

Stability of Saturated Cohesionless Soil Layer Due to Water Flowing from a Broken Underground Pipeline

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Abstract. An experimental study was conducted to assess the effect of the increase in pore water pressure, caused by water flowing from an underground pipeline, on the stability of a saturated cohesionless soil layer. The value of the buildup pore water pressure depends on several factors such as the water pressure inside the pipeline, the size of the hole at the broken section of the pipeline, and the depth of embedment of the pipeline. In this study, three series of tests were run to evaluate the effect of the above mentioned factors on the buildup of pore water pressure and on the stability of the soil layer. The increase of the water pressure inside the pipeline and the increase of the size of the hole at the broken section of the pipeline were found to significantly increase the buildup pore water pressure and to reduce the stability of the soil layer. However, increasing the depth of embedment of the pipeline reduced the effect of the buildup water pressure on the stability of the soil layer due to the increase of the effective stress with depth.

Nomenclature

| | |
|------------|--|
| P | pressure inside the pipeline. |
| D | diameter of the hole at the broken section of the pipeline. |
| T | depth of embedment of the model pipeline. |
| d | the vertical distance from the model pipeline. |
| I | stability factor. |
| q | rate of flow from the broken section, cm^3/sec . |
| S_{red} | reduced shear strength. |
| U | hydrostatic water pressure. |
| ΔU | incremental water pressure. |

| | |
|----------------|---|
| Δh | incremental water pressure head. |
| Z | depth to the point of calculating U . |
| ϕ | angle of internal friction. |
| ϕ_{red} | reduced angle of internal friction. |
| $\bar{\sigma}$ | effective stress. |
| σ | total stress. |
| γ_w | unit weight of water. |

Introduction

Leakage of water from the underground pipeline network could reach about 50% of the total water supply to the network. In Riyadh City, the average loss due to leakage was estimated to be about 34% of the total consumption [1]. This high water loss is a major problem causing considerable waste of national wealth and creating serious geotechnical-engineering problems affecting structures at locations of leakage where most of this leakage occurs (i.e. near house connections).

Several factors can cause damage(s) to embedded pipeline resulting in water leakage into the surrounding soil media. A main factor for complete or partial damage of the pipeline is subjecting the pipeline to external loads that cannot be tolerated by the pipeline. Such loads may be applied during the excavation operations without the awareness of pipes being present in the area of operations. Another type of these external loads are those created by earthquakes, which can happen in some areas of Saudi Arabia like the zones of Tabuk and Jazan [2].

The flow of water from a broken underground pipeline into its surrounding soil layer will increase the pore water pressure and may cause an unstable soil layer in a similar way to that caused by seismic loads [3,4]. Al-Karni [5] found experimentally a significant effect, caused by the flow of water from a model broken pipeline embedded inside the soil layer, on the stability of model shallow footings placed at the top of the soil layer. The results of that study showed that when the water table rises above the sand layer surface due to water flowing from the embedded pipeline at low pressure inside the pipeline (i.e. ≤ 30 kPa), the settlement of the model footings was very low and no bearing capacity failure occurred. This is due to the flow of water into the soil layer with insignificant increase in the pore water pressure. In this case, when the bearing capacity was modified to consider the rising of water table above the surface of the soil layer [6, p.108], the safety factor dropped from 3.0 to 1.885. This indicates that the settlement and the reduction in the bearing capacity due to the change of water table level were tolerable. However, a high settlement of the model footings accompanied with high rotation occurred when the water pressure inside the model pipeline was high

(i.e. > 120 kPa). The cause of such high settlement and rotation is due to the reduction in soil shear strength as a result of increasing pore water pressure. This can be presented mathematically as:

The shear strength of saturated sand is defined by,

$$S_u = \bar{\sigma} \tan \phi = (\sigma - U) \tan \phi \quad (1)$$

Where S_u is the undrained shear strength, σ is the total pressure, $\bar{\sigma}$ is the effective pressure, ϕ is angle of friction of the soil, and U is the hydrostatic pore water pressure which is calculated as,

$$U = \gamma_w z \quad (2)$$

Where γ_w is the unit weight of water and z is the depth from the water table level to the point at which U is calculated. The incremental water pressure (ΔU) due to water flowing from the pipeline to the sand layer media will further reduce the ultimate shear strength (S_{red}) as,

$$S_{red} = (\bar{\sigma} - \Delta U) \tan \phi \quad (3)$$

As shown by Fig. 1, this may also be stated as,

$$S_{red} = \bar{\sigma} \tan \phi_{red} \quad (4)$$

Where ϕ_{red} is the apparent reduced angle of internal friction determining the soil's bearing capacity due to the incremental pore water pressure. From Eqs. (3) and (4), we obtain:

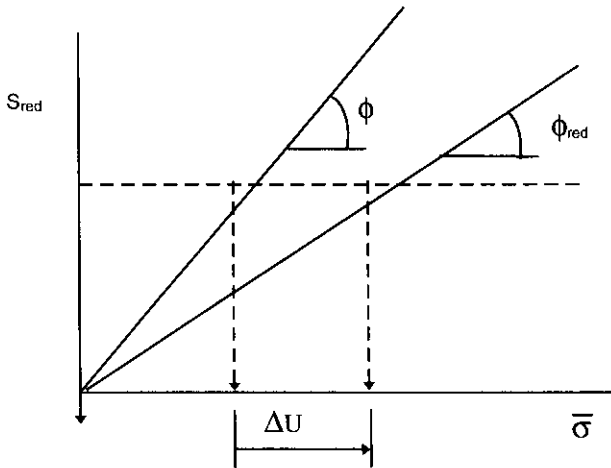


Fig. 1. Reduced shear strength.

