

STATISTICAL DETERMINATIONS OF STEADY-STATE, GROUNDWATER INFLOW IN ROCK TUNNELS FOR THE RADIAL FLOW CONDITION

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ABSTRACT

This paper presents improvements to the current state of the practice in estimating steady-state groundwater inflows into rock tunnels. This analysis applied statistical methods to packer test data obtained from exploratory borings during hydrogeological/geotechnical site investigations from the Chattahoochee, Nancy Creek, and Milwaukee tunnels (Vanarelli, 2007).

The current state of the practice for estimating groundwater inflows in rock tunnels is to apply a semi-empirical procedure developed and published by Dr. Ronald Heuer in 1995. Dr. Heuer (1995) identified two fundamental boundary flow conditions that can exist for a rock tunnel based on the work of Goodman. These flow conditions control the steady state groundwater inflow into a given tunnel. The conditions are referred to as the radial flow condition and vertical recharge flow condition. For the radial flow condition, a statistical analysis presented in this paper indicates that insufficient amount of testing could lead to underestimations of the inflow quantities.

Packer test data plotted in histograms were observed in all cases to be log-normally distributed for the radial flow condition. Underestimation in the inflow could occur if the total number of packer tests was small. Specifically, the extreme high-end permeability fraction of the distribution could be under-represented or absent. Modeling using Monte Carlo simulations was observed to be an effective tool for incorporating high-end permeability data in groundwater inflow estimates.

INTRODUCTION

One of the biggest challenges associated with the construction of rock tunnels has been predicting groundwater inflows along the length of the tunnel. Groundwater inflows, particularly those that are unanticipated and excessive, can cause many problems including delays in construction, health and safety risks to personnel, elevated costs during construction, and termination of the project prior to completion. Public agencies and governmental affiliates (i.e., owners) need to know what problems may be associated with a tunnel project and accurate groundwater inflow estimates can influence the success of these projects. Typically, contractors retained by owners request additional funds to handle and manage excessive groundwater inflow into a tunnel. These additional funds or costs may be very high for the owner (Heuer, 1995).

Historically, engineers have estimated groundwater inflow utilizing concepts and formulae developed by Goodman who treated the ground as homogeneous and the tunnel as a well. Based on this work, Heuer has developed a semi-empirical procedure that is widely used today. To date, no publications has critically reviewed and analyzed these methods in relation to actual field data or tunnel projects (Goodman et al., 1964; Heuer, 1995).

The state of the practice to estimate groundwater inflows into rock tunnels is to apply Heuer's semi-empirical (1995) procedure. Although, widely utilized in the tunneling industry, Heuer's method (1995) can yield varying results.

LITERATURE REVIEW

Heuer presents a semi-empirical method for estimating groundwater inflows. He uses data collected from water pressure tests or packer tests to generate histograms that are assumed to indicate the percentages of tunnel length in different ranges of permeability. The packer testing is normally performed with inflatable straddle packers at 10 to 20 foot spacing throughout the borehole depth below the water table. The primary geologic factors that determine groundwater inflows are discontinuities and other defects in the rock mass (Heuer, 1995).

Heuer identifies two limiting conceptual models that contribute to groundwater inflow in tunnels: vertical recharge with a nearby water source at constant head (e.g., a tunnel overlain by a lake or reservoir) and radial flow with a recharge source far away (e.g., a well turned on its side with flow from all directions) as shown in Figure 1 (Heuer, 1995).

