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LETTER REGARDING SLUG TESTS DONE BY ABB ENVIRONMENTAL SERVICES NSB KINGS BAY GA
4/16/1993
U S DEPARTMENT OF THE INTERIOR

United States Department of the Interior

GEOLOGICAL SURVEY
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April 16, 1993

Mr. Ed Lohr
Southern Division Naval Facilities Engineering Command
2155 Eagle Drive, P.O. Box 190010
North Charleston, SC 29419-9010

Dear Ed:

This letter is in response to your request made by phone on April 6, regarding transmission of review comments on slug tests done by ABB Environmental Services (ABB) on wells at the Kings Bay Sub Base. I have enclosed copies of selected pages from the report in which the tests are described (ABB Technical Memorandum No. 1, June 1992, and referred to in this letter as TM1) because I evidently have your only copy. For simplicity, I have marked these pages, and copies of plots I made, as figures in this letter. The figures are in stapled packets A, B, C, etc., and are numbered sequentially within each packet.

The points made during our phone conversation were: (1) the reference datum used for measurement of water-level recovery during the tests is not explained, and this causes uncertainty about correctness of data input for slug-test analysis, and; (2) the method of fitting the regression line to recovery data probably results in lateral hydraulic conductivity (Kh) values for the shallow aquifer that are too high because early data, rather than later data, were used. This second point has to do with flow from the sand pack in the wells, rather than flow solely from the aquifer. Each point is addressed in the enclosed comments.

Sincerely,

Bud Zehner

Harold H. Zehner
Hydrologist

Enclosures

cc: Ground Water Specialist, WRD, SR, Norcross, GA

Charts

#212

USGS comments on slug tests and slug-test analyses
done by ABB at Kings Bay Sub Base

The method of analysis used by ABB is that of Bouwer and Rice (1976). Cited references are listed at the end of these comments. For this method, as well as others, important measurements are well and aquifer dimensions, and rates of water-level recovery. The well dimensions are described in TM1 and shown as the highlighted parts of figures A1 through A4. The aquifer-test descriptions and methods of analysis (including ABB use of AQTESOLV software) are summarized on figures A3 and A5. Ranges of ABB aquifer-test results are in highlighted parts of figures A6 through A9. All wells have 8-inch diameter hole, 2-inch diameter casing, screen of about 10-foot length, sand pack extending from near the bottom of the screen to a short (varies) distance above the top of the screen, and bentonite & cement seal above the sand pack (fig. A4).

The test of well 11-3 is used as an example. Well data and water-level recovery data are shown on figures B1 through B5, which are copies from Appendices A and B in the TM1 report. Shown on Figure B1 are well dimensions, including a screen length of 10 feet, bottom of the screen at depth 13 feet. The water-level (at the time of well construction?) is shown within the screened and sand-packed interval at a depth of 6 feet. Water-level changes during the slug test of this well reflect the lateral hydraulic conductivity (Kh) of the sand pack and the aquifer.

Information necessary for analysis the test data at well 11-3 (fig. B2) includes the well radius of 0.33 feet (4 inches) and casing radius of 0.1667 feet (2 inches). The casing radius shown on figure B2 and used by ABB is twice that shown on figure B1, probably to account for the water that will flow from the sand pack during the test (though not stated as such in the TM1 report). An equivalent casing radius of 2 inches is required to yield the same volume of water contained in a sand pack of 20 percent effective porosity that surrounds a casing of radius 1 inch in a hole of radius 4 inches, plus the volume of water in the 1-inch radius casing.

The aquifer thickness, well-screen length, and height of water in well 11-3 are all shown on figure B2 as 6.94 feet, which are interpreted to mean that the water level is 6.94 feet above the bottom of the 10-foot screen. Without additional information or description of aquifer boundaries, these are the dimensions that probably should be used with the Bouwer and Rice method to estimate Kh. As more lithostratigraphic information becomes available, a more accurate aquifer thickness could be used to refine the Kh values. The "A,B,C" parameters used in the Bouwer and Rice method are obtained graphically; values for A and B are zero when aquifer thickness is equal to the distance from the water table to the bottom of the well, which is considered to be the condition for all analyses in the TM1 report.

The water-level recovery data for well 11-3 (figs. B3 and B4) include measurement times corresponding to "observed" water levels. The application, or significance, of the "calculated" values used in the ABB analysis is uncertain, but differences between "observed" and "calculated" values are only about 1 foot. Only the "observed" values are used herein when referring to water levels. A problem in using the recovery water levels is that they evidently were obtained by measurements from some undefined reference datum. The relation of the 6.94-foot height of water in well 11-3 and the depth to the pre-test water level are not explained in TM1.

