SEEPAGE CHARACTERISTICS OF STRUCTURAL FILLS

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Paper submitted to:
1990 Guide Book
San Diego Association of Geologists
San Diego, CA

December 2, 1990

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ABSTRACT: An extensive two-dimensional finite element seepage analysis was conducted to study the parameters effecting the wetting-induced behavior of structural fills. The results showed that decreasing the placement water content causes an increase in the time required for hydrocompression and the magnitude of hydrocompression. The analysis also showed that surface infiltration migrates unevenly through the fill material resulting in an uneven dissipation of the suction pressures and thus differential ground movements. The time required for hydrocompression increased almost linearly with fill depth. Since the suction pressures had to be dissipated before a drain could be functional, the installation of a canyon drain and/or side drain did not reduce the amount of hydrocompression or the time required for hydrocompression. In addition, the drains caused the wetting front to migrate more unevenly through the fill. To reduce the amount of infiltration and thus hydrocompression, the site should be carefully graded to promote runoff and drains should be installed beneath the irrigation points to intercept the infiltration. If water is allowed to infiltrate the fill, the structures, pavements, and utilities should be designed for the differential ground movements estimated from the procedure described herein.

INTRODUCTION

Most transportation, residential and commercial construction in southern California involves sites comprised of hills and canyons. A typical development consists of grading the site by excavating the hillsides and filling the canyon with the spoils. The depths of the compacted fills are steadily increasing with some in excess of 50 meters. Previous research by Nwabuokei and Lovell, (1), and Lawton et al., (2) has shown that compacted soil undergoes a softening when the fill becomes soaked or wetted. The soaking removes the initial suction pressures in the soil which results in a decrease in effective stress and thus soil modulus. This phenomena is known as hydrocompression and has resulted in surface deformations that have exceeded tolerable limits. The amount of hydrocompression which occurs depends on the placement water content and relative compaction. In general, the amount of hydrocompression increases with 1.) decreasing placement water content, 2.) decreasing relative compaction, and 3.) increasing overburden pressure.

If expansive soils are incorporated into the fill, the fill behavior and thus the surface deformations become even more complex. As the upper portion of the fill becomes wetted, the soil will expand due to the small vertical stresses applied near the fill surface.

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As the wetting front moves deeper into the fill, the vertical stresses become large enough to resist the soil expansion and the compacted soil will compress. Therefore, if expansive soils are placed in a fill, the fill will swell at shallow depths and compress at deeper depths due to the differences in the applied vertical stress.

From a series of laboratory oedometer tests in which compacted specimens are inundated at various overburden stresses, a relationship between fill depth and axial strain, such as that shown in Figure 1, can be obtained. From such a relationship the amount of expansion or hydrocompression at any depth in the fill, and the depth at which the soil changes from an expansion to hydrocompression can be easily determined. Figure 1 can also be used to estimate the net movement of the ground surface by: 1.) dividing the fill into sublayers, 2.) calculating the fill depth at the mid-point of each sublayer, 3.) estimating the axial strain of each sublayer using Figure 1 and the fill depth at the mid-point of each sublayer, 4.) multiplying the appropriate axial strain by the initial thickness of the sublayer, and 5.) summing the swell or hydrocompression of all the sublayers to estimate the net ground surface movement. The differential settlement between any two points is estimated from the difference of the net ground surface movement at each of the points. These calculations are analogous to those used for the estimation of consolidation settlements.

The major element missing in this analysis is the time rate of the surface movement which is controlled by the time rate of wetting of the fill. Since most, if not all, of the infiltration is due to surface irrigation, the wetting front usually migrates from the top of the fill to the bottom. As a result, the upper portion of the fill usually undergoes expansion or hydrocompression before the bottom of the fill becomes wetted. This paper describes the results of an extensive two-dimensional finite element seepage analysis that was conducted to clarify the following questions concerning the wetting-induced behavior of structural fills:

1. What is the time required for compacted fills to become fully wetted and undergo expansion or hydrocompression?
2. At what time should distressed structures, pavements, and utilities be repaired?
3. What is the effect of placement water content on the rate of wetting?
4. What is the effect of drains placed at various locations in the fill on the migration of the wetting front through the fill?

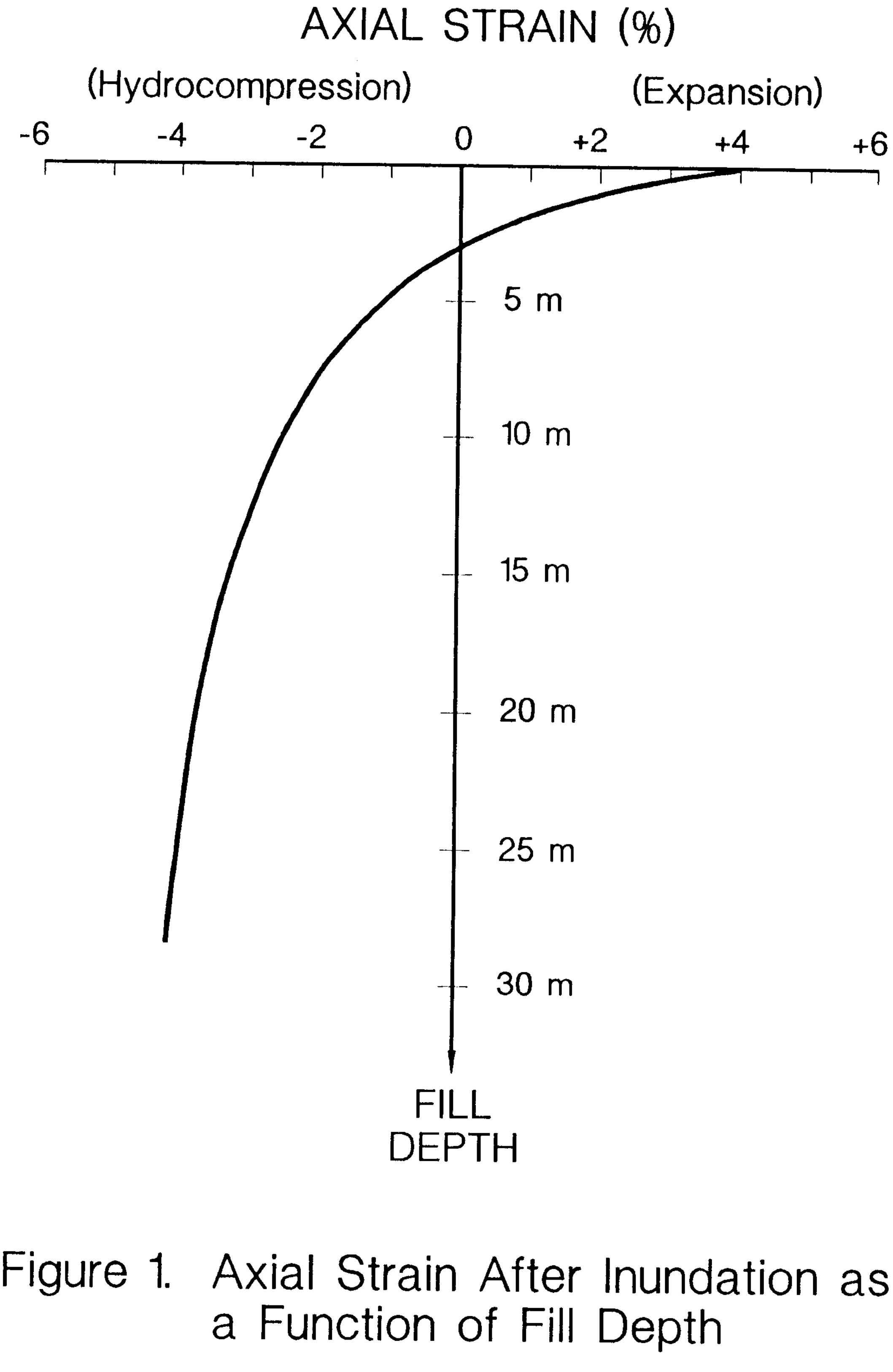

Figure 1. Axial Strain After Inundation as a Function of Fill Depth

CANYON GEOMETRIES AND SOIL PROPERTIES USED IN ANALYSIS

A confined canyon with 2.5 to 1 side slopes and a bottom width of 10 meters was analyzed during this study. Due to the uncertainties involved in modeling the contact between the compacted fill and the formational material of the canyon, the canyon boundaries were assumed to be impermeable. For the shallower depths, 5, 10, 16.7, and 25 meters, the effect of a canyon drain was investigated by analyzing each depth with and without a drain located at the center of the canyon bottom. For the deeper fills, 30 and 50 meters, the effects of placing drains at various locations along the canyon walls were also investigated. The effect of placement water content, 2% dry versus 2% wet of optimum, was investigated using a fill depth of 5 meters.

