3, 4 and 5 mm) were investigated by unplugging the initially sealed holes creating a void around the pipe and allowing the sand to freely flow under gravity. In these set of tests, the soil type A was used as the backfill material. The rate of volume loss was recorded for each test by collecting and weighing the sand flowing into the pipe. In addition surface movements were manually recorded by measuring the vertical displacements on a grid of strings installed at the top of the box as shown in Figure 4. For the third set of tests, experiments were repeated for a hole size of 5 mm and soil type B as a backfill material. Results are summarized in the following section.

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Figure 4. Experimental Set Up for Surface Soil Failure

3. PRELIMINARY EXPERIMENTAL RESULTS

3.1 Contact Pressure Measurement

To calibrate the experimental set up used in measuring the contact pressure between the pipe and the soil, load cell readings were recorded before inducing any defects in the pipe and compared to those calculated using Hoeg (1968)'s analytical solutions. The results of the analytical solutions for free slippage pipe-soil interaction and the pressure measured are presented in Figure 5. The measured pressure at the crown was found to be in good agreement with the theoretical values with a maximum difference of about 15%. Larger difference was found at the springline between the measured and calculated values (about 60%). However, for the purpose of this experiment this was considered acceptable as long as the measured results are repeatable and consistent.

Figure 6 shows the contact pressure measured on the pipe before and after a 5 mm circular hole was introduced at the crown. The results indicated that contact pressure decreased at the crown in the close vicinity of the hole. However, the pressure at the springline was found to increase. The contact pressure measured at the crown decreased by about 70%; whereas the contact pressure at the springline increased by about 60%.

Figure 7 shows the contact pressure measured against the pipe when a 4 mm hole was introduced at the springline. Similar trend of pressure redistribution was recorded. However, the pressure at the crown decreased by about 60%; whereas, the contact pressure at the springline increased by about 65%.

It was also observed that introducing idealized holes of 4 mm and 5 mm in diameter at the springline did not induce significant changes to the contact pressure distribution as shown in Figure 8. The results of the two tests were found to be similar and therefore the pressure distribution resulting from the 4 mm hole at the springline is presented.

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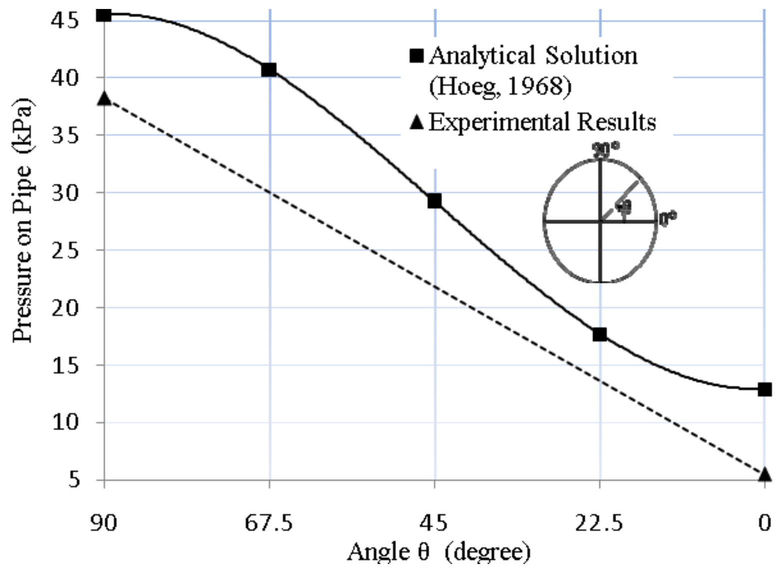