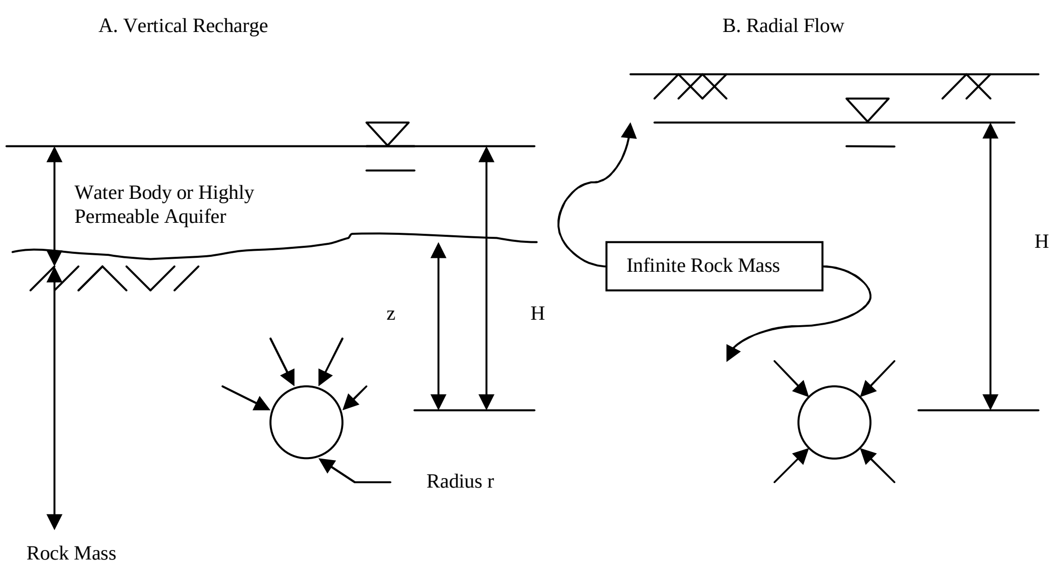

Figure 1 – Conceptual Models: Steady State Limiting Cases (Heuer, 1995)

A histogram of hydraulic conductivity can be constructed from packer test results and this information is used to obtain an equivalent permeability (k_e). Heuer uses this type of information in his 1995 paper. Heuer constructed a chart that graphically correlates the average intensity of long term steady state inflow into a tunnel (q_s) and the equivalent permeability (k_e). The chart was developed by Heuer from data collected from various projects where actual inflow values were available. Heuer uses this chart for estimating all tunnel inflows regardless of geological composition or tunnel construction parameters (e.g., diameter) (Heuer, 1995).

OVERVIEW OF CASE STUDIES

Chattahoochee Tunnel Project in Georgia

The Chattahoochee Tunnel is approximately 49,622 feet long with an excavated diameter of 18 feet. It is aligned in a north-south direction. The depth of the tunnel ranges from 100 to 350 feet below ground surface. The gradient of the tunnel is approximately 0.1 percent grade. The tunnel is composed of two main drives including the north and south drives. The north drive extends approximately 25,852 feet, while the south drive extends approximately 23,770 feet. The tunnel is located in the Piedmont Geomorphic Physiographic Province in the southeastern United States. The geology of the Piedmont in the area of Atlanta, Georgia consists of metamorphic and granitic rocks. Joints are thought to be one of the major physical features in the igneous and metamorphic rocks in the Atlanta area that provide pathways for the movement of groundwater (i.e., groundwater inflow to tunnels)(CCWS, 2000).

Nancy Creek Tunnel Project in Atlanta, Georgia

The Nancy Creek Tunnel is a deep, hard-rock tunnel that is approximately 43,700 feet long. It was excavated by a TBM and has a finished diameter of 16 feet. The Nancy Creek Tunnel is located in the Piedmont physiographic province of the southeastern United States. The regional geology consists of the metamorphic rocks with intrusions of granitic rocks at some locations. Again, as with Chattahoochee, joints are thought to be a major pathway for groundwater movement (City of Atlanta, 2001).

Milwaukee Northwest Side Sewer Relief Tunnel Project

The overall project consists of a system, which includes a 37,400 foot long, 20-foot finished diameter tunnel in bedrock with diversion and drain structure, shafts, gates, odor control facilities, instrument controls and electrical works. The tunnel is constructed in bedrock at a depth of approximately 120 to 165 feet below the ground surface. The Milwaukee tunnel was constructed within the dolomite bedrock aquifer underlying the glacial water table aquifers. Discontinuities are known to exist within this bedrock aquifer that generally consists of faults and joints (MMSD, GBR, 2001).