Due to its availability the Stadium Conglomerate formation has been used in a large number of fills in the San Diego area. The conglomerate formation is classified as a silty gravel, GM, according to the Unified Soil Classification System with particle sizes ranging from over 40 millimeters to less than 0.001 millimeters. To simulate typical fill operations, a relative compaction of 90% based on the Modified Proctor Compaction test, ASTM Standard D1557-78 (3), was used throughout the laboratory testing and finite element analysis.

Cedergren (4) and Cary et al. (5) have shown that the permeability of soils is extremely sensitive to the quantity, character, and distribution of the finest fractions. Their test results on gravelly soils showed that the fines filled the voids and controlled the permeability of the soil. As a result, it was decided that the fine grained particles of the Stadium Conglomerate would control the seepage characteristics. Since the ASTM Standard, D2325-81, for the determination of the capillary-moisture relationship using the porous plate apparatus requires the use of soil passing the No. 10 sieve, all the laboratory tests were conducted on the minus No. 10 material. The minus No. 10 material of the Stadium Conglomerate classifies as a silty sand, SM.

The optimum water content and maximum dry density, obtained from five Modified Proctor Compaction tests using Method A on the minus No. 10 material, are approximately 10% and 19.3 kN/m^3, respectively. Based on the results of four falling head permeability tests, the average steady-state permeability of the minus No. 10 material compacted at 2% wet of optimum was measured to be 2.3×10^{-3} meters/day. The average steady-state permeability at 2% dry of optimum was obtained from the results of three falling head tests and was measured to be 3×10^{-3} meters/day. Both of the measured permeabilities are in good agreement with values reported by Sherard et al. (6) and Stark and Duncan (7) for similar soils and were also in excellent agreement with the permeability of 2.85×10^{-3} meters/day measured by Sorben and Sherrod (8) for a fill composed of Stadium

Conglomerate. Based on data presented by Sherard et al. (6), the horizontal permeability was estimated to be four times the vertical permeability.

The drying portion of the volumetric water content and suction pressure relationship, also referred to as the characteristic curve, was obtained from the results of capillary-moisture tests performed using a laboratory porous-plate apparatus. The wetting portion of the characteristic curve was estimated using the measured drying curve and data presented by Liakopoulos (9) and Croney and Coleman (10). The relationship between permeability and suction pressure was estimated using the Green and Corey (11) analytical procedure. A number of researchers, including Elzeftawy and Cartwright (12) and GEOSLOPE (13), have presented data which shows that the Green and Corey method provides an excellent estimate of the relationship between permeability and suction pressure. An extensive parametric study revealed that the analytical results were not sensitive to the shape of the characteristic curve or the permeability-suction pressure relationship. The parametric study did show that the main parameter effecting the analytical results was the steady-state permeability and the initial suction pressure heads.

To determine the initial suction pressures, twenty oedometer tests were conducted using specimens compacted at 2% wet and 2% dry of optimum and a Modified Proctor relative compaction of 90%. From these tests the relationship between volumetric water content and fill depth was obtained for both placement water contents. This relationship was confirmed by field testing in which moisture content samples were obtained from two 1 meter diameter bucket-auger borings that were drilled immediately after completion of a 24 meter deep Stadium Conglomerate fill. The moisture content samples were carefully excavated from the wall of the boring every 0.3 meter for the entire fill depth. The volumetric water content for each sample was plotted versus fill depth and the resulting relationship was in excellent agreement with the laboratory relationship.

Using the verified relationship between volumetric water content and fill depth and the previously determined characteristic curve, the initial suction pressure at any fill depth could be obtained. As a result, the fact that the volumetric water content increased with depth, and thus the initial suction pressure decreased with depth, was incorporated into the analysis. The final soil parameters used in the seepage analysis of the Stadium Conglomerate at 2% wet and 2% dry of optimum are summarized in Tables 1 and 2, respectively.

FINITE ELEMENT SEEPAGE PROGRAMS AND APPLIED BOUNDARY CONDITIONS

PC-SEEP, developed by GEOSLOPE (13), was used for this study because of its

Table 1 - Seepage Properties of Minus No. 10 Stadium Conglomerate Material at 2% Wet of Optimum and a Modified Proctor Relative Compaction of 90%

1) Steady-State Permeability

Vertical Permeability = $K_v = 2.3 \times 10^{-3}$ meters/day

Horizontal Permeability = $K_h = 9.2 \times 10^{-3}$ meters/day

$K_h = 4K_v$

K_h is inclined 0° to the horizontal

2) Pressure vs. K_h

Suction Pressure (kPa)	K_h (meters/day)
0	9.2×10^{-3}
-6.2	3.7×10^{-3}
-8.4	2.0×10^{-3}
-10.6	9.8×10^{-4}
-13.8	4.2×10^{-4}
-17.3	1.5×10^{-4}
-32.0	3.4×10^{-5}
-62.5	4.9×10^{-6}

3) Pore-water Storage

Volumetric Water Content	Suction Pressure (kPa)
0.35	0
0.33	-3
0.30	-6
0.26	-10
0.24	-20
0.23	-40
0.22	-60
0.21	-80

Table 2 - Seepage Properties of Minus No. 10 Stadium Conglomerate Material at 2% Dry of Optimum and a Modified Proctor Relative Compaction of 90%

1) Steady-State Permeability

Vertical Permeability = $K_v = 3.0 \times 10^{-3}$ meters/day

Horizontal Permeability = $K_h = 1.2 \times 10^{-2}$ meters/day

$K_h = 4K_v$

K_h is inclined 0° to the horizontal

2) Pressure vs. K_h

Suction Pressure (kPa)	K_h (meters/day)
0	1.2×10^{-2}
-2.15	2.02×10^{-3}
-3.7	5.15×10^{-4}
-7.1	8.61×10^{-5}
-38	5.16×10^{-6}
-96	1.26×10^{-6}
-156	3.92×10^{-7}
-216	7.97×10^{-8}

3) Pore-water Storage

Volumetric Water Content	Suction Pressure (kPa)
0.31	0
0.28	-2
0.24	-5
0.225	-10
0.22	-20
0.214	-40
0.20	-80
0.142	-246

capability of producing graphical input and output. Before selecting PC-SEEP, pressure heads were calculated for a number of fill geometries and material properties using PC-SEEP and UNSAT1, developed by Neuman (14). The calculated pressure heads from both programs were in very good agreement.

The effects of precipitation and irrigation were simulated by applying an influx at irrigation locations along the top of the fill. The irrigation pattern shown in Figure 2 was determined from surveying a number of typical commercial building sites. It can be seen that a 30 meter wide irrigated strip usually separates the lots or acts as a buffer between the adjacent street or the 30 meter wide parking lot for each building. A three meter wide irrigated planter was usually found immediately adjacent to the buildings. The ratio of irrigated area to fill surface was measured to be approximately 25%. Based on data presented by Sorben and Sherrod (8), an infiltration rate of 0.46 meters per year was used in the irrigation pattern.

Extensive seepage analyses showed that the full canyon geometry, see Figure 2, could be modeled using half of the canyon and designating the centerline of the canyon as a no flow boundary. Thus, the pressure head contours presented throughout the paper only illustrate half of the canyon.