$$\phi_{\text{red}} = \tan^{-1} \left[\left(1 - \frac{\Delta U}{\bar{\sigma}} \right) \tan \phi \right] \quad (5)$$

From this equation, a stability factor (I) will be defined as,

$$I = \left[1 - \frac{\Delta U}{\bar{\sigma}} \right] \quad (6)$$

Equation (6) shows that the stability factor depends on the incremental pore water pressure and the value of the effective stress. Increasing the pore water pressure inside the soil layer will reduce the stability factor, and increasing the effective stress will increase the stability factor. As the value of the stability factor reduces, the stability of the soil layer decreases. When the value of the stability factor is equal to one, there is no effect of the pore water pressure on the stability of the soil layer except the one due to the hydrostatic water pressure. The stability of the soil will start to decrease when the stability factor becomes lower than one. At high value of the buildup pore water pressure, the value of the stability factor becomes equal to zero at which the soil had reached a state of complete liquefaction. When the buildup pore water pressure becomes greater than the effective stress, the value of the stability factor becomes negative and the soil can be treated as a viscous fluid with very low shear strength.

The value of the stability factor can be used to predict the reduction in the value of the bearing capacity of the soil at a certain value of the incremental pore water pressure. For example, for shallow surface footing, the ultimate bearing capacity is proportional to Terzaghi's bearing capacity factor N_γ [7, p. 221]. Thus, the ratio of ultimate bearing capacity due to the incremental water pressure (q_{red}) to the ultimate bearing capacity (q_u) is approximately:

$$\frac{q_{\text{red}}}{q_u} = \frac{N_\gamma (\phi_{\text{red}})}{N_\gamma (\phi)} \quad (7)$$

Where the value of ϕ_{red} can be determined from Eq. (5) as a function of the stability factor. The value given by Eq. (7) represents the reduction in the ultimate bearing capacity at a certain value of the incremental pore water pressure. Hence, evaluating the incremental water pressure is necessary to calculate the bearing capacity reduction using Eq. (7). However, the evaluation of the effect of the buildup pore water pressure on the bearing capacity is beyond the scope of this study.

This study represents the experimental results of the effect of the pore water pressure increment (ΔU) on the stability of a cohesionless soil layer considering different values of the applied water pressure inside the pipeline, different values of the hole size at the broken section, the effect of embedment of the model pipeline, and the effect of the rate of water flowing from the broken model pipeline.

Experimental Setup

To study the effect of water flowing from an underground broken pipeline on the value of buildup water pressure inside a sandy soil layer, an experimental setup was developed which included a test box, a model pipeline, water pressure gauge and a piezometers panel assembly. The test box was made from 0.5 cm thick Plexiglas measuring 124.5 cm x 45.5 cm x 24.0 cm with a steel frame surrounding it (Figs.2 and 3). Nylon tubes with filters at their ends were placed at various locations inside the test box through especially fabricated openings on the box sides. These tubes were connected to the Manometer Panel Assembly to read the changes in the measurements of the water pressure inside the soil layer. Two water tubes with valves were added at the bottom of the box used for either saturating the soil or for draining the water from the soil sample. A steel tube with 1-cm diameter was used as a model pipeline in the experiments as shown in Fig. 4. The section at which the pipeline was broken was simulated by a hole on the side of the model pipeline. The hole diameters used were 2mm, 3.5 mm, and 5 mm. The model pipeline was connected from the inflow end to the source of water supply through a water pressure gauge and the outlet end was left open to permit a free flow of the water (Fig. 2). The water pressure inside the pipeline was measured by a water pressure gauge installed at the inflow end of the model pipeline. At the beginning of the test, the applied water pressure inside the model pipeline was set at an initial value that was kept constant during the test. A pressure-controlling valve was used to connect the model pipeline to the water inflow source. The maximum pressure of the water that can be applied is about 1.8 bars (180 kPa). Figure 2 shows the connection of the water pressure gauge to the model pipeline and the inflow control valve.

Material Properties

Local uniform white sand was used in this study. A series of tests complying with ASTM was conducted on the sand. The relevant results show that the sand is white, poorly graded sand, with little fines according to the unified classification system; mean grain size is 0.4 mm; specific gravity, $G_s = 2.667$; coefficient of uniformity, $C_u = 2$; minimum void ratio, $e_{\min} = 0.491$; maximum void ratio, $e_{\max} = 0.771$, and the angles of friction from simple shear tests at different relative densities are shown in Fig.5. All the tests in this study were run on a dense soil layer with density of 1.78 gm/cm³ and relative density of 94%.