ANALYSIS OF CASE STUDIES

Chattahoochee Tunnel Project

The original analysis by Dr. Heuer divided the entire tunnel into two segments: a north drive and a south drive. This was done because the south drive was interpreted to be generally closer to the transition zone, with the likelihood of an overall slightly more permeable mass. A total of 367 packer tests were performed in the rock formation along the tunnel alignment. The results of this analysis determined that appropriately 300 and 600 gallons per minute of steady state inflow would occur in the north and south drives. Therefore, the total estimated steady state inflow in the tunnel would be appropriately 900 gpm. Actual inflows into the tunnel were approximately 1400 gpm. Therefore, Heuer's method appears to underestimate inflows by 36 percent in this case (Heuer, 1999; 2005).

A separate independent analysis was performed as part of this paper, utilizing the procedures developed by Heuer, 1995. This analysis considered packer test data along the entire tunnel length, as opposed to, dividing the tunnel into a north and south drive. The histogram of this data is shown in Figure 2. The new estimated or corrected steady state groundwater inflow was 1465 gpm. The results of this analysis more closely approximate the actual inflows of the tunnel. The reason for this discrepancy is interpreted to be that the packer test data from each tunnel drive did not adequately describe the full range of hydraulic character of the rock mass. Possibly due to an unintentional bias superimposed in the data or a lack of adequate packer test data in each separate drive. In other words, because of the limited or reduced number of packer tests, the extreme end of the histogram representing high permeability values were not measured.

Nancy Creek Tunnel Project

The Nancy Creek Tunnel is constructed in the same rock formation as the Chattahoochee Tunnel. A total of 178 packer tests were performed in the rock formation. An analysis using Heuer's procedure was conducted as part of this paper was based on raw/original data and the histogram is shown in Figure 3. This analysis yields an estimated steady state inflow of 1198 gpm. The estimated value of 1198 gpm is approximately 14 percent below the actual inflow of 1395 gpm (City of Atlanta, 2001).

Milwaukee Tunnel Project

The Milwaukee Tunnel is constructed in a dolomitic rock formation where solution cavities or voids may be present. The analysis of this project was developed from 155 packer tests. Heuer's original estimated groundwater inflow, as documented in personnel correspondence, yields approximately 2100 and 600 gpm in the north and south tunnel drives. Therefore, Heuer's total estimated steady state groundwater inflow into the tunnel was 2700 gpm. The actual groundwater inflows were 2670 gpm, but a range of steady state inflow of 2400 to 3000 gpm was observed in the field data. Peak groundwater inflow of 3333 gpm was also observed. An analysis of the packer test data was conducted and the histogram of the data is presented in Figure 4. The new estimated or corrected steady state inflow determined from raw data is 2607 gpm, which is consistent with Dr. Heuer's original estimate (MMSD, 2001).