CALIBRATION OF SOIL PROPERTIES

To investigate the accuracy of the seepage parameters previously described, the measured time rate of settlement of a local fill was compared with the time calculated for migration of the wetting front through the fill. From late 1975 to early 1985 a subdivision in San Diego County experienced settlements in excess of 0.3 meters due to hydrocompression in the 22 meter deep fill. Forensic investigations of the fill revealed that the average placement water content and relative compaction satisfied the initial compaction specifications. Therefore, the settlement was attributed to hydrocompression and not variations in fill placement.

The settlement data showed that hydrocompression was completed after approximately 10.1 years of irrigation. Because the fill material was predominantly Stadium Conglomerate, it was decided to use this case history to compare the measured time rate of settlement with that estimated using PC-SEEP and the previously described soil parameters for a placement water content of 2% wet of optimum.

After approximately 8.8 years of irrigation, the calculated wetting front had passed through the entire fill and reached the bottom of the 22 meter deep fill. As a result, the majority of the suction pressures had been dissipated and thus the majority of the fill would have undergone hydrocompression after 8.8 years of irrigation. The calculated time was

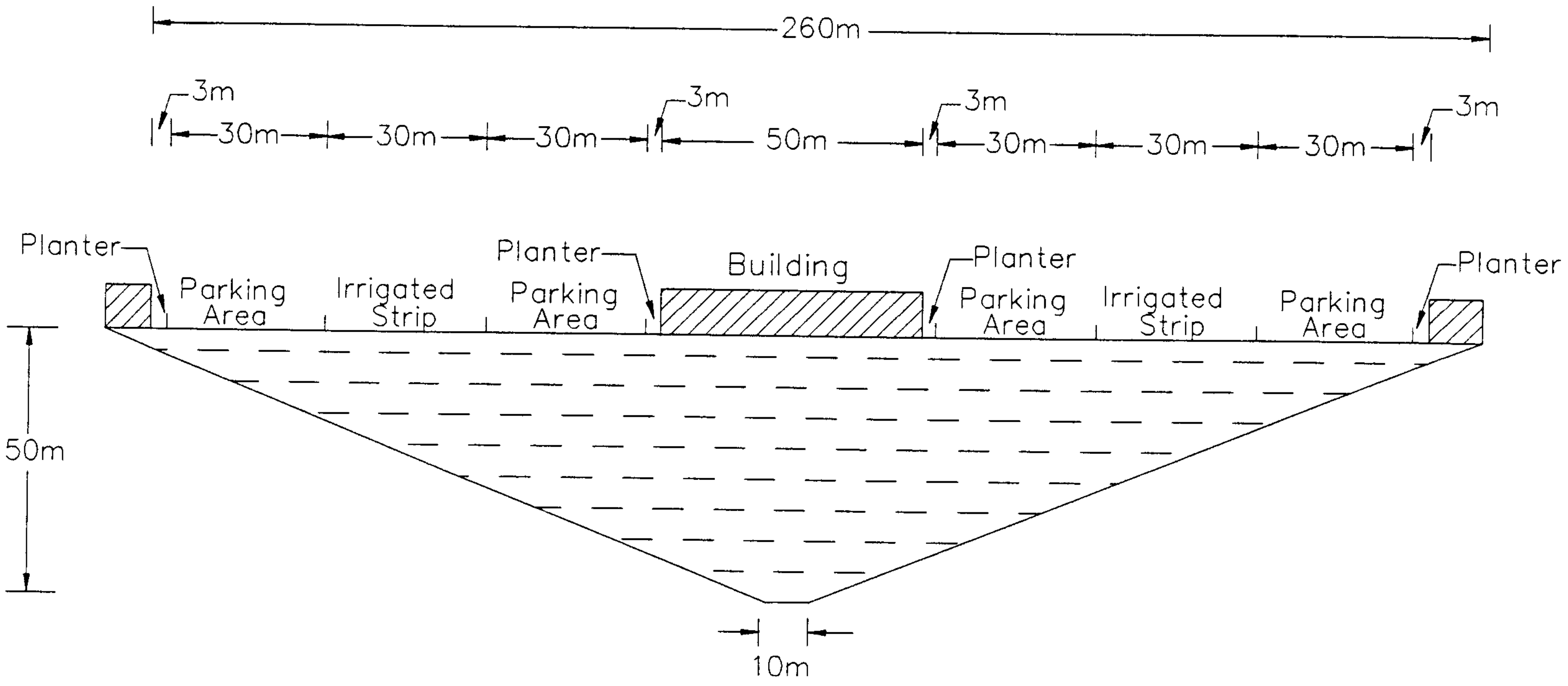

Figure 2. Typical Irrigation Pattern for a 50 Meter Deep Canyon Fill

approximately 1.5 years faster than the measured time. Soil classification tests of the fill material showed that 75% of the fill material classified as an SC and the remaining 25% classified as an SM. In addition, the placement water content varied from -2 to +2% of the optimum with the average placement water content being approximately 0.6% wet of optimum. Therefore, the difference in the measured and calculated hydrocompression times was attributed to the difference in the seepage properties between a clayey-sand and silty-sand and the slight difference in placement water content. However, the good agreement between the measured and calculated times provides a good indication that the seepage parameters used for the Stadium Conglomerate are reasonable and can be used to estimate the hydrocompression times for the other fill depths.

SEEPAGE CHARACTERISTICS IN A FIVE METER DEEP COMPACTED FILL

Figures 3 through 6 show the behavior of the pressure head contours in the 5 meter deep fill without a canyon drain and the Stadium Conglomerate compacted at a water content 2% wet of optimum. Since 25% of the ground surface is irrigated, only an irrigation strip at the centerline of the canyon, see Figure 3, was used in the 5 meter deep fill. Figure 3 shows the pressure head contours, in meters, after one day of irrigation. Placement of the Stadium Conglomerate at 2% wet of optimum results in suction pressures of almost -7.4 meters at the surface of the fill and -7.2 meters near the bottom of the fill. Therefore, the entire fill is partially saturated and susceptible to swell or hydrocompression. After one day of irrigation, the infiltration has started to dissipate the suction pressures and a -7 meter pressure head contour has appeared beneath the irrigation strip. After one year of irrigation, Figure 4, the infiltration has caused a large dissipation of the suction pressures near the centerline of the fill. The zero pressure head contour, shown in Figure 4 as a dashed line, is approximately 2 to 3 meters below the ground surface. The zero pressure head contour or wetting front delineates the boundary between soaked and unsoaked conditions and thus, the soil which has and has not undergone hydrocompression.

After an elapsed irrigation time of about 1.5 years, Figure 5, the wetting front has reached the impermeable boundary at the bottom of the canyon fill. The suction pressures in the shallow portion of the fill continue to dissipate due to horizontal seepage while the deeper portion of the fill has already undergone hydrocompression. Prior to this time a drain installed at the bottom center of the canyon would not have functioned because of the existence of suction pressures and thus, a lack of "free" water. Once the wetting front reaches the bottom of the canyon and dissipates the suction pressures, the canyon drain could become operational and remove any free or excess water. Therefore, to accurately simulate the influence of a canyon drain in subsequent analyses, the drain was not activated