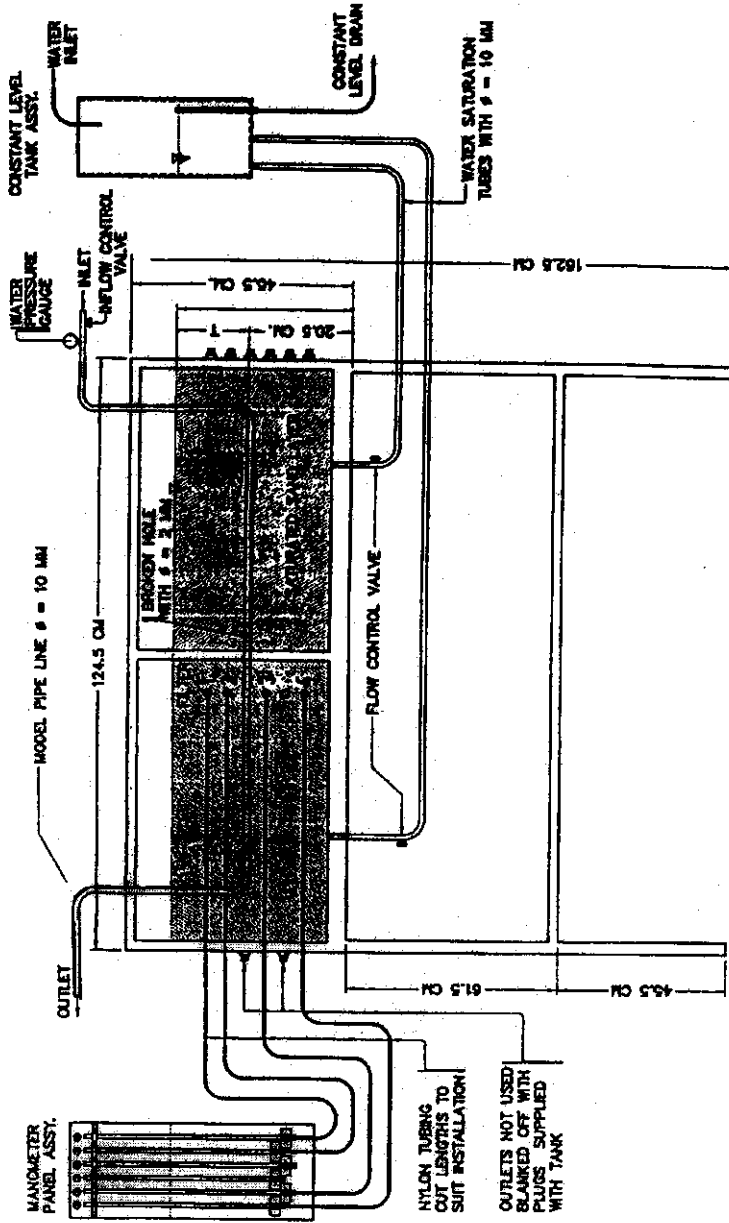


Fig. 2. Experimental setup.