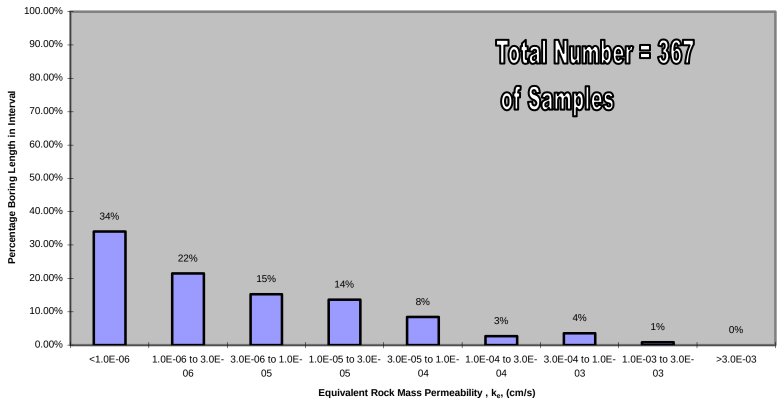

Figure 2 - Histogram of Packer Test Data from Chattahoochee Tunnel Project

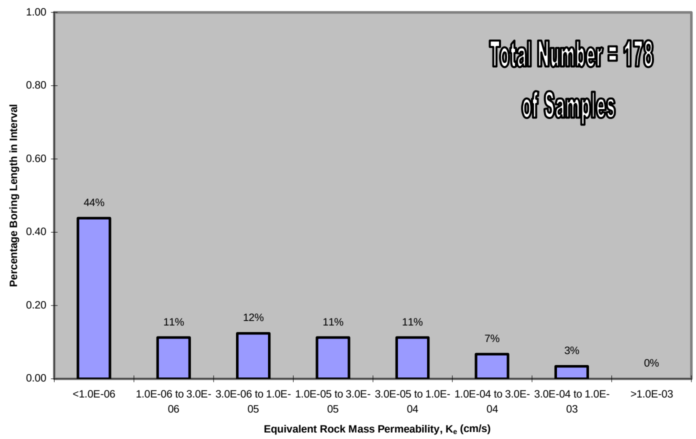

Figure 3 - Histogram of Packer Test Data for Nancy Creek Tunnel based on Raw Data

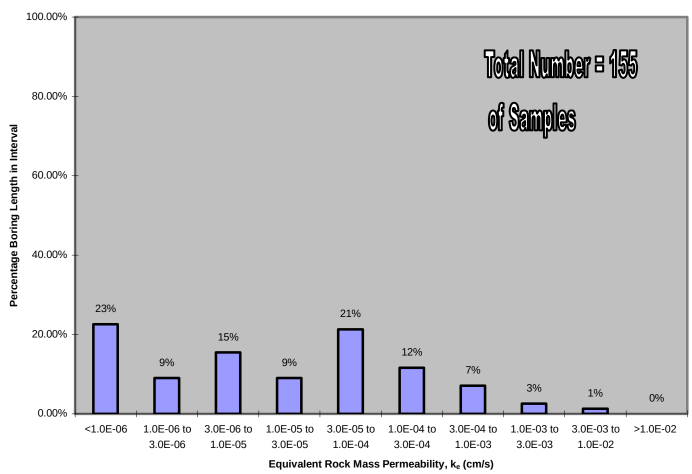

Figure 4 - Histogram of Packer Test Results Milwaukee NWSR

Log-normal Distribution and the High-End Permeability

These histograms presented above can generally be presented graphically as shown in the example of data from the Chattahoochee Tunnel in Figure 5. Generally, the shape of the data from these projects approximates a log-normal distribution. In the literature review, several researchers have observed this log-normal distribution in the various types of geological data including packer test data.

It has been observed by Raymer that the high-end permeability distribution depicted in packer test histograms can be used to account for large inflows into a rock tunnel. At a minimum, the extreme right-end of the log-normal distribution may be used to derive some measure of inflow, in some cases, enough to account for discrepancies in Heuer’s original groundwater inflow estimate. This extreme right-end of the log-normal distribution, although, representing a very small fraction of the total distribution, may account for a large proportion of the inflows. (Raymer, 2001).

Estimating Inflow from Small Sampling Programs

It appears from the results present thus far that underestimations occur in small sampling programs. In order to verify and evaluate the effect of small sampling programs on estimates of groundwater inflows into tunnels, modeling using statistical analysis was performed in which permeability values were randomly selected from data of a known case study. The case study that was selected for this analysis was the Chattahoochee Tunnel project. The Chattahoochee Tunnel project was selected because a large number of packer tests (e.g., 367) were available for analysis and the estimates obtained from the original analysis using Heuer’s 1995 procedure, closely approximated the actual inflow values recorded in the field.

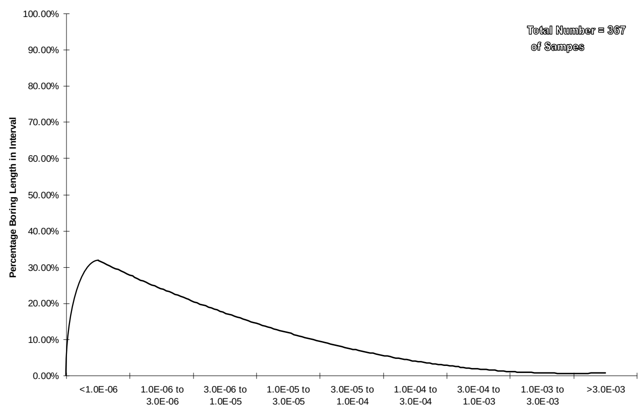

Figure 5 – Example of the General Shape Distribution of the Data from the Chattahoochee Tunnel Project