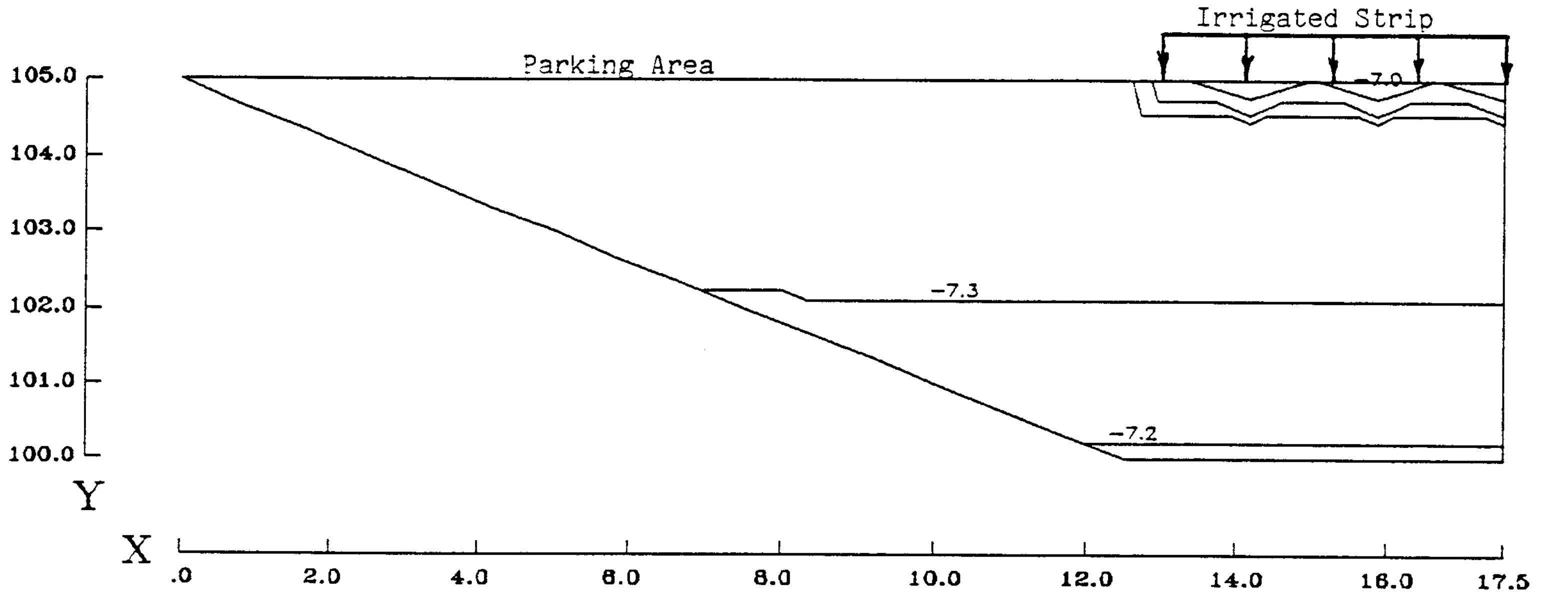

Figure 3. Pressure Head Contours after 1 day of Irrigation for the 5 Meter Deep Fill Placed at 2% Wet of Optimum

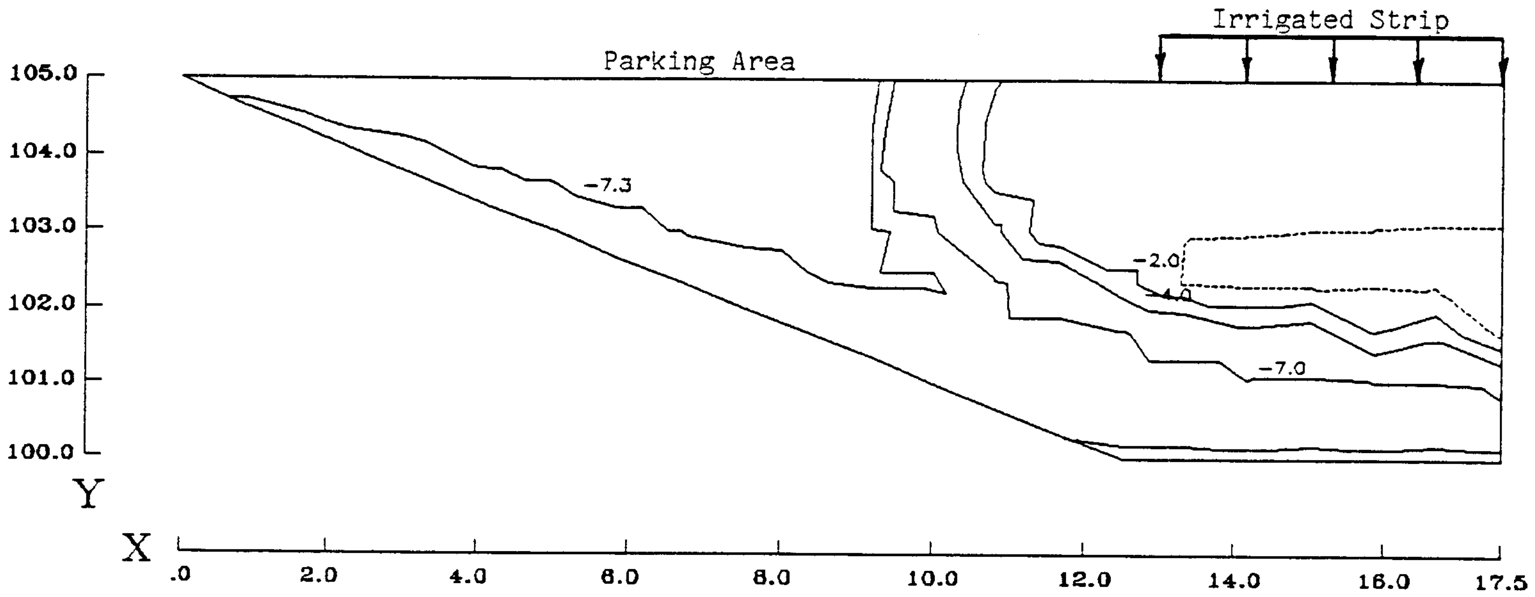

Figure 4. Pressure Head Contours after One Year of Irrigation for the 5 Meter Deep Fill Placed at 2% Wet of Optimum

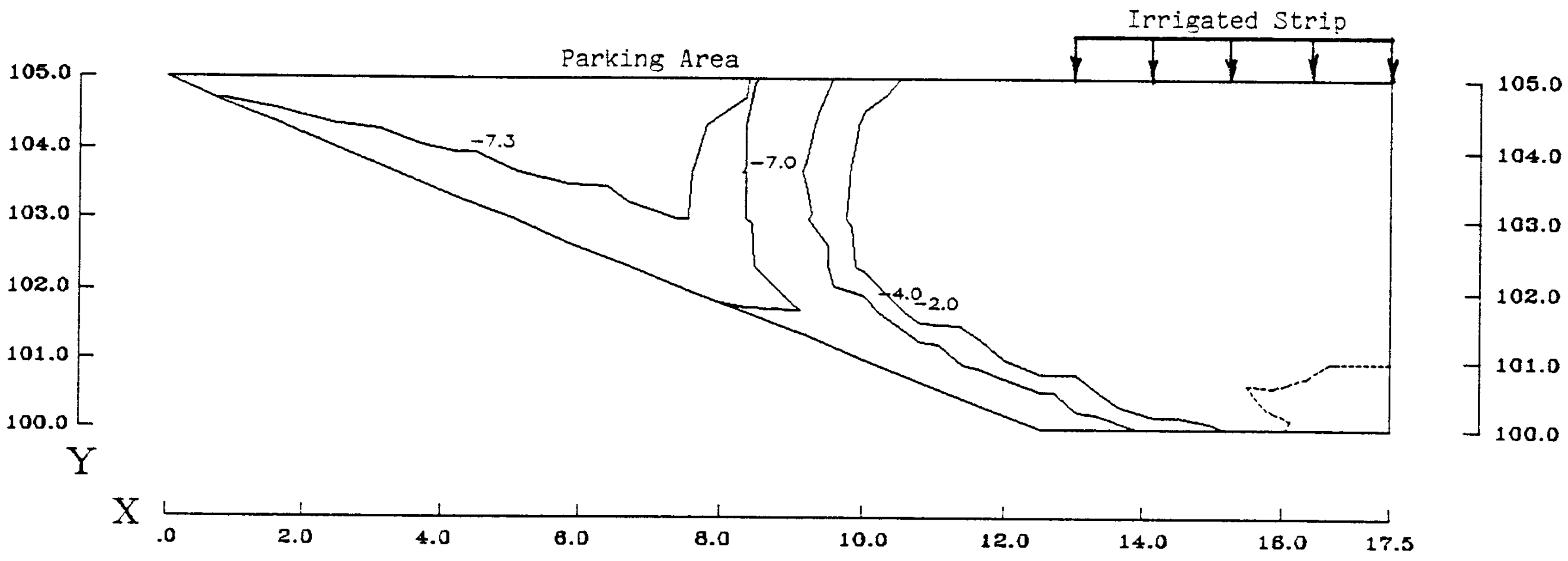

Figure 5. Pressure Head Contours after 1.5 Years of Irrigation for the 5 Meter Deep Fill Placed at 2% Wet of Optimum

