TRANSPORTATION RESEARCH RECORD

No. 1309

Soils, Geology, and Foundations

Geotechnical Engineering 1991

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1991

Finite Element Analysis of Partially Saturated Seepage Through Compacted Fills

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An extensive two-dimensional finite element seepage analysis was conducted to study the parameters affecting the wetting-induced behavior of compacted fills. The results showed that decreasing the placement water content increases the initial suction pressures, which increases the time required for hydrocompression and the magnitude of hydrocompression. The analysis also showed that the time required for hydrocompression increased almost linearly with fill depth. The surface infiltration was found to migrate unevenly through the fill material, resulting in an uneven dissipation of the suction pressures and thus differential ground movements. Because the suction pressures had to be dissipated before a drain could be functional, the installation of a canyon drain or side drain or both did not reduce the amount of hydrocompression or the time required for hydrocompression. However, the drains did cause the wetting front to migrate through the fill in a more uneven pattern than without a drain. 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 pavements and structures should be designed for the differential ground movements estimated from the procedure described herein.

Most transportation and residential and commercial construction in southern California involves sites composed 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 m. Previous research by Nwabuokei and Lovell, (*1*), Brandon et al., (*2*), and Lawton et al., (*3*) 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 phenomenon is known as hydrocompression and has resulted in surface deformations that have exceeded tolerable limits. The amount of hydrocompression that occurs depends on the placement water content and relative compaction. In general, the amount of hydrocompression increases with decreasing placement water content, decreasing relative compaction, and 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 as a result of the small vertical stresses applied near the fill surface. 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 hydrocompress. Therefore, if expansive soils are placed in a fill, the compacted soil will swell at shallow depths and compress at deeper depths as a result of 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 or overburden stress and axial strain, such as that shown in Figure 1, can be obtained. From such a relationship the amount of swell or hydrocompression at various depths in the fill and the depth at which the soil changes from an expansive behavior to a hydrocompression behavior can be easily determined. Figure 1 can also be used to estimate the net movement of the ground surface by (a) dividing the fill into sublayers, (b) calculating the fill depth at the mid-point of each sublayer, (c) estimating the axial strain of each sublayer using Figure 1 and the fill depth at the mid-point of each sublayer, (d) multiplying the appropriate axial strain by the initial thickness of the sublayer, and (e) 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. Because most, if not all, of the infiltration is due to surface irrigation, the wetting front usually migrates from the top to the bottom of the fill. As a result, the upper portion of the fill usually undergoes expansion or hydrocompression before the bottom of the fill becomes wetted. This uneven wetting of the fill led to the following questions concerning the wetting-induced behavior of compacted 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 pavements and structures 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?

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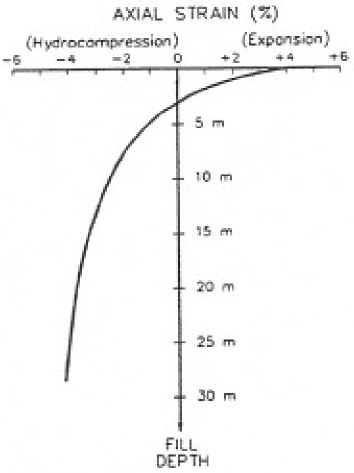

FIGURE 1 Axial strain after inundation as a function of fill depth.

The results of an extensive two-dimensional finite element seepage analysis that was conducted to clarify these aspects of the wetting-induced behavior of compacted fills are described in this paper.

CANYON GEOMETRIES AND SOIL PROPERTIES USED IN ANALYSIS

A confined canyon with 2.5 to 1 side slopes and a bottom width of 10 m was analyzed. Because of 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 m) 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 m) the effects of placing drains at various locations along the canyon walls were also investigated. The effect of placement water content, 2 percent dry versus 2 percent wet of optimum, was investigated using a fill depth of 5 m.

Because of 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 more than 40 mm to less than 0.001 mm. To simulate typical fill operations, a relative compaction of 90 percent based on the Modified Proctor Compaction test (ASTM Standard D1557-78) was used throughout the laboratory testing and finite element analysis.

Cedergren (*4*) and Carey 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 also control the seepage characteristics. Because 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 of the laboratory tests were conducted on the minus No. 10 material. The minus No. 10 material makes up approximately 50 percent by weight of the Stadium Conglomerate and classifies as a silty sand (SM).

The optimum water content and maximum dry density, obtained from five Modified Proctor Compaction tests using Method A and the minus No. 10 material, are approximately 10 percent 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 percent wet of optimum was measured to be 2.3×10^{-3} m/day. The average steady-state permeability at 2 percent dry of optimum was obtained from the results of 3 falling head tests and was measured to be 3×10^{-3} m/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} m/day measured by Sorben and Sherrod (*8*) for a local 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 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, such as Elzeftawy and Cartwright (*12*) and GEOSLOPE (*13*), have presented data that show 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 also showed that the main parameter affecting the analytical results is the steady-state permeability and the initial suction pressure heads.