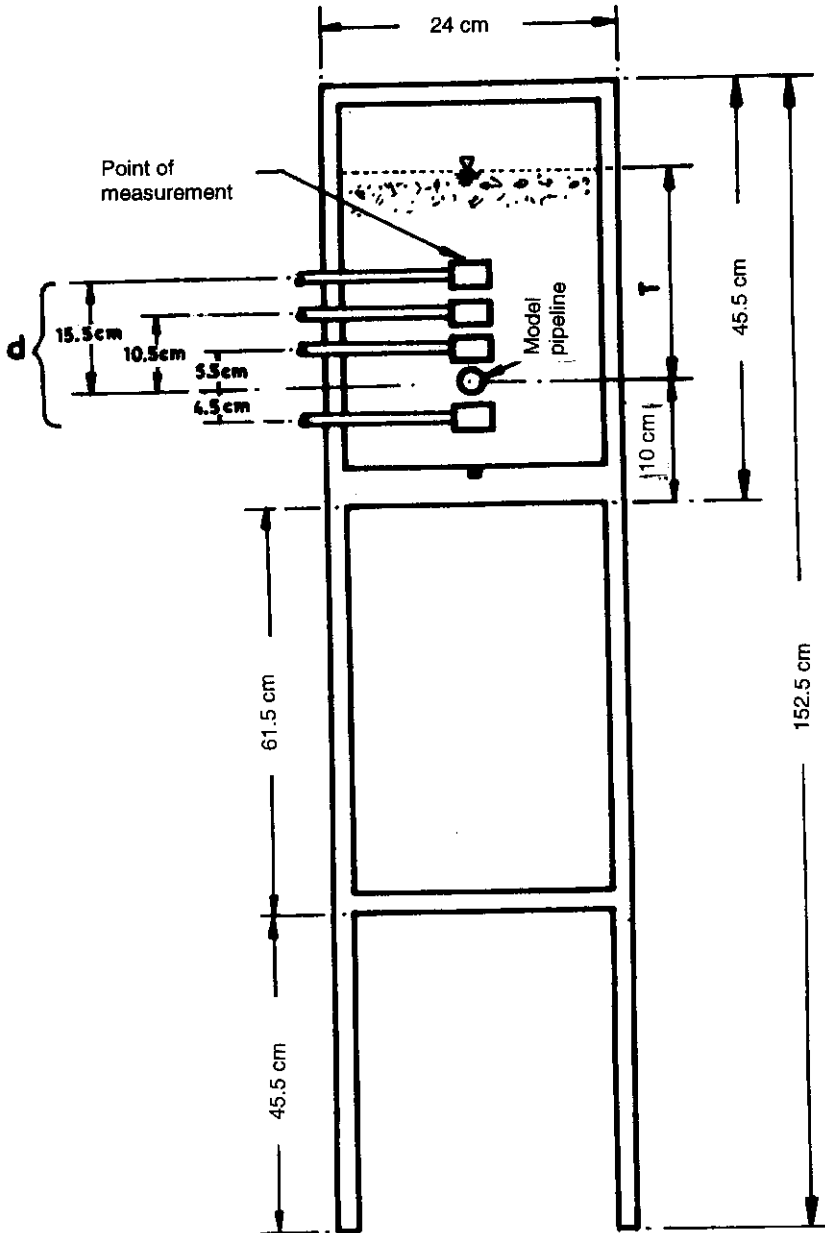


Fig. 3. Side view of the experimental setup.

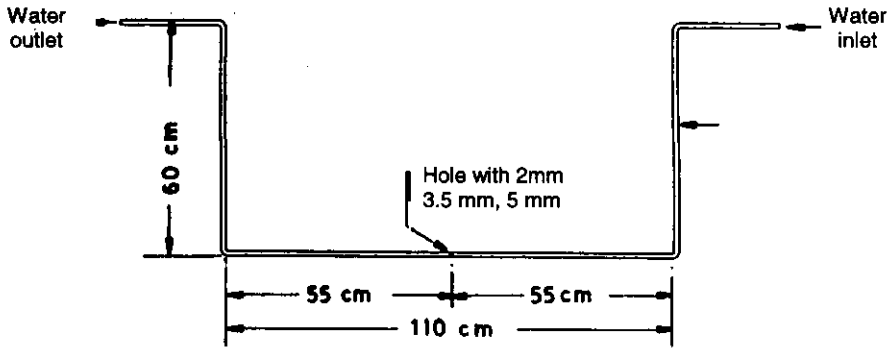


Fig. 4. Schematic diagram of the model pipeline.

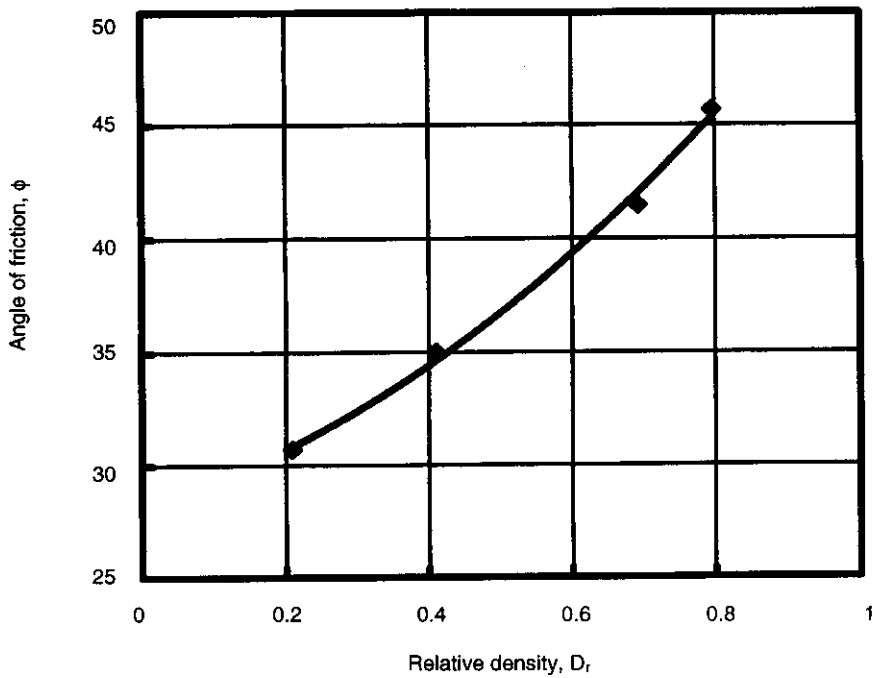


Fig. 5. Variation of angle of friction with soil dry density for soil.

Results and Discussion

Before starting the testing program, measurements of the rate of water flowing from the hole of the broken section were taken for different hole sizes and for different values of applied water pressure inside the model pipeline (P). The results of these measurements are shown in Fig.6. Increasing the value of P will effect the rate of flow (q) more when the diameter of the hole at the broken section increases. The results in Fig. 6 are for a completely open outlet end. In some cases, a valve was used to partially close the outlet end which resulted in an increase of the rate of flow of water (q) from the broken section. Some tests were performed to investigate this condition at low value of P. The results of this study are presented below.