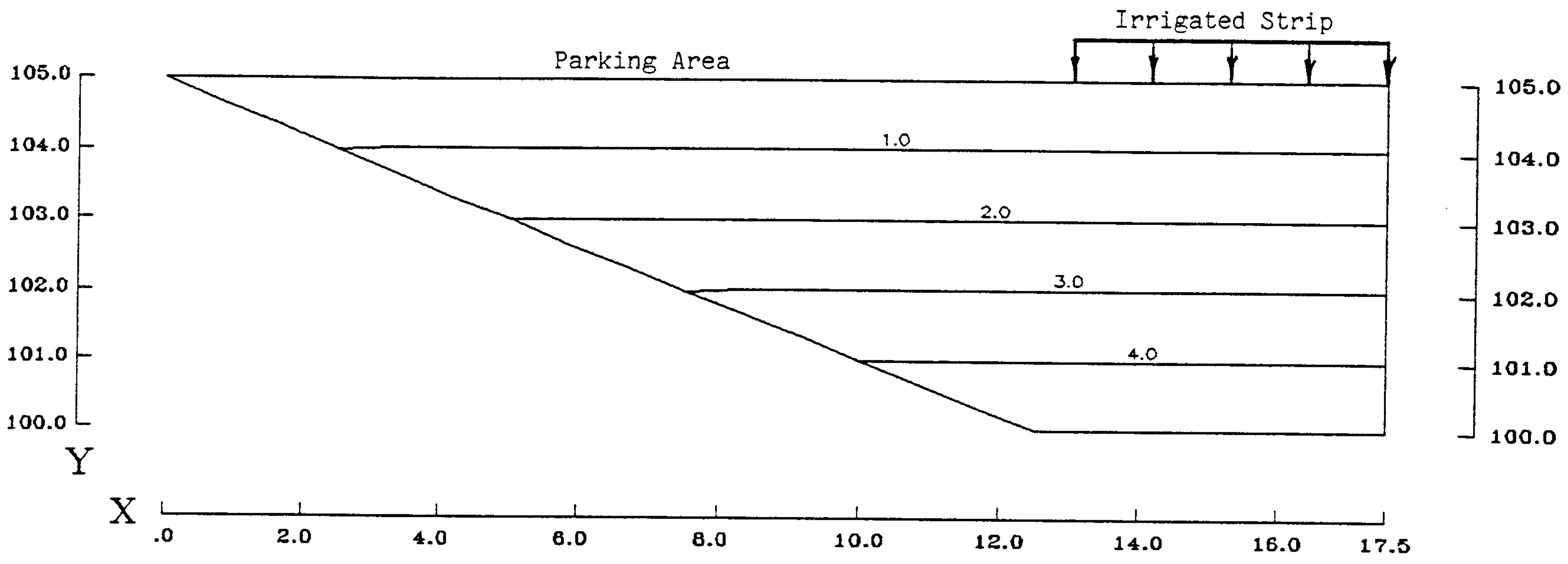

Figure 6. Pressure Head Contours after 4 Years of Irrigation for the 5 Meter Deep Fill Placed at 2% Wet of Optimum

until the wetting front reached the canyon bottom, i.e. after 1.5 years of irrigation.

After approximately 4 years of irrigation, Figure 6, a steady-state seepage condition is reached with the long-term zero pressure head contour, or phreatic surface, rising to the ground surface. This is due to the impermeable canyon walls preventing water from leaving the fill. The final location of the long-term phreatic surface will depend on the actual permeability of the canyon walls, and whether or not a canyon drain is installed.

The results of falling head permeability and oedometer tests revealed that the degree of saturation of the test specimens after a steady-state seepage condition was obtained ranged from 90 to 98%. Therefore, the time required for full hydrocompression is the time necessary to remove the majority of the suction pressures and not necessarily obtain a fully saturated condition. In the five meter deep fill, approximately 2.5 years was required for the entire fill to become fully soaked and thus undergo hydrocompression.

The effects of different irrigation patterns on the hydrocompression of the fill were also studied by varying the location of the irrigation strip. Figure 7 shows the behavior of the pressure head contours with the irrigation strip moved to the left side of the canyon instead of at the centerline. It can be seen that after two years of irrigation the wetting front has descended along the canyon wall and has reached the canyon bottom. Therefore, the shallow portion of the fill has undergone hydrocompression and/or expansion while the suction pressures in the middle of the fill are still dissipating. In the previous case, after 1.5 years of irrigation, see Figure 5, the center portion of the canyon had undergone full soaking and thus hydrocompression. Therefore, differences in irrigation patterns will result in different migration patterns of the wetting front and thus hydrocompression.

After 5.3 years of irrigation, the long term phreatic surface returns to the ground surface, just as it did in Figure 6, and a steady-state seepage condition was achieved. This is approximately 1.3 years longer than was required for the previous case in which the irrigation strip was located at the centerline of the fill. During the analysis it was found that the irrigation was ponding because of the shallow fill depths below the irrigation strip. Since ponding was not allowed in the analysis, this loss of irrigation contributed to the additional 1.3 years required for a steady-state seepage condition.

From this comparison it can be concluded that the irrigation pattern will effect the time required for hydrocompression to occur and the pattern of differential settlements. If an infinitely wide and deep homogeneous fill is irrigated uniformly, the wetting front should migrate uniformly through the fill. This should result in a uniform hydrocompression and/or expansion. However, the irrigation pattern, fill geometry, and soil properties are rarely homogeneous and the infiltration migrates unevenly through the fill especially in the non-irrigated areas. This causes deformations to occur at different

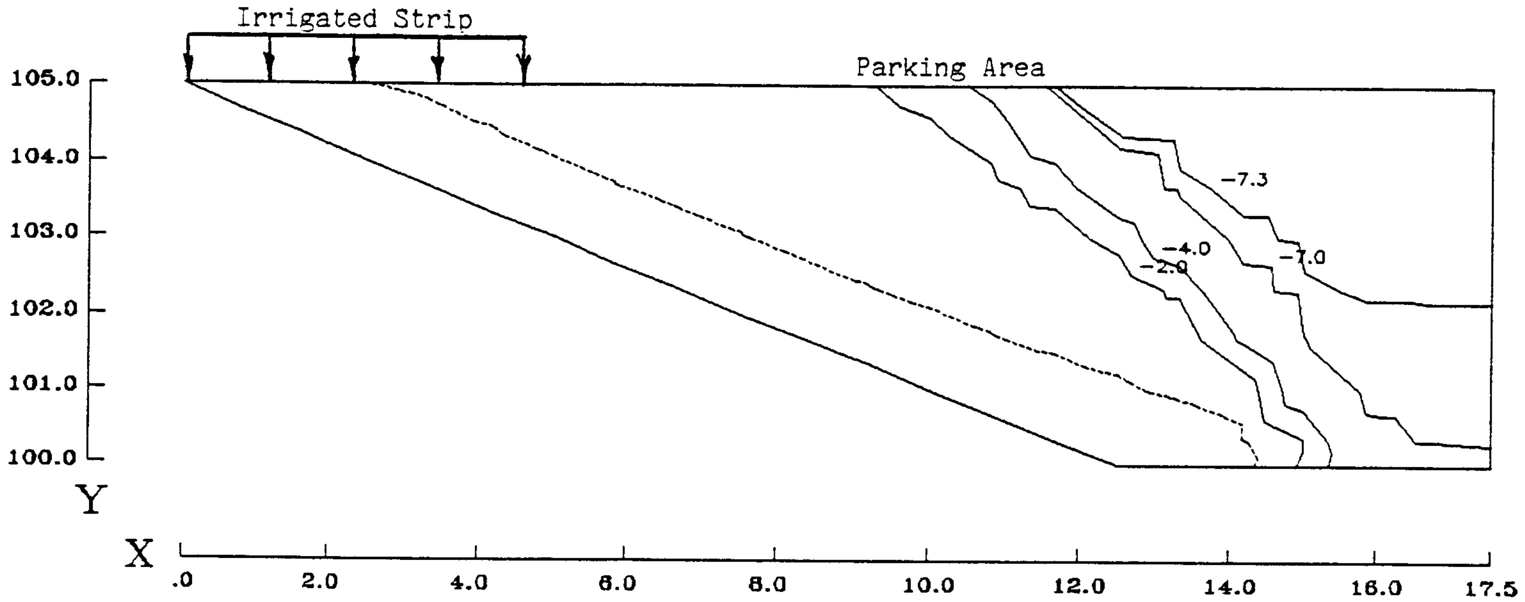

Figure 7. Pressure Head Contours after 2 Years of Irrigation in the Shallow Portion of the 5 Meter Deep Fill Placed at 2% Wet of Optimum