To determine the initial suction pressures, 20 oedometer tests were conducted using specimens compacted at 2 percent wet (volumetric water content of 0.214) and 2 percent dry (volumetric water content of 0.144) of optimum and a Modified Proctor relative compaction of 90 percent. From these tests the relationship between volumetric water content and fill depth or overburden stress was obtained for both placement water contents. This relationship was confirmed by field testing in which moisture content samples were obtained from two 1-m-diameter bucket-auger borings that were drilled immediately after completion of a 24-m-deep Stadium Conglomerate fill. The moisture content samples were carefully excavated from the wall of the boring every 0.3 m for the entire fill depth. The volumetric water content for each sample was plotted versus fill depth; 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 was incorporated into the analysis. The final soil parameters used in the seepage analysis of the Stadium Conglomerate at 2 percent wet of optimum are summarized below. The steady-state permeability properties were as follows:

- Vertical permeability = $K_v = 2.3 \times 10^{-3}$ m/day,
- Horizontal permeability = $K_h = 9.2 \times 10^{-3}$ m/day,
- $K_h = 4K_v$, and
- K_h is inclined 0° to the horizontal.

The pressure versus K_h properties are summarized in the following table.

Suction Pressure (kPa)	*K_h (m/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}

The pore-water storage properties are summarized in the following table.

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

The soil parameters used in the seepage analysis of the Stadium Conglomerate at 2 percent dry of optimum are summarized below. The steady-state permeability properties were as follows:

- Vertical permeability = $K_v = 3.0 \times 10^{-3}$ m/day,
- Horizontal permeability = $K_h = 1.2 \times 10^{-2}$ m/day,
- $K_h = 4K_v$, and
- K_h is inclined 0° to the horizontal.

The pressure versus K_h properties are presented in the following table.

Suction Pressure (kPa)	*K_h (m/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}

The pore-water storage properties are summarized in the following table.

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

FINITE ELEMENT SEEPAGE PROGRAMS AND APPLIED BOUNDARY CONDITIONS

PC-SEEP, developed by GEOSLOPE (*13*), was used for this study because of its 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 good agreement. It should be noted that both programs assume constant total volume and volume change due to hydrocompression and expansion, which is not taken into account in the analysis.

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-m-wide irrigated strip usually separates the lots or acts as a buffer between the adjacent street, and a 30-m-wide parking lot is provided for each build-

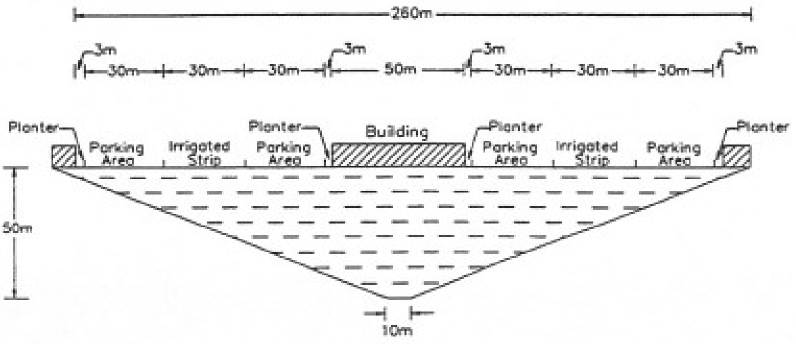

FIGURE 2 Typical irrigation pattern for a 50-m-deep canyon fill.

ing. A 3-m-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 percent. Based on data presented by Sorben and Sherrod (*8*), an infiltration rate of 0.46 m/year was used in the irrigation pattern.

Extensive seepage analyses showed that the full canyon geometry, shown in 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 here 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. The Villa Trinidad subdivision in San Diego County experienced settlements in excess of 0.3 m due to hydrocompression in the 22-m-deep fill. Brandon et al. (*2*) reported that the average placement water content of the fill was approximately 0.6 percent wet of optimum and the Modified Proctor relative compaction was at or near 90 percent throughout the fill. Therefore, the settlement was attributed to hydrocompression and not variations in the placement conditions.

Brandon et al. (*2*) also presented settlement survey data which 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 percent wet of optimum. However, the initial suction pressures were based on a water content of 0.6 percent 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-m-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 approximately 1.5 years faster than the measured time. Soil classification tests of the Villa Trinidad fill material showed that 75 percent of the fill material classified as a clayey sand (SC), and the remaining 25 percent classified as an SM. In addition, the placement water content varied from −2 to +2 percent of the optimum, with the average placement water content being approximately 0.6 percent wet of optimum. The slightly lower average placement water content will cause higher initial suction pressures and thus a lower permeability. Therefore, the difference in the measured and calculated hydrocompression times was attributed to the slight difference in the placement water content and the difference in seepage characteristics of a clayey-sand and silty-sand. However, the good agreement between the measured and calculated times for the Villa Trinidad fill 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 5-m-DEEP COMPACTED FILL

Figures 3 through 6 show the behavior of the presure head contours in the 5-m fill without a canyon drain and the Stadium Conglomerate compacted at a water content 2 percent wet of optimum. Because 25 percent of the ground surface is irrigated, only an irrigation strip at the centerline of the canyon was used in the 5 meter deep fill (Figure 3). The figure shows the pressure head contours, in meters, after one day of irrigation. Placement of the Stadium Conglomerate at 2 percent wet of optimum results in suction pressures of almost −7.4 m at the surface of the fill and −7.2 m 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 m pressure head contour has appeared beneath the irrigation strip. After 1 year of irrigation the infiltration has caused a large dissipation of the suction pressures near the centerline of the fill (Figure 4). The zero pressure head contour, shown in Figure 4 as a dashed line, is