Random permeability values were selected from the population of 367 packer tests. A random number generator from Microsoft Excel software was used to select a permeability value from the original population. The total number of samples collected from the population was gradually reduced in 10 percent increments beginning at the 90 percent and ending at the 10 percent interval. Four iterations were completed for each sample interval. The results are summarized in Table 1. As shown in this table, the results indicated that as the number of packer tests is reduced in the analysis, the standard deviation consistently increases and the coefficient of variation (i.e., standard deviation divided by the mean of the four runs) also increases. For example, the standard deviation of the 90 percent sample interval to the 10 percent sample interval ranges from 90 to 599 and the coefficient of variation ranges from plus or minus 6 to 41 percent.

Monte Carlo Simulation Modeling for the Nancy Creek Tunnel

In order to verify the trend of the coefficients of variation or statistical errors observed in the inflow estimates derived from sampling a portion or fraction of the data from the Chattahoochee Tunnel Project, another model was developed for the Nancy Creek Tunnel Project. This model was constructed using a Monte Carlo simulation program called @Risk. The program can simulate a true log normal distribution if the mean (e.g., average) and the standard deviation are known. The program generates randomly selected values along the curve of the log normal distribution.

The program generated a model using the mean and the standard deviation from the recorded 178 permeability values of the Nancy Creek Tunnel project. The first step in generating the model was to identify the number of simulated values whose resultant closely approximates the actual inflows observed in the Nancy Creek Tunnel project. This number would determine the "ground truth" or true average inflow for the model. A number or data set of 1000 simulated values was selected to provide a representation of the average inflow into the tunnel model. A total of twenty iterations or runs were performed.

The results of the analysis produced a mean or average inflow into the tunnel model of 1443 gpm with a coefficient of variation of 13 percent. The model with a population of 1000 simulated values closely approximated the actual inflow observed in the Nancy Creek Tunnel of 1395 gpm. It appears that a data set of 1000 selected simulated values provided a reasonable accurate representation of inflows for the Nancy Creek Tunnel project. For the data set of 1000 simulated values, a confidence interval of 68 percent is obtained from the mean of 1443 gpm plus or minus 13 percent and a confidence interval of 95 percent is obtained from a mean of 1443 gpm plus or minus 26 percent.

Subsequently, additional simulations were performed using data sets of 400, 300, 200, 178, 150, 100 and 50 simulated values. These simulations with varying data sets sizes represented sampling from the model population of 1000 simulated values. Again, a total of twenty iterations or runs were performed. The results of these simulations produced average simulated inflows for the above data sets of 1516, 1510, 1504, 1504, 1630, 1724 and 1850 gpm with coefficients of variation of 38, 24, 33, 40, 70, 60, and 101 percent. Generally, the coefficients of variation increased as the sample size were reduced. It should be noted that estimates from individual runs could sometimes produce reasonable estimates from small data sets such as 50 and 100, although this occurrence was not likely In particular, it should be noted that underestimations occurred frequently

Table 1
Summary of Random Number Analysis
Optimization of Packer Tests - Chattahoochee Tunnel Project

Orginal Packer Test Population Fraction/Percent	**1.0/100%**
# of Packer Test	**367**
Actual Inflow/Estimted Inflow (Heuer's Proc.)	**1427/1465**
Difference betw. Actual vs. Estimated	**38 or 2.6%**

Sample Proportion/Percent	**0.9/90%**				**0.8/80%**				**0.7/70%**			
Run Number	Run 1	Run2	Run 3	Run 4	Run 1	Run2	Run 3	Run 4	Run 1	Run2	Run 3	Run 4
# of Packer Tests	327	329	333	324	303	277	290	290	256	263	264	253
Estimated Inflow w/o End Addition	1614	1538	1412	1455	1602	1638	1390	1262	1431	1611	1232	1649
Mean	1505				1473				1481			
Variance	8040				31759				36542			
Std. Deviation	90				178				191			
Coefficient of Variation	**6%**				**12%**				**13%**			
Average Population	328				290				259			