The recovery values at well 11-3, as referenced to the undefined datum, were apparently used in the ABB analyses. The beginning Y0 value shown on figures B4 and B5 is 10.02 feet, and probably represents the value of the initial water level after removal of the slug. The drawdown, as listed and graphed, does not become zero at the end of the test. If the depth to water at well 11-3, as referenced to some undefined datum near ground level, was 10.28 feet immediately after withdrawal of the slug (the first "observed" water level), and the water level recovered to a pre-test level of 8.16 feet, then the undefined datum is probably at a height of about 8.16 feet. The appropriate Y0 in this case would be 10.28 - 8.16 = 2.12 feet, not 10.02 feet.

The slope of the solution line used in the Bouwer and Rice method of slug-test analysis is obtained from the ratio of the initial drawdown (Y0), at the time the test started, to a value (YT) selected from the unrecovered part of the drawdown curve at a later time. Based on the recovery plot shown on figure B5, the slope computed by ABB was the ratio of the initial depth to water from an undefined reference datum to the depth to water at a later time from the undefined reference datum. These two slopes (the slope of Bouwer and Rice and the slope computed by ABB) are not equal and the slope obtained by the ABB method cannot be correctly applied to the Bouwer and Rice method for computing Kh.

The slug used by ABB was a 5-foot long, "0.75-inch diameter" (the TM1 report does not say I.D. or O.D.) pipe capped at both ends (fig. A3, TM1 report. A water-level rise of 2.1 feet would be produced in a 2-inch I.D. casing by a 5-foot long, 1.3-inch O.D. slug. Considering caps on the pipe ends and an outside dimension, the effective diameter of the slug may have been about 1.3 inches. Therefore, the initial drawdown Y0 of 2.12 feet is probably correct. Also, the "Y0" of 10.02 feet used by ABB could be correct, if a reference datum is also used for correction to the likely true Y0 of 2.12 feet.

An explanation of the use of a reference datum should have been given in the TM1 manuscript or appendices, and a new plot made, if a datum correction were made by the AQTESOLV software. However, I asked one of the ABB personnel in the Knoxville office about this point, and she said that the water-level values, as used for slug-test analysis, were not correct. The values are to be corrected in a following report.

The relative drawdown values shown in the TM1 report were assumed to be correct. Accordingly, analyses of the slug-test data, as described below, were continued without waiting for the revised report. An initial adjustment for the undefined reference datum was made by assuming that recovery was complete. The water-level value at the end of the test, which is probably the height of the reference datum, was subtracted from all other values of water-level recovery to obtain the corrected recovery heads throughout the duration of the test. Support for this approach is indicated by ABB data from tests on the other wells at the Kings Bay site, which also show initial drawdowns of about 2 feet after adjustment, and stable water levels at the ends of the tests.

The position of the solution line on the data plot of well 11-3 (fig. B5), and the positions of similar lines used by ABB on other plots, is of particular interest when applying the Bouwer and Rice method. ABB apparently used extrapolation of a straight solution line through early data to obtain the Y0 value of 10.02 feet at the axis intercept at time 0 (fig. B5), as well as for the water level YT at a later time (not shown by ABB). The early data probably represent change in head due to flow from the sand pack, rather than to flow from the aquifer.

Two USGS plots of data from well 11-3 were made, after adjusting the reported recovery data as explained above. The first plot (fig. B6) shows the early data in detail (before about 0.35 minute), and was used to determine a straight solution line through early data. The line was used to obtain, by extrapolation, a Y0 value of 1.8 feet at time 0 and the head YT of 0.001 feet at 1.25 minutes. The second plot (fig. B7) shows both early and later data, and shows use of a solution line through the later data to obtain a Y0 of 0.2 feet at time 0 and YT of 0.001 feet at 3.3 minutes.

The heading of each of the early and later data plots (figs. B6 and B7) show: (1) the -8.16 USGS value used to adjust the water-level data given by ABB; (2) the L, H, and D values (all 6.94 feet) that, respectively, are measurements of the length of the well open to the saturated part of the aquifer, distance from the water table to the bottom of the well, and the saturated thickness of the aquifer, and; (3) the computed Kh, in centimeters/second (cm/s), determined by use of the Bouwer and Rice method of analysis. Other data used in these analyses, were well radius 4 inches, and casing radius 2 inches. A 20 percent effective porosity was used to account for a sand pack outside a casing of radius 1 inch.

Bouwer (1989) suggests using the extrapolation, as shown on figure B7, for determining Kh when water drains from a sand pack during a test. The location of the change in slope, and the direction of slope change, during the test are used, respectively, to identify the beginning of later data and to determine the relative permeability contrast between the sand pack and the aquifer. At well 11-3, the sand pack is more permeable than the adjacent aquifer. Emphasis on the early data for positioning a solution line may mean that the Kh computed by ABB is representative of the sand pack rather than the aquifer. The ABB plots of water-level recoveries at all other sites tested (figures C1 through C11) indicate, by the linear extrapolation and Y0 values shown on the plots, that early data were used in the analyses.