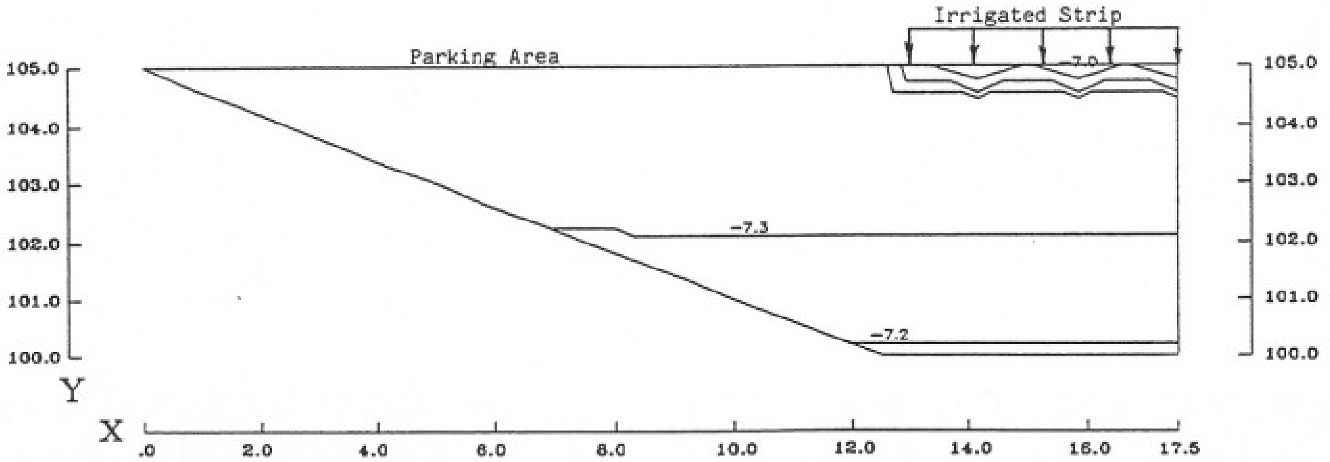

FIGURE 3 Pressure head contours after 1 day of irrigation for the 5-m-deep fill placed at 2 percent wet of optimum.

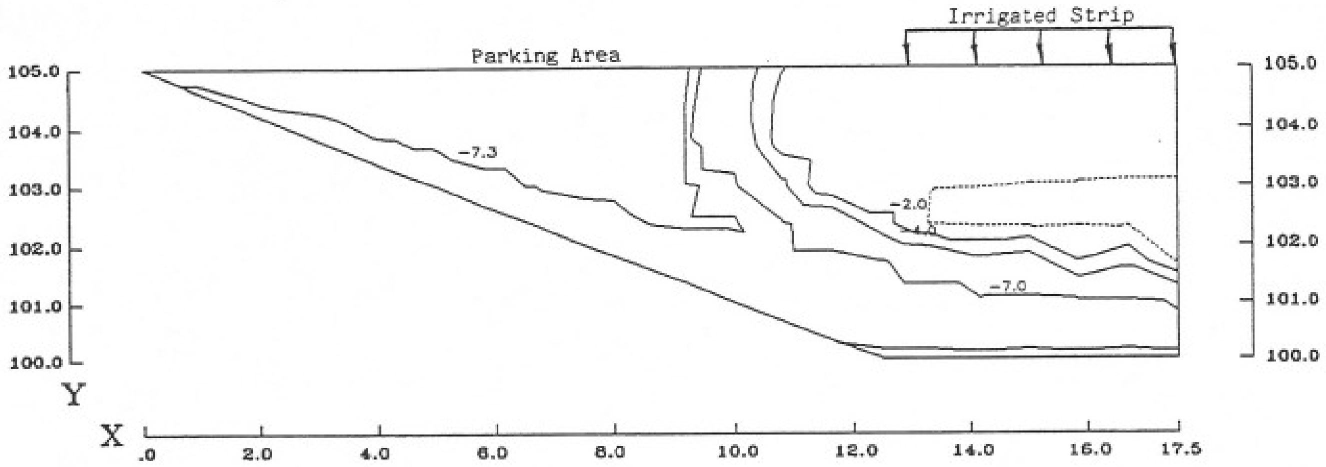

FIGURE 4 **Pressure head contours after 1 year of irrigation for the 5-m-deep fill placed at 2 percent wet of optimum.**

approximately 2 to 3 m below the ground surface. The zero pressure head contour or wetting front delineates the boundary between partially saturated and fully soaked conditions, the soil that has and has not undergone hydrocompression.

After an elapsed irrigation time of about 1.5 years the wetting front has reached the impermeable boundary at the bottom of the canyon fill (Figure 5). The suction pressures in the shallow portion of the fill continue to dissipate as a result of horizontal seepage, whereas the deeper portion of the fill has already undergone hydrocompression. Before, 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 reached the bottom of the canyon and dissipated 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 of the 5-m-deep fill, the drain was not activated until the wetting front reached the canyon bottom, that is, after 1.5 years of irrigation.