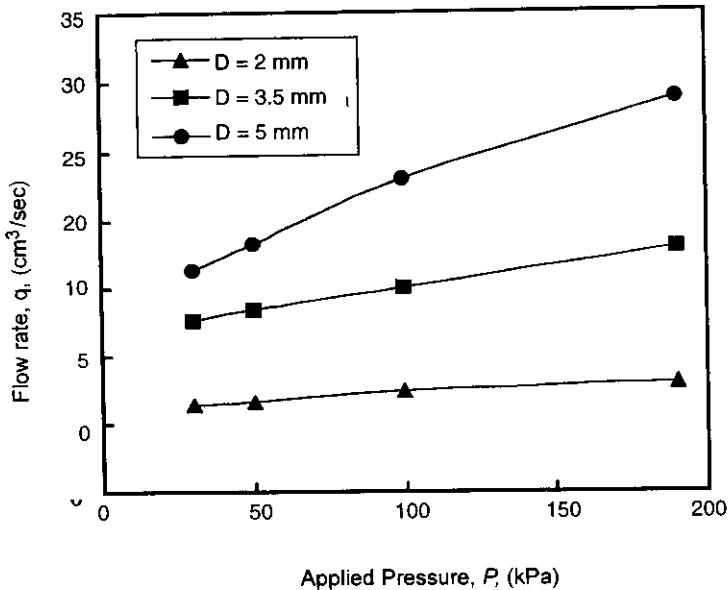


Fig. 6. Variation of rate of flow of water (q) from the hole at the broken section with water pressure (p) for different hole sizes.

A. Effect of the applied water pressure (P) inside the pipeline

First, a series of tests was run at different values of water pressure inside the model pipeline (P). These values were in the range of 20 kPa to 170 kPa. During these tests, the outlet end of the model pipeline was completely open. The depth of embedment (T) of the model pipeline was equal to 30 cm, and the diameter of the hole at its broken section was equal to 2 mm. The depth of embedment was chosen to be relatively high so as to have high effective stress that can prevent the buildup water pressure from

developing a state of liquefaction in the soil layer. The results are presented graphically as water pressure head in cm (Δh , where $\Delta U = \Delta h \times \gamma_w$) versus the applied pressure inside the modeled pipeline as shown in Fig. (7). As shown by this figure, the incremental pore water pressure (ΔU) increases significantly as the water pressure inside the model pipeline (P) increases. At vertical distance (d) equal to 5.5 cm from the position of the broken section, the incremental pore water pressure (ΔU) at P equal to 170 kPa was about 300% of that at P equal to 30 kPa. The ratio of ΔU at any value of P with that at $P=170$ kPa at different locations from the model pipeline is almost the same as shown in Fig. 8. However, Fig. 9 shows that the stability factor (as defined by Eq. 6) at the locations of measurements has different values. This is due to the changes in the values of the effective stress which increases as the depth increases and also due to the changes in the values of the incremental pressure which decreases as the distance between the broken section and the point of measurement increases. The results of this test represent the importance of controlling the value of the pressure inside the pipeline. Where increasing P to a certain value will increase the incremental water pressure (ΔU) to a value equal to the total stress at which the soil liquefaction could occur.

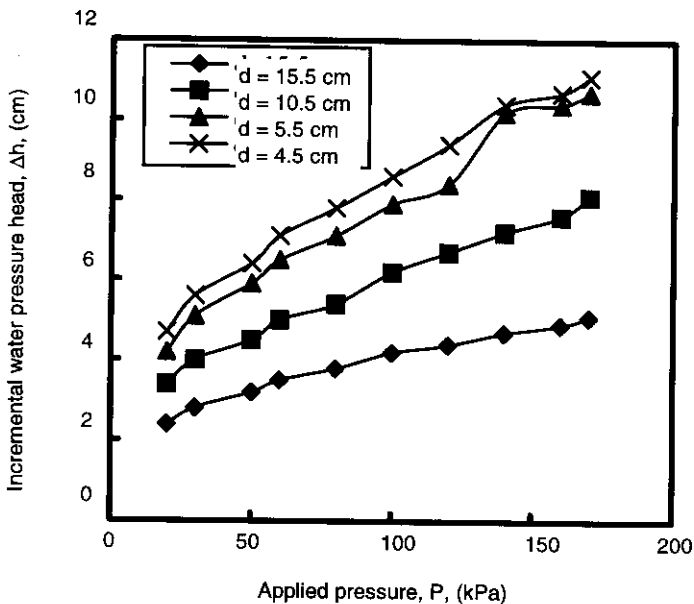


Fig. 7. Variation of incremental water pressure head with the applied pressure inside the model pipeline at $T=30$ cm, and $D=2$ mm.

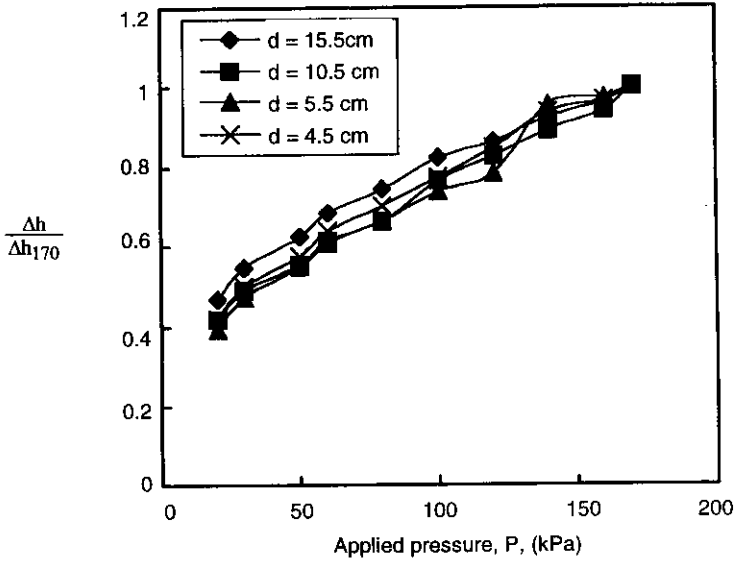


Fig. 8. Ratio of incremental water pressure head at different values of applied pressure with that at applied pressure of 170 kPa, at T=30 cm, and D=2 mm.