times and locations. These results show that irrigation patterns as well as soil variability contribute significantly to the development of differential settlements. The location of the irrigation areas should be carefully selected and the building sites or roadway easements carefully graded to minimize the amount of infiltration. The installation of drains beneath the irrigation areas may aid in reducing the amount of infiltration and thus surface movement which occurs.

Since the time required for a steady-state condition is shorter when the irrigation strip is placed at the centerline of the fill, this was considered to be the "worst case" and the remaining analyses were conducted with the largest irrigation strip placed at the centerline of the canyon.

Figure 8 illustrates the behavior of the pressure head contours in the 5 meter deep fill placed at 2% dry of optimum. It can be seen from Figure 8, that the initial suction pressures ranged from -25 to -25.1 meters which is significantly higher than the -7 to -7.3 meter suction pressures observed for a placement water content 2% wet of optimum. After approximately 4 years of irrigation, Figure 8, the suction pressures have only dissipated to a depth of 1.5 meters. In the 2% wet of optimum case, a steady-state condition was reached after 4 years, see Figure 6. This is due to the large initial suction pressures and the accompanying decrease in permeability. After almost 14 years of irrigation, the 5 meter deep fill with a placement water content 2% dry of optimum reached a steady-state seepage condition with the phreatic surface returning to the ground surface as shown previously in Figure 6.

Figure 9 shows the behavior of the pressure head contours in the 5 meter fill with a canyon drain installed at the centerline of the canyon and a placement water content of 2% wet of optimum. Canyon drains are usually installed to remove any water that is encountered during the canyon "clean-out" and/or seepage migrating through the fill material after construction. As noted earlier, the drain will not begin to function until the surrounding suction pressures have been dissipated. As a result, the drain was activated 1.5 years after the start of irrigation which was the time required for the wetting front to reach the bottom of the canyon, see Figure 5. Approximately 3 years after the drain began to function, 4.5 years after the start of irrigation, the steady-state condition shown in Figure 9 was reached. Despite the existence of a free flowing drain, the continued irrigation at the canyon centerline caused the long-term phreatic surface to rise above the canyon bottom. From this study it was estimated that a 1 meter wide drain has a radius of influence of 1 to 3 meters. However, the canyon drain does prevent the phreatic surface from rising to the ground surface as shown previously in Figure 6. It is important to note that the installation of a canyon drain does not reduce the amount of hydrocompression that takes place near

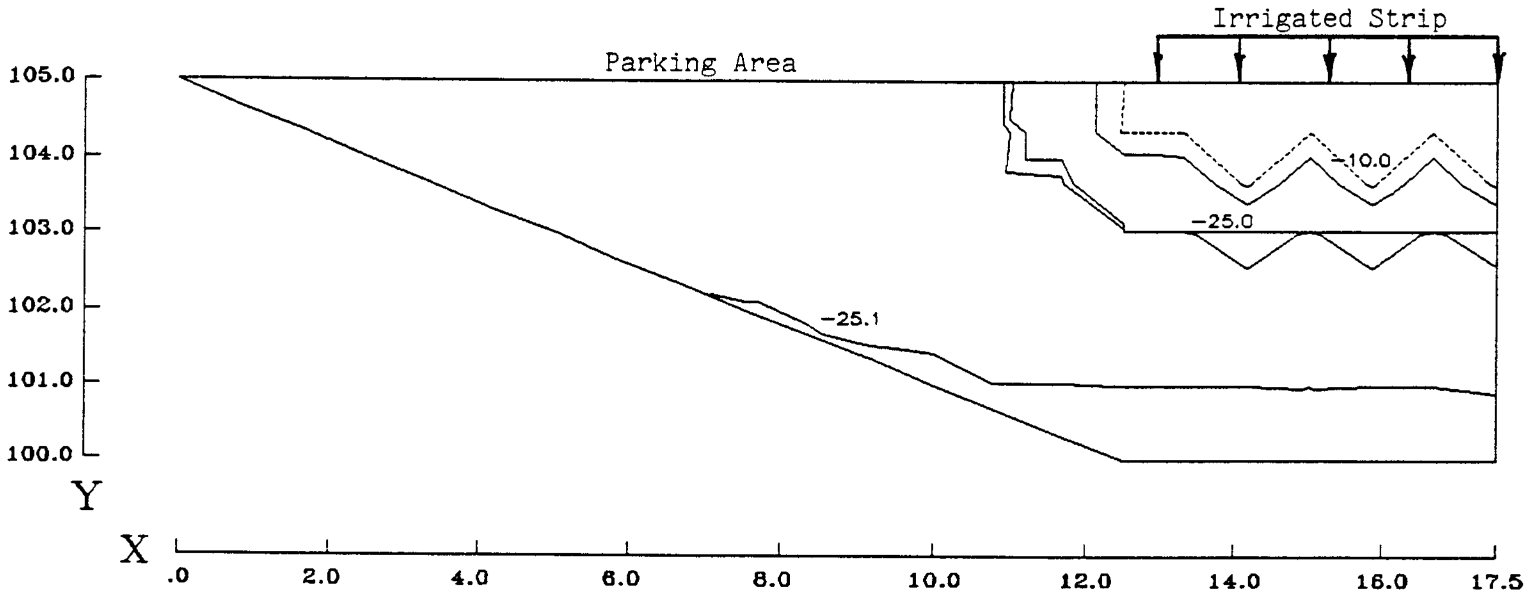

Figure 8. Pressure Head Contours after 4 Years of Irrigation in a 5 Meter Deep Fill Placed at 2% Dry of Optimum without a Canyon Drain