After approximately 4 years of irrigation a steady-state seepage condition is reached with the long-term zero pressure head contour or phreatic surface rising to the ground surface (Figure 6). This is due to the impermeable canyon walls preventing water from leaving the fill. The final location of the phreatic surface will depend on the actual permeability of the canyon walls, and whether 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 percent. 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 5-m-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 center. It can be seen that after 2 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 under-

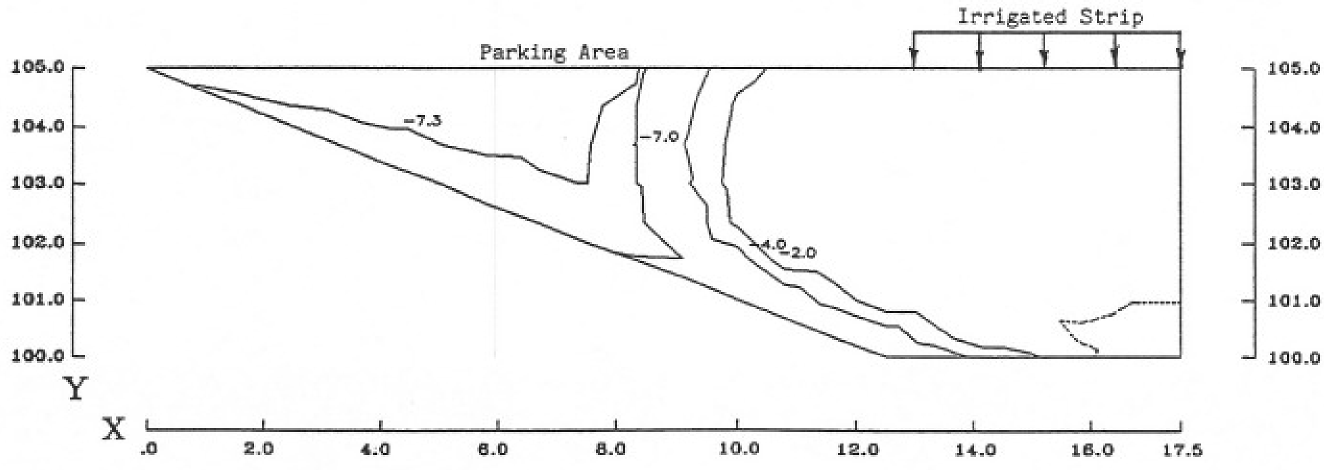

FIGURE 5 **Pressure head contours after 1.5 years of irrigation for the 5-m-deep fill placed at 2 percent wet of optimum.**

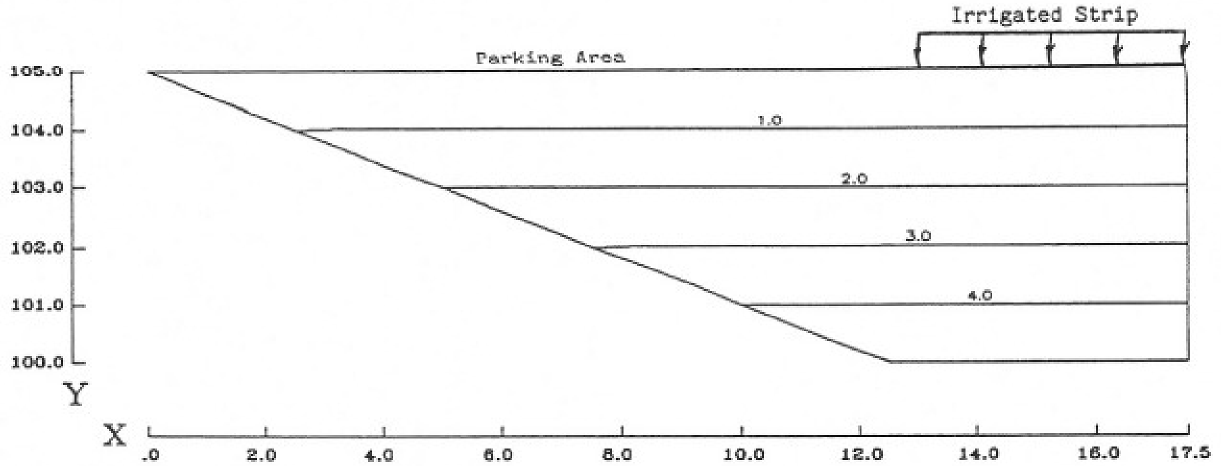

FIGURE 6 Pressure head contours after 4 years of irrigation for the 5-m-deep fill placed at 2 percent wet of optimum.