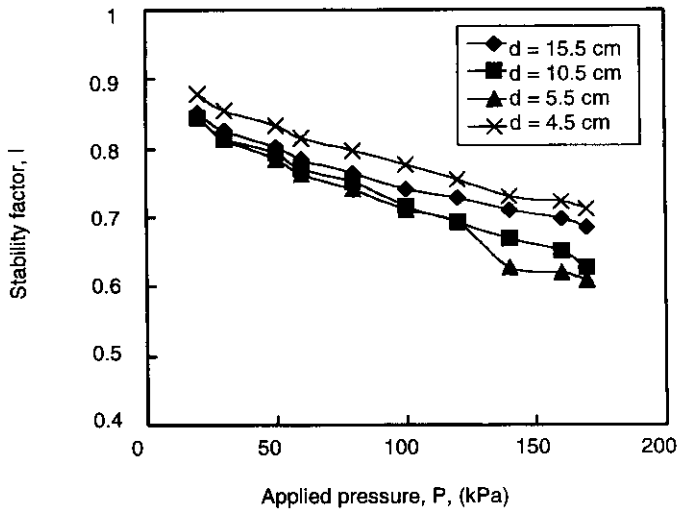


Fig. 9. Variation of stability factor (I) with the applied pressure at T=30 cm, and D=2 mm.

B. Effect of hole size (D) at the broken section

Three series of tests were run to investigate the effect of the hole size at the broken section of the model pipeline on the incremental water pressure (ΔU). Different hole sizes (i.e. $D=2$ mm, $D=3.5$ mm, and $D=5$ mm) were used in each series. The tests in each series were repeated for different values of P in the range of 20 kPa to 170 kPa. By comparing the tests' results, at the same applied pressure inside the model pipeline (P), it is noted that the incremental water pressure increases significantly as the hole size (D) increases as presented in Fig. 10 for depth of embedment of soil (T) equal to 30 cm. For example, as shown in Fig. 10, at pressure of 100 kPa and at vertical distance from the model pipe, $d=10.5$ cm, the water pressure head, Δh , is 7.9 cm for a hole size of 2 mm and it increases to 19.1 cm for a hole size of 3.5 mm. This is due to the high flow rate of water (q) from the broken section with water pressure (P) much higher than the one inside the soil mass. The variation of the stability factor (I) with P is shown by Fig. 11. Since the effect of P on q at $D=2$ mm is not as high as that when $D=3.5$ mm (as presented in Fig.6), the variation of I with P at $D=2$ mm is more flat than that when $D=3.5$ mm.

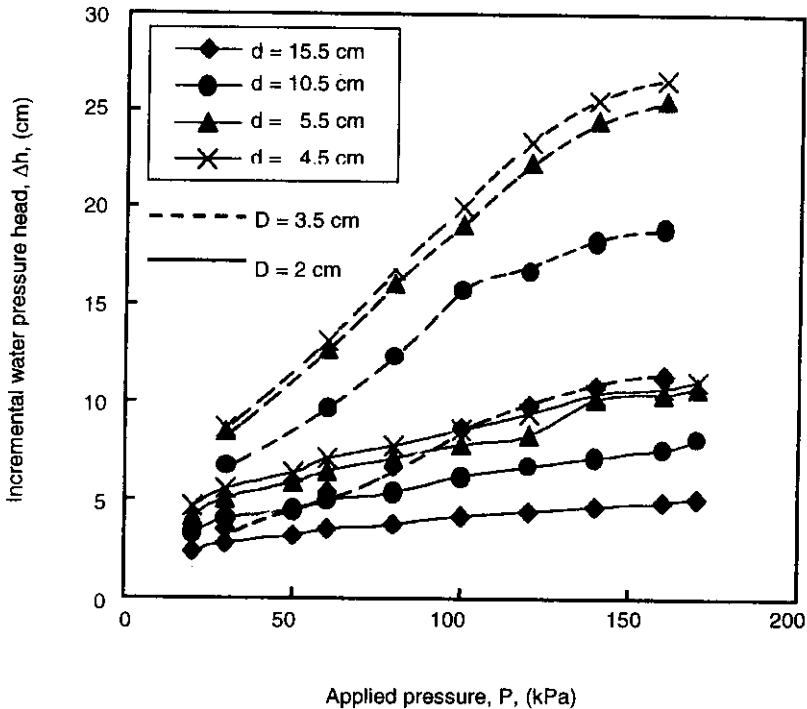


Fig. 10. Effect of hole size on the incremental water pressure head for $T=30$ cm.