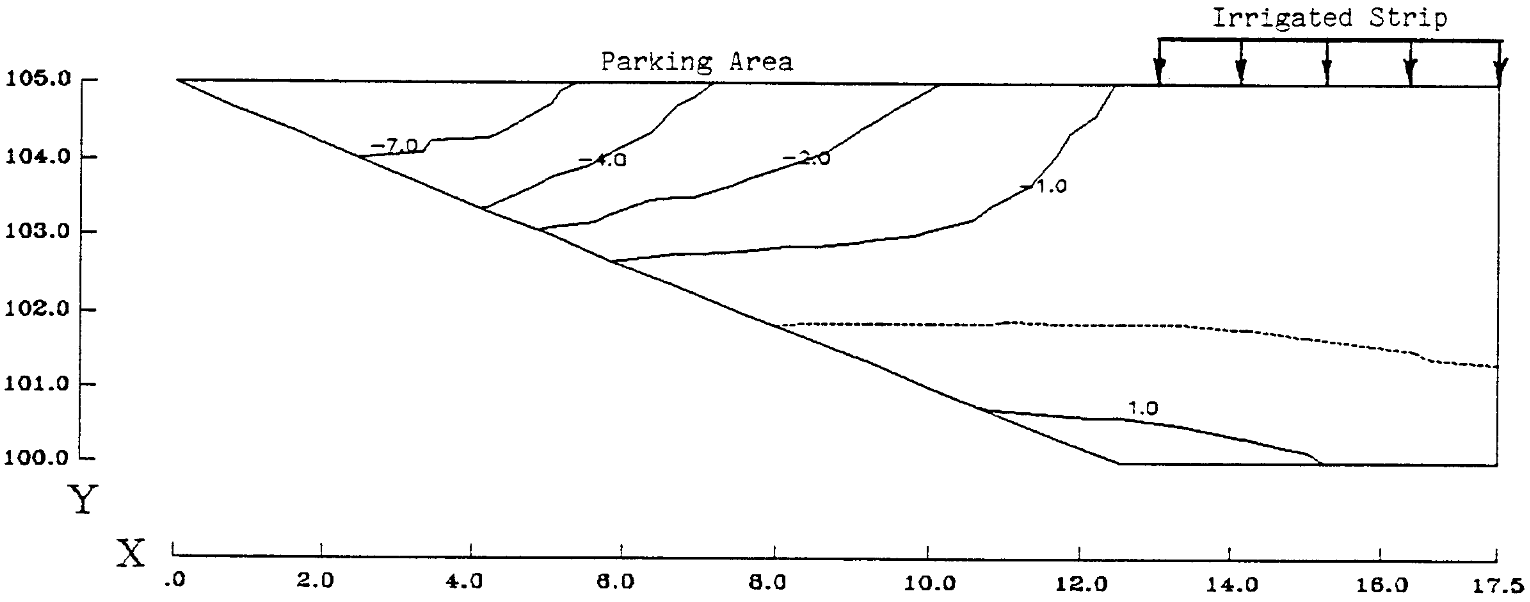

Figure 9. Pressure Head Contours after 4.5 Years of Irrigation in a 5 Meter Deep Fill Placed at 2% Wet of Optimum with a Canyon Drain

the center of the fill. In fact the differential settlement may be even greater in fills that have a canyon drain because the wetting front migrates more unevenly through the fill when a drain is installed, see Figure 9.

SEEPAGE CHARACTERISTICS IN A FIFTY METER DEEP COMPACTED FILL

Figure 10 shows the behavior of the pressure head contours in the 50 meter fill with a canyon drain and drains installed in the canyon wall directly below the three irrigated strips. The first side drain located at an x-coordinate of 10 meters began functioning after approximately 2.4 years of irrigation. This is the time required for the first wetting front to reach this location and dissipate the surrounding suction pressures. Approximately 10.7 years after irrigation began, the wetting front had migrated along the canyon wall and reached the location of the second side drain which is directly below the planter at an x-coordinate of 40 meters. Approximately 14.8 years after irrigation began, the wetting front reached the canyon bottom. This is the same amount of time that was required for the wetting front to reach the canyon bottom in the 50 meter fill with only a canyon drain. This reaffirms the conclusion that drains have a limited zone of influence. After 33.8 years of irrigation, the wetting front has descended along the canyon wall and reached the location of the final side drain at an x-coordinate of 95 meters. After 37.7 years of irrigation the steady-state seepage condition shown in Figure 10 was achieved. The long-term phreatic surface parallels the canyon wall except where it intersects the three side drains. At the deepest part of the fill, the phreatic surface remains approximately 10 meters above the canyon drain due to the limited influence of the canyon drain.

It can also be seen from Figure 10 that the majority of the suction pressures in the fill have been dissipated except underneath the building pad. At the edges of the building pad the suction pressures are less than -2.0 meters whereas at the center of the pad the suction pressures are approximately equal to the initial pressure of -7.2 meters. This will result in differential movements between the center and edge of the building pad. This differential dissipation of suction pressures is also important in forensic investigations because the boring locations may influence the measured values of water content and density. For example, in irrigated areas the fill has already undergone full soaking and hydrocompression and thus has a new water content and density. Conversely, the soil underneath the center of the building pad has not undergone full soaking and thus may have a water content and density that is more representative of the placement conditions than the irrigated areas.

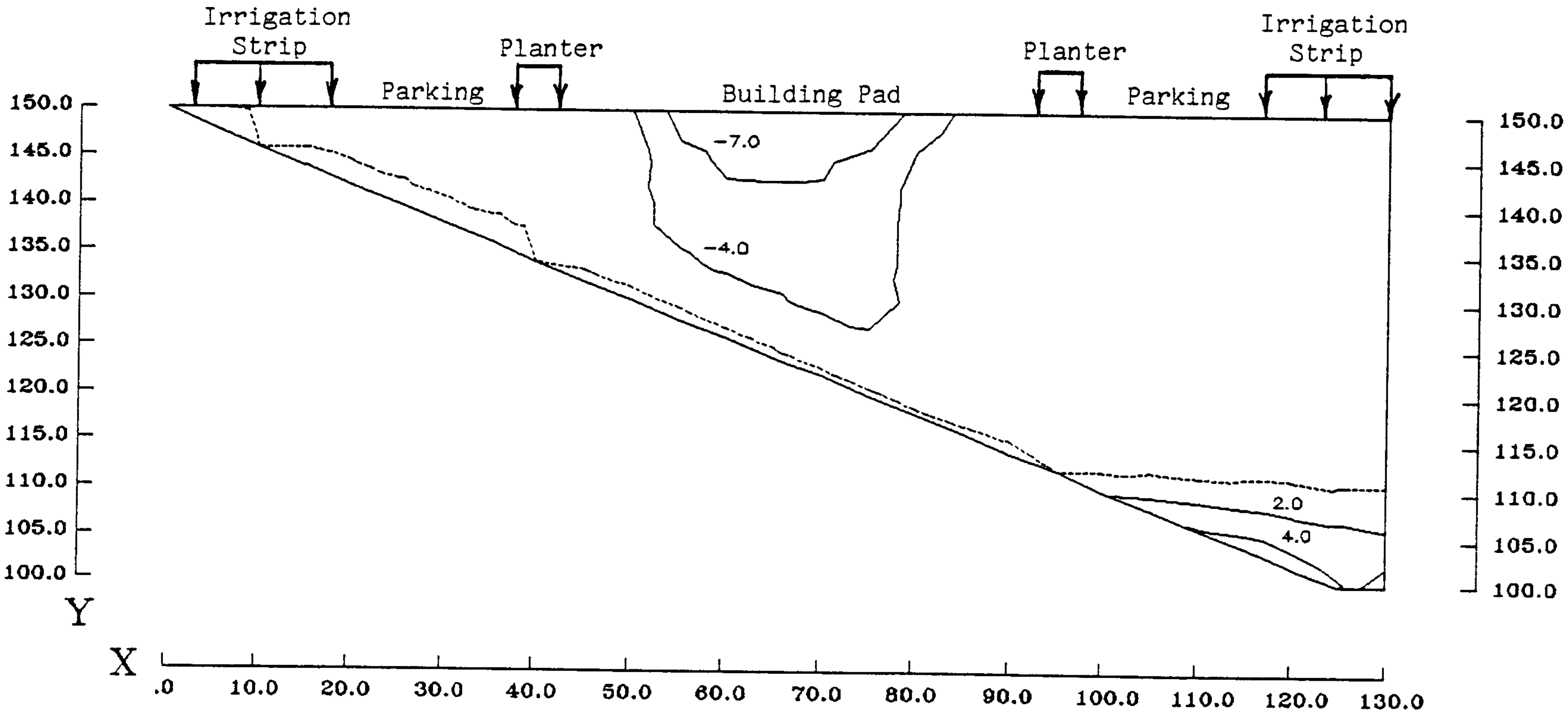

Figure 10. Pressure Head Contours After 37.7 Years of Irrigation in a 50 Meter Deep Fill Placed at 2% Wet of Optimum with Canyon and Side Drains

CONCLUSIONS

The extensive finite element seepage analysis described herein showed that the most important parameter affecting the time required for hydrocompression is the placement water content. If the Stadium Conglomerate is placed at a water content of 2% wet of optimum and a Modified Proctor relative compaction of 90%, the initial suction pressures are approximately -7.4 meters at the fill surface. If the Stadium Conglomerate is placed at a water content of 2% dry of optimum, the initial pressure heads exceed -25 meters at the fill surface. The finite element analysis showed that approximately 2.5 and 14 years of irrigation is required to complete hydrocompression in a 5 meter deep compacted fill with placement water contents of 2% wet and 2% dry of optimum, respectively. This substantial time difference is due to the larger initial suction pressures, and thus the lower permeability associated with the 2% dry of optimum water content. A lower placement water content will also cause a larger amount of hydrocompression and/or expansion due to the larger initial suction pressures.