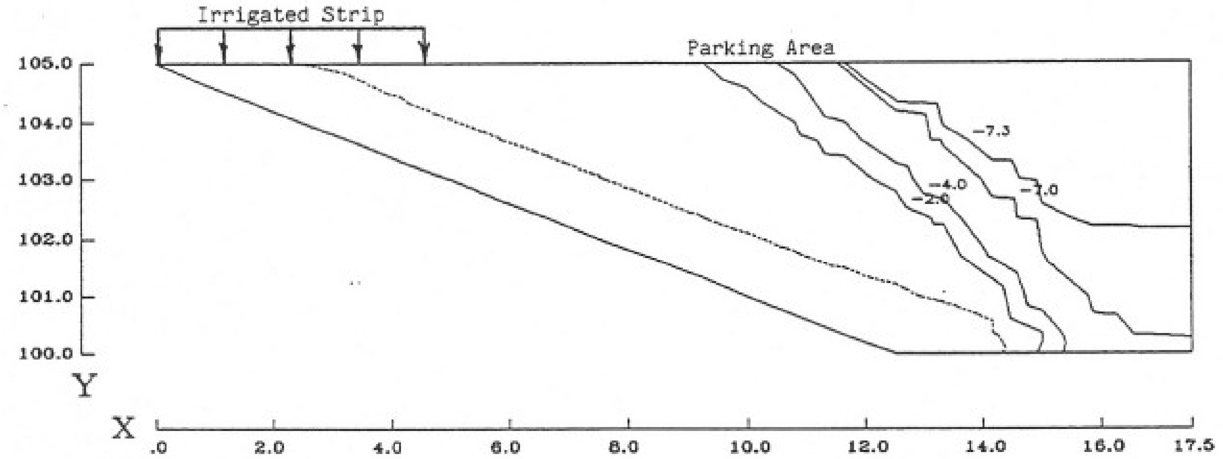

FIGURE 7 Pressure head contours after 2 years of irrigation in the shallow portion of the 5-m-deep fill placed at 2 percent wet of optimum.

gone hydrocompression or expansion or both while the suction pressures in the middle of the fill are still dissipating. In the previous case, after 1.5 years of irrigation the center portion of the canyon had undergone full soaking and thus hydrocompression (Figure 5). 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 returned 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. Because 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 affect 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 or expansion or both. However, the irrigation pattern, fill geometry, and soil properties are rarely homogeneous, and the infiltration migrates unevenly through the fill, especially in the nonirrigated areas. This causes deformations to occur at different 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 deformation that occurs.

Because 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 shows the behavior of the pressure head contours in the 5-m-deep fill placed at 2 percent dry of optimum. It can be seen from Figure 8 that the initial suction pressures

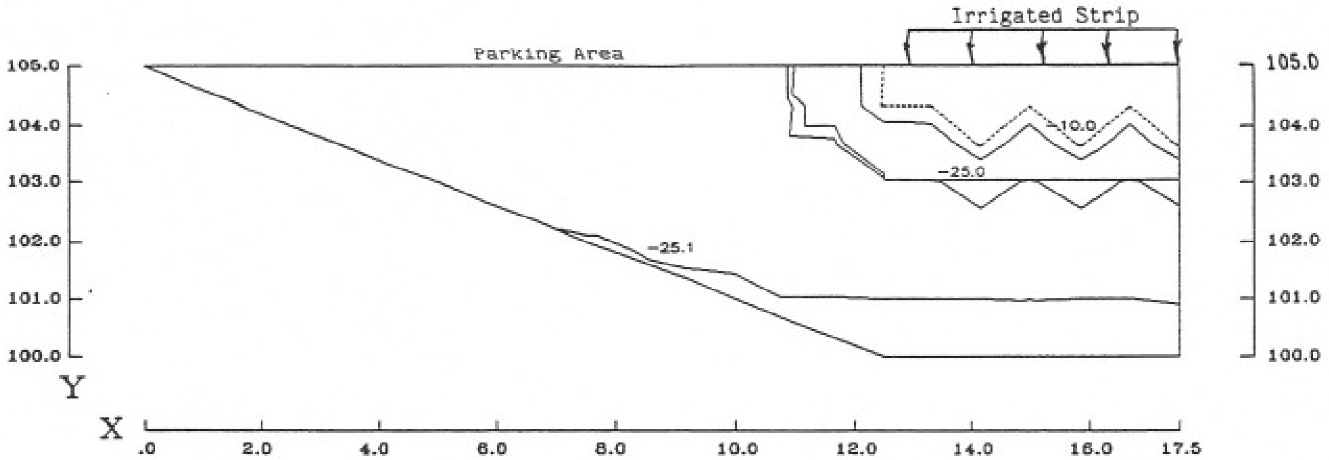

FIGURE 8 Pressure head contours after 4 years of irrigation in a 5-m-deep fill placed at 2 percent dry of optimum without a canyon drain.

ranged from −25 to −25.1 m, which is significantly higher than the −7 to −7.3 m suction pressures observed for a placement water content 2 percent wet of optimum. After approximately 4 years of irrigation the suction pressures have only dissipated to a depth of 1.5 meter (Figure 8). In the 2 percent wet of optimum case, a steady-state condition was reached after 4 years (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-m-deep fill with a placement water content 2 percent dry of optimum reached a steady-state seepage condition with the phreatic surface at or near the ground surface, shown previously in Figure 6.

Figure 9 shows the behavior of the pressure head contours in the 5-m fill with a canyon drain installed at the centerline of the canyon and a placement water content of 2 percent wet of optimum. Canyon drains are usually installed to remove any water that is encountered during the canyon "clean-out" and seepage that migrates through the fill after construction. As noted earlier, the drain will not begin to function until the surrounding suction pressures have been dissipated. As a result, the canyon 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 (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-m-wide drain has a radius of influence of 1 to 3 m. However, the canyon drain does prevent the wetting front 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 the center of the fill. 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 (Figure 9).