Sample Proportion	**0.6/60%**				**0.5/50%**				**0.4/40%**			
Run Number	Run 1	Run2	Run 3	Run 4	Run 1	Run2	Run 3	Run 4	Run 1	Run2	Run 3	Run 4
# of Packer Tests	221	221	225	233	192	172	183	180	157	138	161	161
Estimated Inflow w/o End Addition	1872	1462	1264	1278	1274	1383	1743	1887	1691	1061	1712	1713
Mean	1469				1572				1544			
Variance	80321				84330				103894			
Std. Deviation	283				290				322			
Coefficient of Variation	**19%**				**20%**				**22%**			
Average Population	225				182				154			

Sample Proportion	**0.3/30%**				**0.2/20%**				**0.1/10%**			
Run Number	Run 1	Run2	Run 3	Run 4	Run 1	Run2	Run 3	Run 4	Run 1	Run2	Run 3	Run 4
# of Packer Tests	105	118	108	107	71	81	71	65	39	37	38	31
Estimated Inflow w/o End Addition	1306	1532	1680	879	2348	1468	1159	1530	1585	1385	417	1756
Mean	1349				1626				1286			
Variance	121933				257851				358421			
Std. Deviation	349				508				599			
Coefficient of Variation	**24%**				**35%**				**41%**			
Average Population	110				72				36			

in small data set of 50 and 100, whereas, underestimations rarely occurred in larger data sets of 1000 and 400.In addition, the results from the data with 1000 simulated values showed that very few estimates were below 1300 gpm indicating that underestimations were less likely to be observed. The overall trend in the estimates shows greater uncertainty with smaller packer testing programs.

Monte Carlo Simulation Modeling for the Milwaukee Tunnel

A model was constructed for the Milwaukee tunnel project using a true log normal distribution with a mean and standard deviation that was determined from the 155 permeability values obtained in the field. The Monte Carlo simulation program called @Risk was used to develop the model. As before, the model was first constructed with 1000 simulated values to establish a ground truth or representative value of the true inflow into the tunnel based on a log normal distribution. A total of twenty iterations or runs were performed. The results of this analysis produced a mean inflow of 3252 gpm with a coefficient of variation of 19 percent. This value closely approximates the actual high inflow value of 3000 gpm. The difference between the model mean and the actual high inflow was 8.4 percent. For the data set of 1000 simulated values, a confidence interval of 68 percent is obtained from the mean of 3252 gpm plus or minus 19 percent and a confidence interval of 95 percent is obtained from a mean of 3252 gpm plus or minus 38 percent.

Additional simulations were performed on data sets of 400, 300, 200, 155, 100 and 50. These simulations with varying data set sizes represented sampling from the model population of 1000 simulated values. The average simulated inflows for the above data sets were 3169, 3627, 3613, 3824, 3220 and 3767 gpm with coefficients of variation of 30.3, 43.4, 48.1, 58.7, 65.2 and 102.6 percent. Once again, the coefficients of variation or statistical error increased as the model sample sizes were reduced. As in the case of the Nancy Creek model, estimated inflows observed in the model with 1000 simulated values shows very few underestimations of inflow, in fact, the lowest estimated value for inflow was 2462 gpm. The highest estimated value of inflow was 4528 gpm. In comparison, the data set of 50 simulated values produced a high inflow estimate of 19,295 gpm and several underestimations of inflow below 1900 gpm.

Monte Carlo Simulation Modeling for the Chattahoochee Tunnel

Finally, a model was generated for the Chattahoochee tunnel project. The model was constructed with an assumed true log normal distribution with a known mean permeability and standard deviation from the 367 permeability values derived from field measurements.