The time required for hydrocompression was also a function of the fill depth. It can be seen from Figure 11 that without canyon or side drains installed in the fill, the time required for hydrocompression increased almost linearly with fill depth. It can also be seen from Figure 11 that the installation of a canyon drain resulted in hydrocompression times that were slightly longer than the no drain case. The drains also caused the wetting front to migrate through the fill in a more uneven pattern than the no drain case. Therefore, it was concluded that the installation of canyon and/or side drains may increase the amount of differential settlement because the fill is undergoing a more uneven wetting pattern.

Based on the analytical results, it was concluded that a canyon drain did not become operational until the suction pressures around the drain were dissipated. Once the suction pressures were dissipated, "free" water could flow to the drain and the drain would remove it from the fill. Since the fill material must become soaked or wetted before the canyon and/or side drains will function, the installation of drains will not reduce the amount of hydrocompression and/or expansion that will occur.

The seepage analysis also showed that typical surface irrigation patterns will result in an uneven migration of the wetting front through the fill material. The actual migration pattern of the wetting front depends on the location and number of irrigation points and drains installed in the fill. Uneven migration of the wetting front will result in hydrocompression occurring at different times and at different locations in the fill. If expansive soils are incorporated into the fill, the ground movements will become even more complex because some of the fill will be swelling while other portions are hydrocompressing. It is anticipated that this uneven migration of seepage contributes

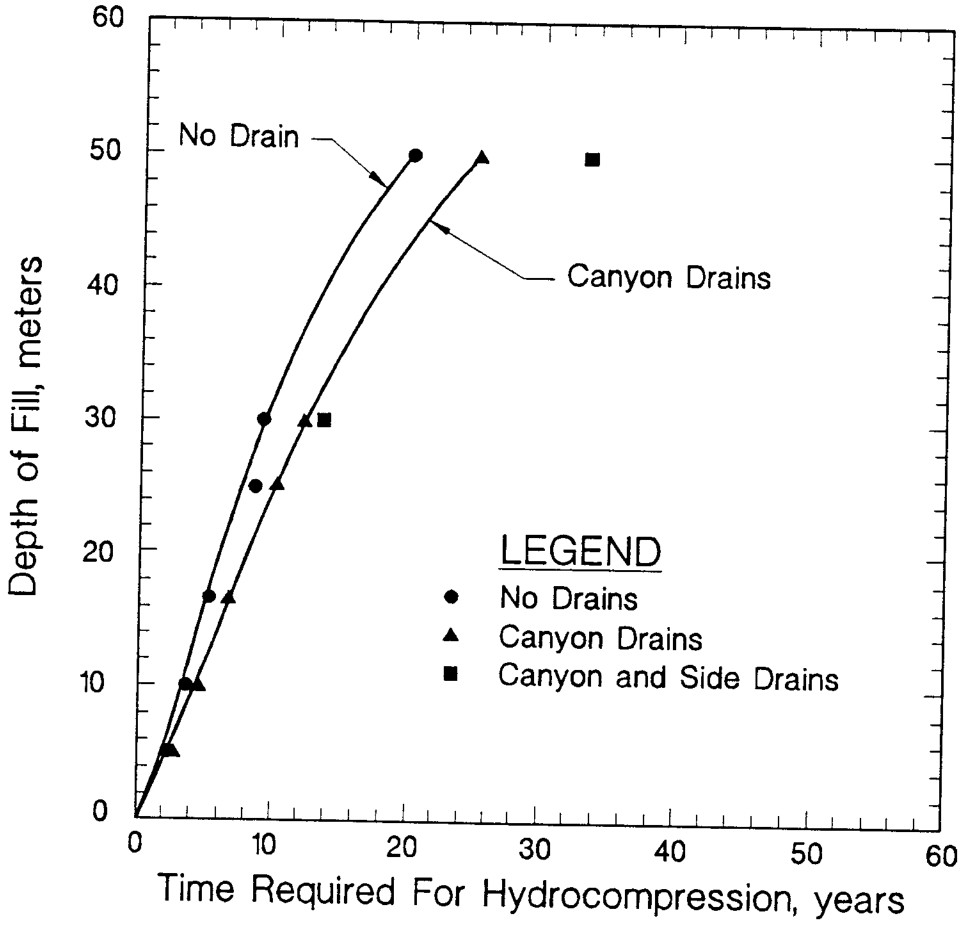

Figure 11. Time Required for Hydrocompression of Stadium Conglomerate Fills Placed at 2% Wet of Optimum and a Modified Proctor Relative Compaction of 90%

significantly to the differential settlements observed in structures built on compacted fills. To reduce the amount of differential settlement due to seepage, the fill should be carefully graded to reduce the amount of infiltration. Drains can be installed underneath the irrigation points to intercept the infiltration. If drains are not installed, the fill should be irrigated as evenly as possible so that the wetting front will migrate as uniformly as possible through the fill. If water is allowed to infiltrate the fill, the pavements and structures should be designed for the movements estimated using the procedure described herein.

ACKNOWLEDGEMENTS

The writers express their appreciation to Geocon, Inc. of San Diego, CA, for providing financial support, and the Stadium Conglomerate samples tested herein. In particular, the writers wish to thank Messrs. Jim Likins, Tom Langpap, Mike Hart and John Hoobs of Geocon, Inc., for their helpful suggestions during the course of this study. Messrs. Joe Vettel and Dan Diehr, research assistants at San Diego State University, performed the laboratory tests and assisted with the finite element analyses, respectively.

REFERENCES

1. Nwabuokei, S.O. and Lovell, C.W. (1986). "Compressibility and Settlement of Compacted Fills," Consolidation of Soils: Testing and Evaluation, ASTM STP 892, pp. 184-202.

2. Lawton, E.C., Fragaszy, R.J. and Hardcastle, J.H. (1989). "Collapse of Compacted Clayey Sand," J. Geotechnical Engineering, ASCE, Vol. 115, No. 9, pp. 1252-1267.

3. *Annual Book of ASTM Standards.* (1989). Am. Soc. of Testing and Materials, Philadelphia, PA.

4. Cedergren, H. R. (1988). "Seepage, Drainage and Flow Nets," J. Wiley and Sons, Inc., Fourth Edition.

5. Cary, A.S., Walter, B.H., and Harstad, H.T. (1943), "Permeability of Mud Mountain Dam Core Material," Transactions, ASCE, Vol. 108, pp. 719-728.

6. Sherard, J.L., Woodward, R.J., Giziensk, S.F., and Clevenger, W.A. (1963), *Earth-Rock Dams*, John Wiley and Sons, Inc., 725 pp.

7. Stark, T.D. and Duncan, J.M., "Mechanisms of Strength Loss in Stiff Clays," Geotechnical Engineering Research Report No. GT 87-5, Virginia Polytechnic Institute, August 1987.

8. Sorben, D.R. and Sherrod, U.L. (1977), "Groundwater Occurrence in the Urban Environment: San Diego, California." Geology of Southwestern San Diego County, California and Northwestern Baja California, Edited by Fassard, San Diego Association of Geologists.

9. Liakopoulos, A.C. (1965), "Theoretical Solution of the Unsteady Unsaturated Flow Problems in Soils," Int'l. Association of Scientific Hydrology, Vol. 10.

10. Croney, D. and Coleman, J.D. (1954), "Soil Structure in Relation to Soil Suction (pF)," J. of Soil Science, Vol. 5, No. 1, p. 75-84.