SEEPAGE CHARACTERISTICS IN 50-m-DEEP COMPACTED FILL

Figures 10 and 11 illustrate the behavior of the pressure head contours in the 50-m-deep fill with only a canyon drain

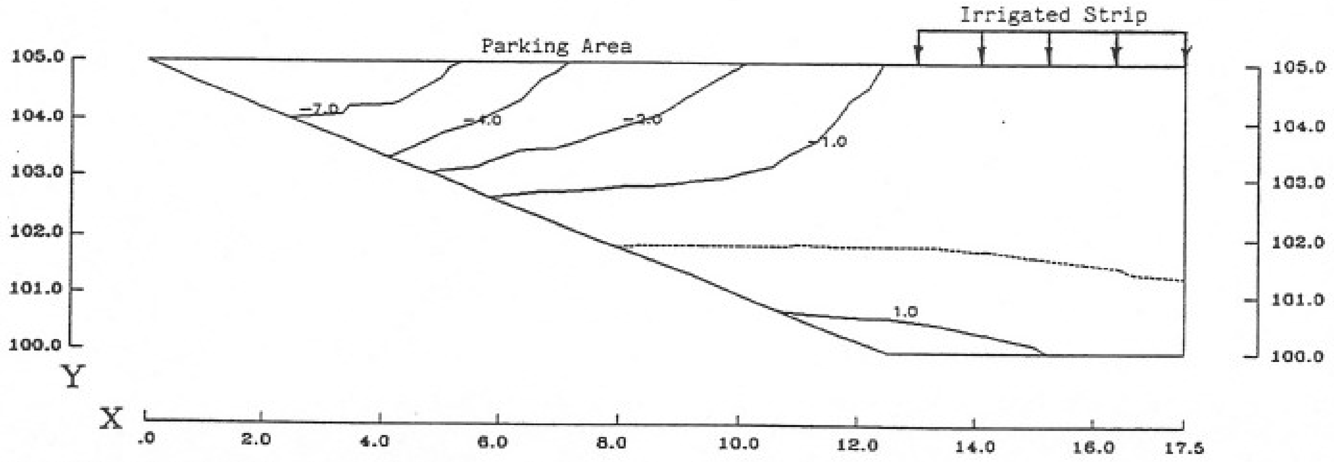

FIGURE 9 Pressure head contours after 4.5 years of irrigation in a 50-m-deep fill placed at 2 percent wet of optimum with a canyon drain.

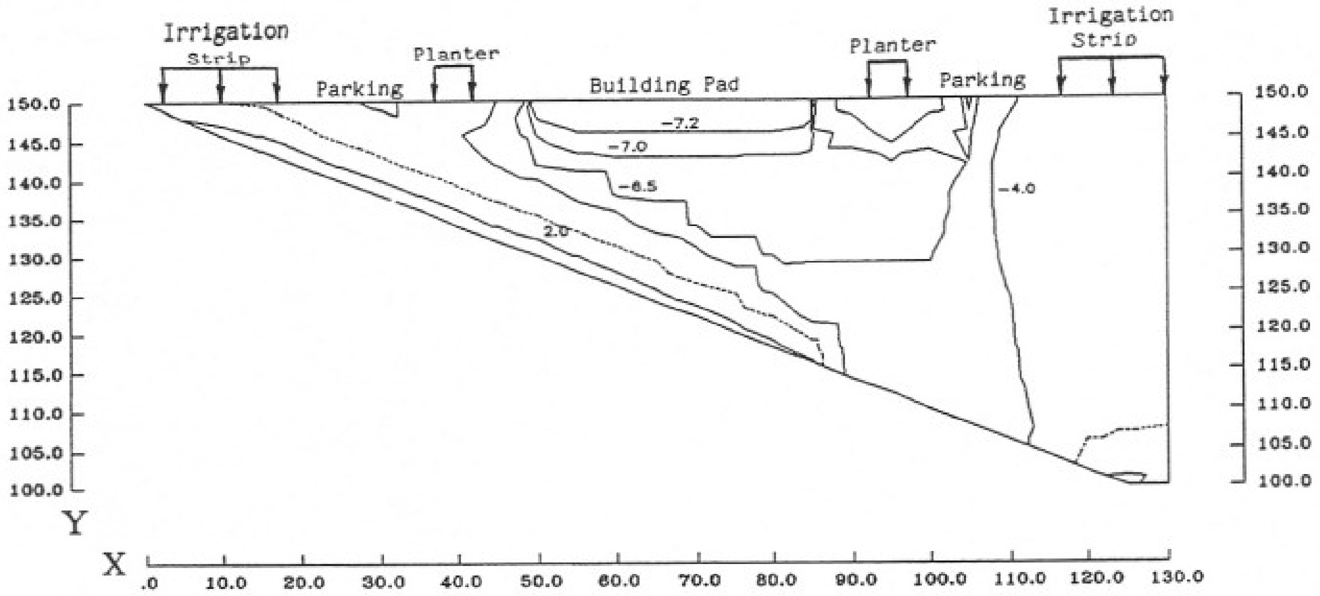

FIGURE 10 Pressure head contours after 14.8 years of irrigation in a 50-m-deep fill placed at 2 percent wet of optimum with a canyon drain.