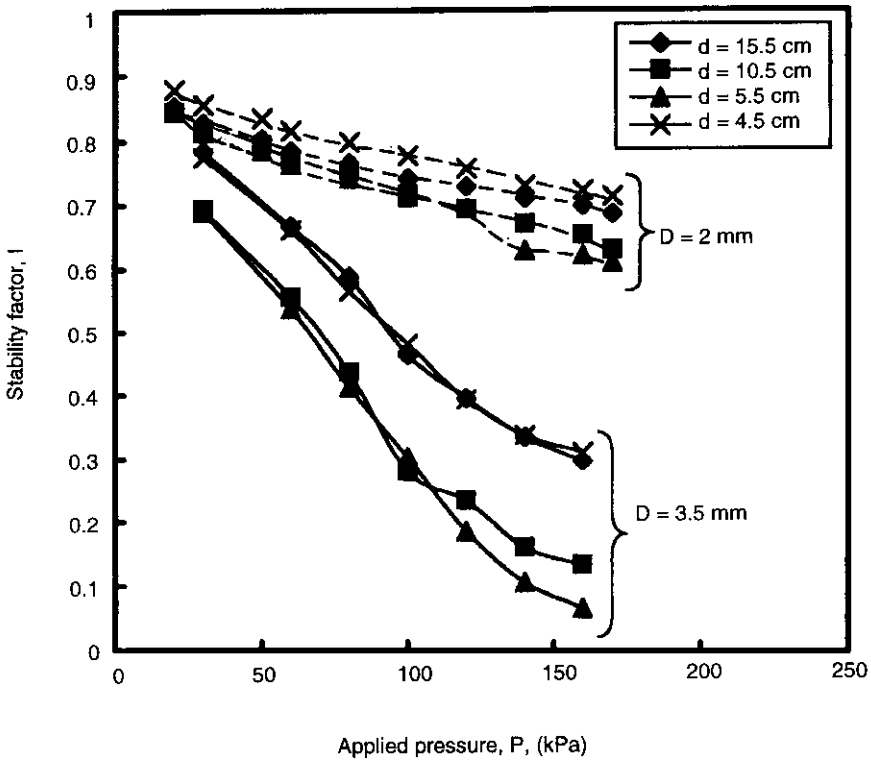


Fig.11. Effect of hole size on the variation of stability factor (I) with the applied pressure at $T=30$ cm.

C. Effect of depth of embedment (T)

Another series of tests was run to investigate the effect of depth of embedment (T) of the model pipeline on the value of the incremental pore water pressure. The variation of Δh versus the applied water pressure (P) is shown in Fig. 12 for different depths of embedment at $D=3.5$ mm. This figure shows that the incremental pore water pressure at $T=30$ cm is higher than that at $T=20$ cm. This is due to the higher resistance of water to flow to the soil as a result of the increase in the total stress. Figure 13 shows that the soil layer did not reach the stage of liquefaction at $T=30$ cm and $d=5.5$ cm, indeed it reached the liquefaction stage at $T=20$ cm. This result recommends the construction of the pipelines at deeper depths from the ground surface.

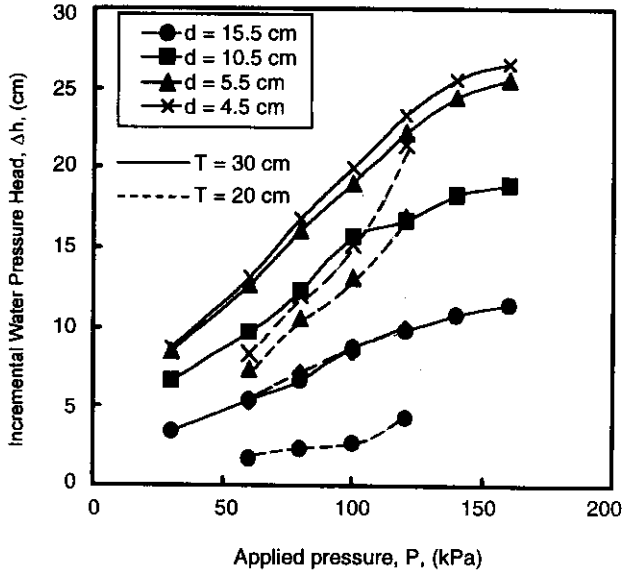


Fig.12. Effect of depth of embedment of pipeline on the buildup water pressure for $D=3.5$ mm.

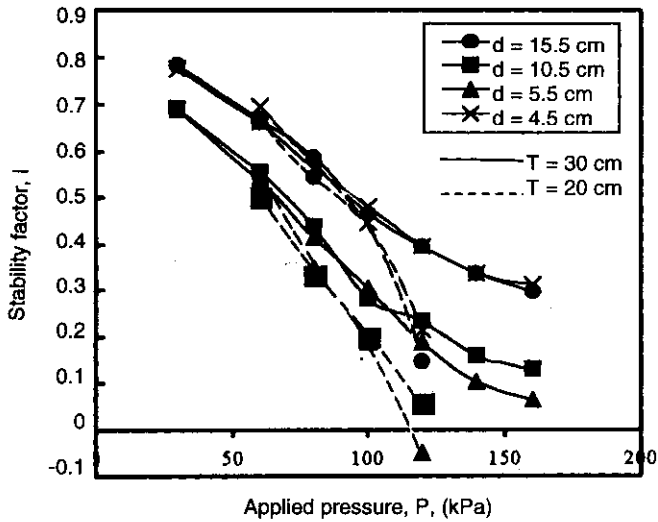


Fig.13. Effect of depth of embedment of pipeline (T) on the stability of the stability of soil layer for $D=3.5$ mm.