A total of twenty iterations or runs were performed in this analysis. The results of the analysis for 1000 simulated values produced a mean inflow estimated of 1658 gpm, which closely approximates the high inflow estimate with the high end addition of 1633 gpm presented. The coefficient of variation of the 1000 simulated values was 24 percent. The difference between the model mean and the estimated inflow with high end addition was 1.5 percent. The difference between the actual inflow values measured in the field and the mean inflow estimate from the 1000 simulated values was 231 gpm or 16 percent. This difference is well within the margin of error defined by the coefficient of variation of 24 percent. For the data set of 1000 simulated values, a confidence interval of 68 percent is obtained from the mean of 1658 gpm plus or minus 24 percent and a confidence interval of 95 percent is obtained from a mean of 1658 gpm plus or minus 48 percent.

Additional simulations were performed on data sets of 400, 300, 367, 200, 100 and 50. Again, these simulations with varying data sets sizes represented sampling from the model population of 1000 simulated values. The average simulated inflows for the above data sets were 1465, 1725, 1844, 1836, 1699 and 2222 gpm with coefficients of variation of 15, 37, 55, 67, 98 and 206 percent. Once again, the coefficients of variation or statistical error increased as the model sample sizes were reduced. In comparison to Nancy Creek and Milwaukee, the Chattahoochee model with data set of 1000 showed very few estimates below 1300 gpm and the highest inflow estimate of 2230 gpm. Whereas the data set with 50 simulated values produced several estimates below 900 gpm and the highest inflow estimate was 16,444 gpm.

CONCLUSION

Models were created of true log normal distributions using the means and variances of permeability values from the Nancy Creek, Milwaukee and the Chattahoochee Tunnel projects. These models used Monte Carlo simulations of varying sample sizes. The results of this analysis indicated that uncertainty (i.e., statistical errors) increased in the inflow estimates as the sizes of the sampling programs were reduced. In summary, small packer testing programs could produce larger statistical errors in steady-state inflows. If the inflows from the high-end permeability range of the histogram for a given project were taken into consideration in Heuer's original estimate, then good estimates of steady-state groundwater inflow could be derived in many cases where the radial flow condition existed. It has been shown that modeling can be used as an effective tool to incorporate high-end permeability data in groundwater inflow estimates.

REFERENCES

[1] City of Atlanta, "Geotechnical Data Report – Nancy Creek Tunnel", Prepared by Jordan, Jones, and Goulding, Project No. 2061.712, 2001.

[2] City of Atlanta, "Geotechnical Data Report – West Area Combined Sewer Overflow (CSO) Storage Tunnel Facilities", Prepared by Jordon, Jones and Goulding et al, 2003.

[3] Cobb County Water System, "Geotechnical Baseline Report – Chattahoochee Tunnel Project", Prepared by Jordan, Jones, and Goulding, 2000.

[4] Goodman, R. E., D.G. Moye, A. Van Schalkwyk, and I. Javandel, "Groundwater inflows during tunnel driving", Annual Meeting of the Association of Engineering Geologists, p. 39-56, 1964.

[5] Heuer, R. E., "Estimating rock tunnel water inflow", in G.E., Williamson and I.M. Gowring, Proceedings from Rapid Excavation and Tunneling Conference, p. 41-60, 1995.

[6] Heuer, R.E., "Estimating Rock Tunnel Water Inflow – II", Proceedings from Rapid Excavation and Tunneling Conference, p. 394-407, 2005.

[7] Milwaukee Metropolitan Sewerage District (MMSD), "Geotechnical Baseline Report for the Northwest Side Relief Sewer, Contract No. C03003C01", 2001.

[8] Raymer, J. H., "Predicting groundwater inflow into hard-rock tunnels: estimating the high-end of the permeability distribution", in W.H. Hansmire and I.M. Gowring. Proceedings: Rapid Excavation and Tunneling Conference, p. 1027-1038, 2001.

[9] Vanarelli, Mark J., "Improvements to the Current State of the Practice in Steady-State, Groundwater Inflow Estimates into Rock Tunnels based on the Application of Statistical Analysis Methods of Packer Test Data obtained from Exploratory Borings During Geotechnical Site Investigations", PhD Thesis, Colorado School of Mines, 2007.