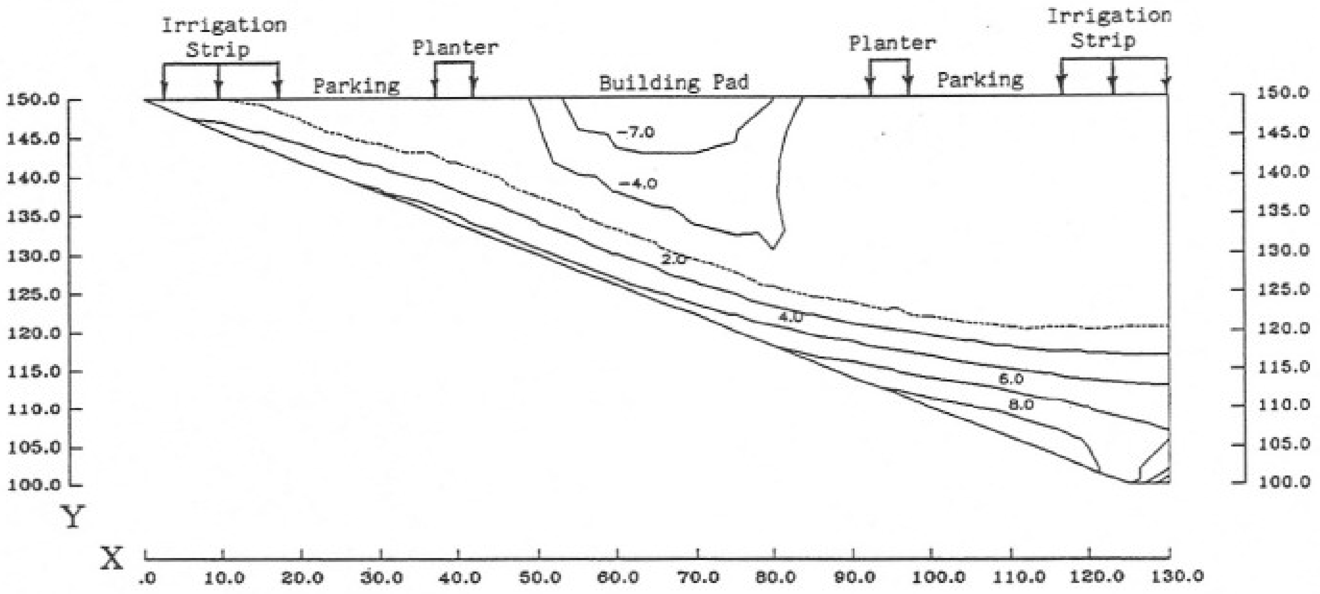

FIGURE 11 Pressure head contours after 30.7 years of irrigation in a 50-m-deep fill placed at 2 percent wet of optimum with a canyon drain.

installed at the centerline of the canyon. The placement conditions are a water content 2 percent wet of optimum and a Modified Proctor relative compaction of 90 percent. The irrigation pattern shown in Figure 2 was used for the 50-m-deep fill. After 14.8 years of irrigation the wetting front beneath the irrigation strip at the centerline of the fill reached the canyon bottom and the canyon drain began to function (Figure 10). It can be seen that the initial suction pressures of −7.2 m were still present below the building pad. The irrigation at the shallow end of the fill resulted in a wetting front that developed and descended along the canyon wall. After 30.7 years of irrigation, or 16 years after the canyon drain began functioning the two wetting fronts have joined and a steady-state condition is achieved (Figure 11). The long-term phreatic surface remains about 30 m below the surface because of the installation of a canyon drain, which dissipates the positive pressure heads in the fill. It can also be seen that the majority of the suction pressures in the fill have been dissipated except underneath the building pad. The initial suction pressure of −7.2 m has dissipated unevenly underneath the building pad, which will probably result in differential soil expansion or hydrocompression or both.

Figure 12 shows the behavior of the pressure head contours in the 50-m fill with a canyon drain and drains installed in the canyon wall directly below the 3 irrigated strips. The first side drain, located at an *x* coordinate of 10 m, began functioning