Figure 5. Measured Pressures Vs. Computed Pressures

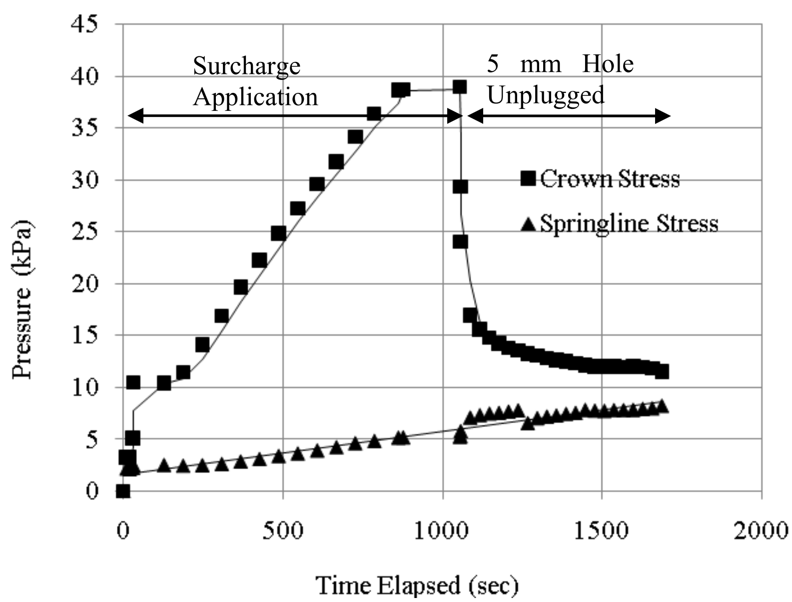

Figure 6.Pressure Distribution due to Soil Erosion Induced by 5 mm Hole at Crown

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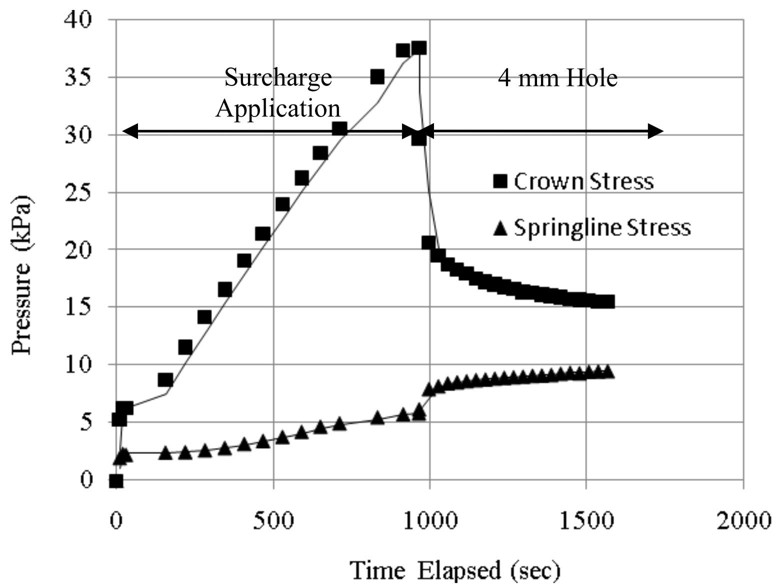

Figure 7. Pressure Distribution due to Soil Erosion Induced by 4 mm Hole at Crown