D. Effect of the rate of flow of water (q) from the broken section

Since the outlet of the model pipeline was fully opened during the above described tests, the rate of flow of water from the broken section was at its minimum value. Therefore, the results shown above can be considered as the minimum values of the incremental water pressure. When the outlet end of the pipeline was not fully open, the flow rate of water (q) to the soil increased significantly as discussed earlier. Since the permeability of the soil is constant, the higher water flow rate will be resisted to flow through the soil. As a result, the water pressure will increase quickly as in the case of the liquefaction phenomenon.

The results show that the stability of the soil layer decreases tremendously as the flow rate (q) through the broken section increases (see Fig. 14). A state of liquefaction could develop within seconds due to the high rate of change of pore water pressure. For example, when the outlet end of the model pipeline is closed by half of the original opening, the incremental water pressure at P equal to 30 kPa was about 3 times the one when the outlet end was completely open. In addition, the soil layer got liquefied within 5 seconds. In test, a model footing with safety factor of three was placed at the top of the soil layer. The model footing sunk completely into the soil layer due to quick soil liquefaction.

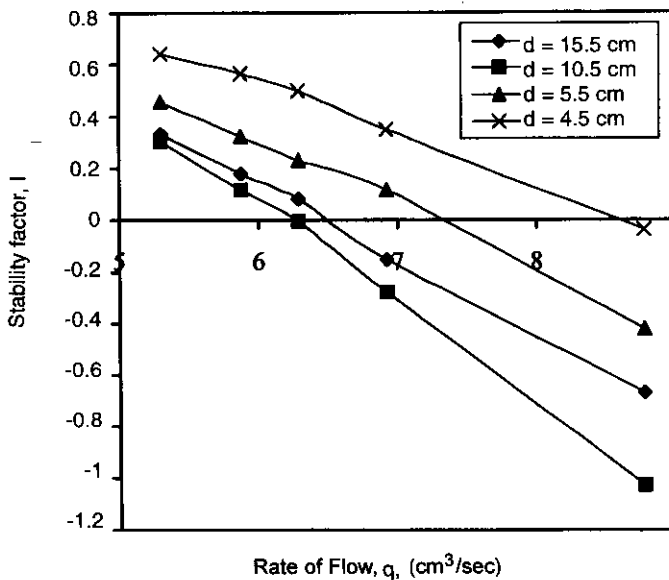


Fig. 14. Effect of rate of flow of water from the hole at the broken section on the soil layer stability, at $P=30$ kPa, and $D=2$ mm.

This in turn, shows the significant effect of the buildup water pressure from the broken underground pipelines on the stability of surrounding structure.

Conclusion

The effects of the water pressure inside the pipeline, the size of the hole at the broken section, the depth of embedment of the pipeline, and the flow rate of water from the broken section were investigated and the following conclusions were drawn:

1. As the water pressure inside the pipeline increases the water pressure inside the soil mass increases causing a reduction in the stability of the soil layer.
2. The size of the broken section is significantly effecting the stability of the soil, whereas the hole becomes larger the incremental pressure becomes higher and the stability of the soil is reduced.
3. Increasing the depth of embedment of the pipeline will increase the effective stress and hence the stability of the soil will also increase.
4. The stability of the soil mass is reduced significantly as the rate of flow of water from the hole of the broken increases.

To reduce the effect of the buildup water pressure on the stability of a soil layer, the following points could be considered:

1. Placing the pipeline away from the structures is required to avoid probable damages since the buildup water pressure decreases as the distance from the pipeline increases.
2. Applying a technique to control the water pressure inside the pipeline is recommended.
3. Deep embedment of the pipeline will increase the soil stability, but shallow embedment is preferred to allow quick flow of the water to the surface and reduce the affected area.

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استقرار طبقة الرمل المشبعة تحت تأثير تسرب الماء من الأنابيب المدفونة

عوض علي سلطان القرني

قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود ، ص.ب. ٨٠٠ ،

الرياض ١١٤٢١ ، المملكة العربية السعودية

(استلم في ٤ / ٣ / ١٩٩٨ م ؛ وقبل للنشر في ١٩ / ١٠ / ١٩٩٨ م)

ملخص البحث. تم في هذا البحث، إجراء دراسة معملية لتقويم تأثير زيادة ضغط الماء في التربة، نتيجة لتسرب الماء من الأنابيب المدفونة، على استقرار طبقة التربة الرملية المشبعة بالماء. وحيث إن الزيادة في ضغط الماء يعتمد على عدة عوامل مثل ضغط الماء داخل الأنبوب، وسع الكسر الذي يتسرب منه الماء، وعمق الأنبوب داخل طبقة التربة، فقد تم إجراء ثلاث مجموعات من التجارب لتقويم تأثير هذه العوامل على مقدار الزيادة في ضغط الماء داخل التربة وبالتالي على استقرار طبقة التربة. وجد من خلال هذه الدراسة، أن الزيادة في ضغط الماء داخل الأنبوب والزيادة في وسع الكسر الذي يتسرب منه الماء تسبب بدرجة كبيرة في زيادة ضغط الماء داخل التربة وتقلل من استقرار طبقة التربة الرملية. في حين أن زيادة عمق دفن الأنبوب يقلل من تأثير زيادة ضغط الماء على استقرار طبقة التربة الرملية نتيجة لزيادة قيمة الجهد الفعال مع زيادة العمق.