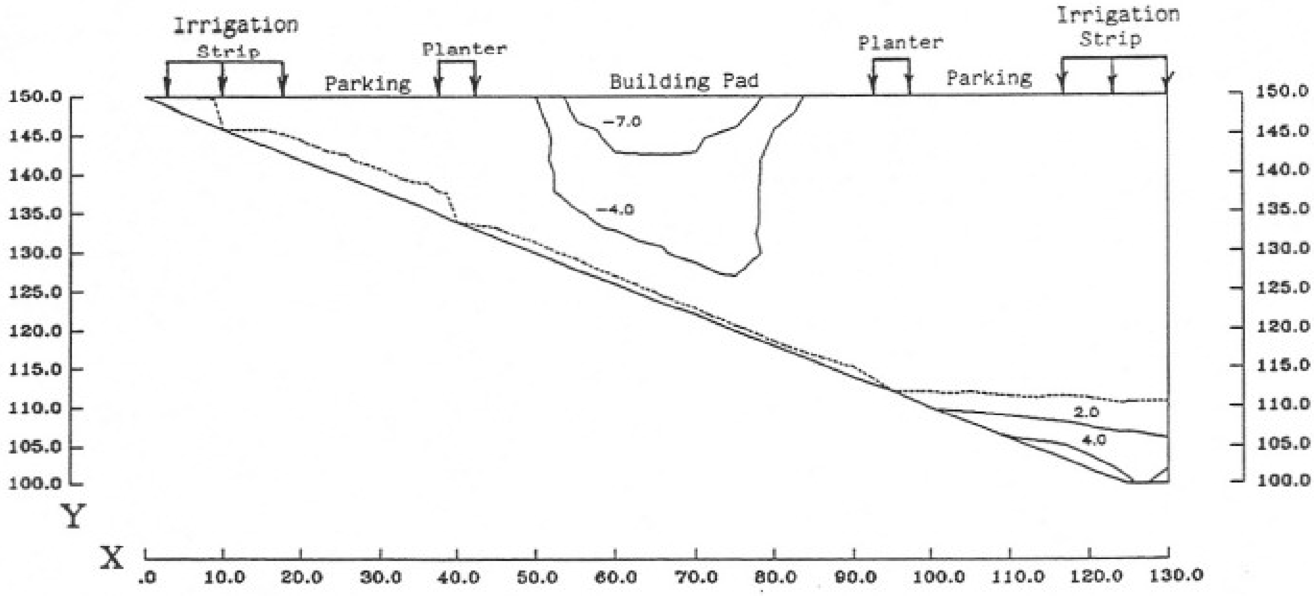

FIGURE 12 Pressure head contours after 37.7 years of irrigation in a 50-m-deep fill placed at 2 percent wet of optimum with canyon and side drains.

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 pressure. 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 m. 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-m 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 had descended along the canyon wall and reached the location of the final side drain at an *x* coordinate of 95 m. After 37.7 years of irrigation the steady-state seepage condition shown in Figure 12 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 line remains approximately 10 m above the canyon drain as a result of the limited influence of the canyon drain.

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 percent wet of optimum and a Modified Proctor relative compaction of 90 percent, the initial suction pressures are approximately −7.4 m at the fill surface. If the Stadium Conglomerate is placed at a water content of 2 percent dry of optimum, the initial pressure heads exceed −25 m at the fill surface. The finite element analysis showed that approximately 2.5 and 14 years of irrigation are required to complete hydrocompression in a 5-m-deep compacted fill with placement water contents of 2 percent wet and 2 percent 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 percent dry of optimum water content. A lower placement water content will also cause a larger amount of hydrocompression or expansion or both as a result of the larger initial suction pressures.

The time required for hydrocompression was also a function of the fill depth. It can be seen from Figure 13 that without canyon or side drains installed in the fill, the time required for hydrocompression increased almost linearly with fill depth. In all of the cases shown in Figure 13, 25 percent of the fill surface was irrigated at a rate of 0.46 m/year, on the basis of data presented by Sorben and Sherrod (*8*).

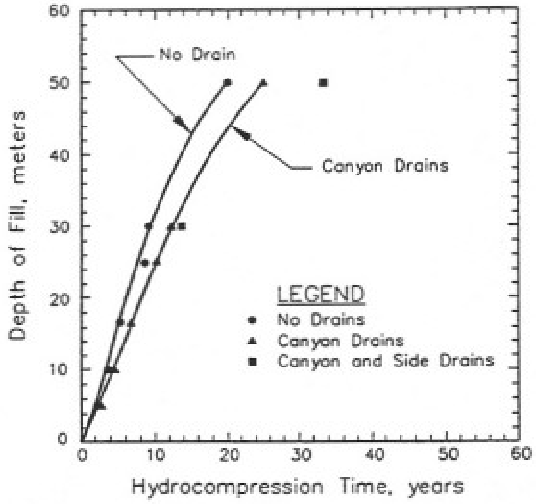

FIGURE 13 Time required for hydrocompression of Stadium Conglomerate fills placed at 2 percent wet of optimum and a Modified Proctor relative compaction of 90 percent.

It can also be seen from Figure 13 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 or side drains or both may increase the amount of differential settlement because the fill undergoes a more uneven wetting pattern.

Because the canyon boundaries were assumed to be impermeable, the steady-state phreatic surface was located at or near the ground surface if a canyon drain was not installed. The installation of a canyon drain prevented the phreatic surface from rising to the surface of the fill by dissipating some of the positive pressure heads. If a canyon drain was installed, the steady-state phreatic surface was located at a depth of 0.5 to 0.7 times the depth of the fill.

Based on the analytical results, it was also concluded that the 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, which would remove the excess water from the fill. Because the fill material must become soaked or wetted before the canyon and side drains will function, the installation of drains will not reduce the amount of hydrocompression and 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 wetting contributes significantly to the differential settlements observed in roadways and 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 procedures described herein.

ACKNOWLEDGMENTS

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

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Publication of this paper sponsored by Committee on Transportation Earthworks.