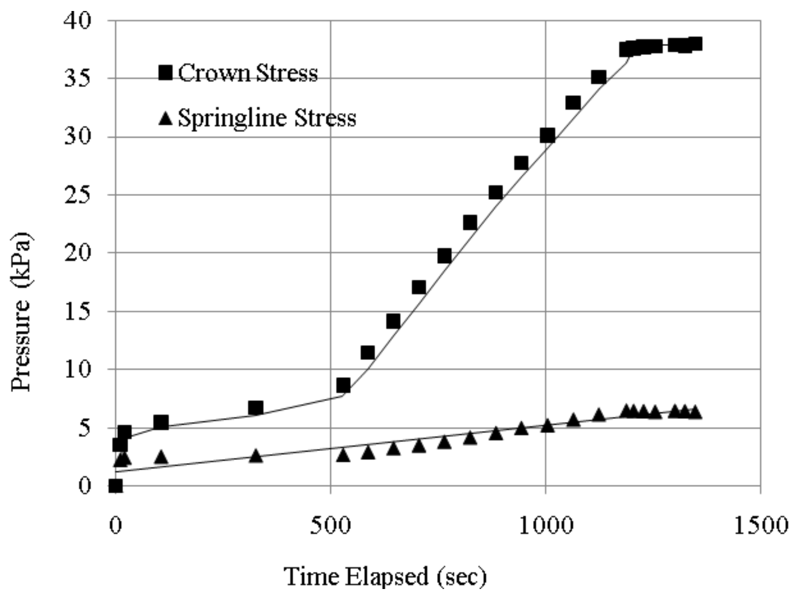

Figure 8. Pressure Distribution due to Soil Erosion Induced by 4 mm Hole at Springline

3.2 Soil Surface Failure

To examine the effect of the relative size between the soil and the induced hole on the volume loss into the pipe, a reference particle diameter (D_{60}) was adopted in these experiments. The ratio between particle to hole size is plotted against the normalized volume loss as shown in Figure 9. The volume loss is normalized with respect to the volume of the surface depression for each case. For the examined range of particle and hole sizes, a reduction in volume loss was observed as the particle to hole size ratio increased. Soil surface settlement developed when excessive sand has eroded into the pipe.

The size of the surface depression developing due to the sand movement into the induced opening, located exactly above the pipe crown and at angle of 45° from the springline, is illustrated in Figure 10.

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Both the depth and radius are plotted for the three examined openings (3, 4 and 5 mm). Results indicated that for the same backfill material, if the sand is allowed to flow freely into a hole at the pipe crown, the size of the conically shaped depressions is directly related to the size of the opening. Rotating the hole location 45° from the crown caused an offset of the conically shaped depressions in direction of the holes rotation and in size decrease.

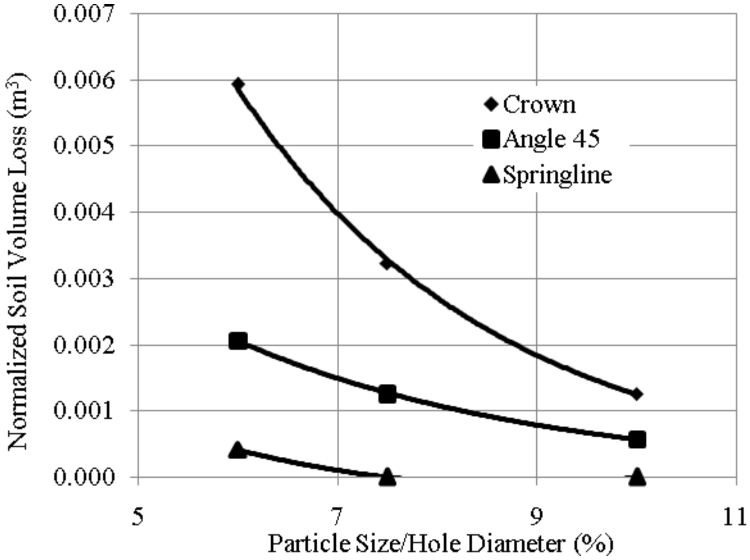

Figure 9. Ratio of Backfill Particle Size to Induced Opening Size Effect on Normalized Volume Loss

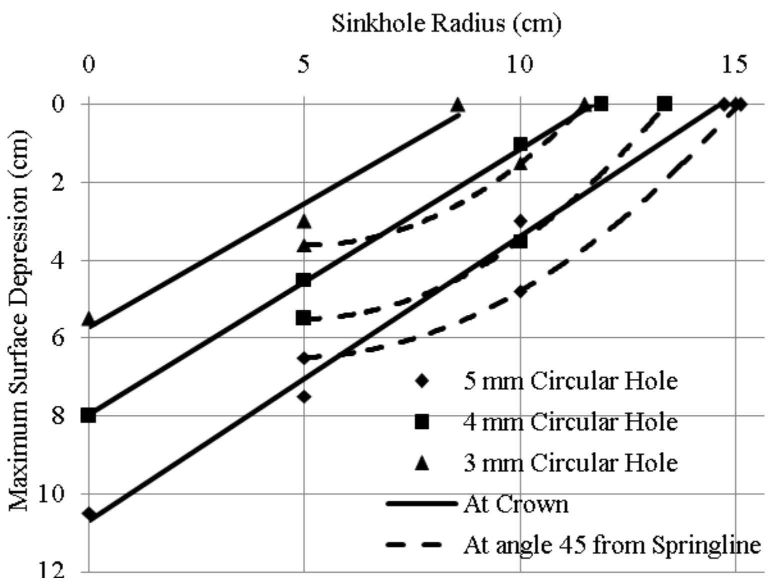

Figure 10. Effect of Hole Size and Location on Surface Depression Shape

Effect of changing the percentage of fines in the backfill material on the volume loss induced due to soil movement through the 5 mm hole is presented in Figure 11. Four tests were conducted for each soil type by varying the hole location starting from the springline (0^o) towards the crown (90^o). The volume loss is again normalized with respect to the volume of the surface depression for each case. It was observed that the location of the hole has a significant effect on the rate of sand movement into the pipe. A small void with very little or no sand erosion was observed for the case where the hole was located at the springline. As the induced hole is moved towards the crown, more sand eroded into the pipe the maximum erosion was measured at the pipe crown for soil type A. For soil type B, the maximum soil erosion was measured at an angle of 67.5°. This finding emphasizes that the presence of coarse grained material around small holes can slow down the erosion process and minimizing the volume loss around the pipe. Clogging was also observed to occur in most of these cases and the erosion process completely stopped.

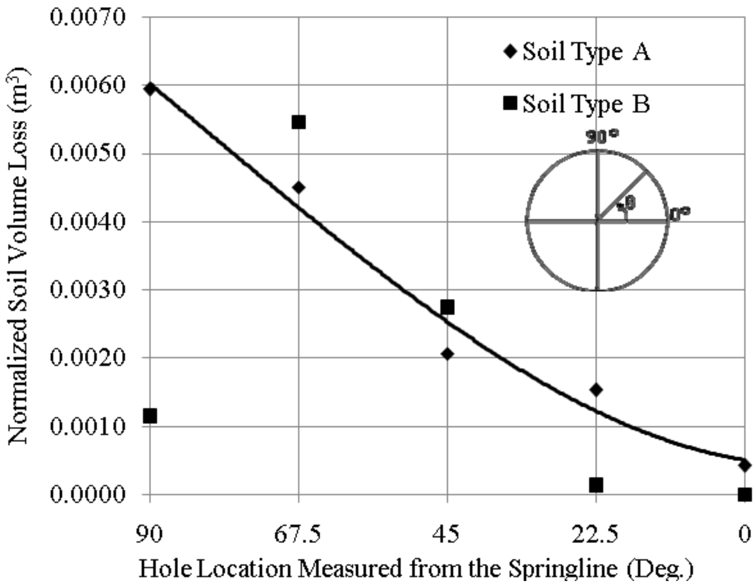

Figure 11. Effect of Backfill Particle Composition on Soil Volume Loss

4. CONCLUSION

The preliminary results of this experimental study indicated that contact pressure against a rigid pipe during and after soil erosion through an idealized circular hole can significantly increase. The location and size of the hole are two key parameters affecting both the pressure redistribution and the soil surface settlement. The size of the hole is directly related to both the magnitude of contact pressure and the surface settlement. Introducing the same hole size at different locations across the pipe section led to the development of surface pits at a distance from the location of the deteriorated section. Increasing the percentage of coarse grained soil in the backfill material lead to a reduction in the soil volume loss and complete clogging. Addition large scale or centrifuge tests are required to confirm the above results for full scale pipes.

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