The USGS plots of other ABB data, with scale-expanded early data (figures D1 through D11), and both early and later data (figures E1 through E11), show Y0 values and other information used in the Bower and Rice method of analysis. Use of the early data to position a solution line, as shown in figures D1 through D11, probably results in a Kh for the sand pack. Use of the later data to position a solution line, as shown in figures E1 through E11, probably results in a Kh for the aquifer.

All information used for the USGS analyses of the early recovery data, and results of the analyses, are listed in table 1: parameters are as previously explained, except that TR is transmissivity and RE is the "effective radius". Bouwer and Rice explain the "effective radius", as the distance, from the center of the well, within which most water flows to the well. All information used for analyses of the later recovery data, and results of the analyses, are listed in table 2.

A plot of the Kh values determined by the USGS (fig. F1) illustrates the differences in the results when using early vs later data. The A/B plot (fig. F1, scale on right) shows the ratios of the two Kh values; use of early data results in Kh values that are generally about 5 times greater than Kh values determined using later data. The difference is 10 to 15 times greater for two tests at site 16.

The Kh values determined by USGS, using early and later data, were plotted with Kh values determined by ABB (fig. F2). The ABB values are from figures B5 and C1 through C11 in the TM1 report. Results shown on this plot are inconsistent. Many of the ABB values, evidently computed from early data, are similar to USGS values computed from later data. Also, several of the ABB values are about 2 to 3 times less than the USGS values obtained using later data. The ABB values of Kh should be consistently greater than the Kh values computed by USGS from later data, if previous explanations regarding computation results using early versus later data are valid.

The probable explanation for the inconsistencies in Kh values determined by USGS and ABB (fig. F2) is that ABB values were computed using incorrect recovery slopes; that is, data used to locate solution lines had not been adjusted for the reference datums. Hopefully, the revised ABB report will include both datum-adjusted values and solution lines fitted to later data, rather than to early data. If the water-level values selected for the time t during the recovery (not provided in the TM1 report) were included in the revised report, a step-by-step check of their results could be made. Also, the method of analysis is sensitive to RC, radius of the casing, and RC is partly determined by the effective porosity of the sand pack. The determination of the effective porosity of the sand pack should be explained in the revised report.

The remainder of the comments are in regards to slug testing in general, and to specific problems that might be expected at the Kings Bay Sub Base, rather than to further review of the TM1 report. The interpretation of data obtained from the slug tests, though seemingly straigtforward, entails a number of pitfalls that may result in significant error.

The volume of aquifer investigated is limited in slug testing. The effective radius, RE, from which most water flows to the well during the test, has a range of only 3 to 4 feet for wells at Kings Bay (table 2). Aquifer characteristics could be different at greater distances that are not tested.

Most of the water-level recovery in the slug tests at Kings Bay evidently results from drainage of the sand pack. This is be due to sand-pack dimensions, the contrast between sand pack and aquifer permeability, and perhaps, to the small (about 2 feet) drawdown during the tests. The fit of the solution line to later recovery data shows that only a few tenths of a foot of the total recovery head can be used to determine the Kh of the aquifer. The error associated with tests of such small aquifer stress is uncertain. Moreover, the delay in drainage of the sand pack does not result in the instantaneous drawdown in the aquifer that is required in the slug-test method.

Slug-test results are very sensitive to the casing radius, RC, because Kh is directly proportional to the square of RC. Therefore, Kh is affected when an adjustment is made to RC for effective porosity of the sand pack. For example, if the well radius, RW, is 4 inches and the RC (unadjusted for sand pack) is 1 inch, as are the dimensions of the wells tested at Kings Bay, an estimate of 30 percent effective porosity would give an adjusted RC of 2.35 inches. An estimate of 10 percent effective porosity would give an adjusted RC of 1.58 inches. The ratio of the determined Kh values, using each porosity, is increased by the square of 2.35 to the square of 1.58, which is a factor of 2.2.

The sensitivity of Kh to differences in RW is not as great as for differences in RC for the Bouwer and Rice method of analysis because the natural log, rather than the square, of RW is involved. Moreover, the relation is inversely proportional. The later data from the test of well 11-3 (fig. B7) may be used as an example. The Kh determined by USGS for ABB data at well 11-3 was 3.68E-3 cm/s, given an RW of 4 inches and adjusted RC of 2 inches. If the RC of well 11-3 were doubled from 2 inches to 4 inches, the Kh value would quadruple. However, if the RC were held at 2 inches and the RW doubled from 4 to 8 inches, the Kh value would be 2.78E-3 cm/s. The increase in RW, therefore, causes a decrease in Kh by the ratio of 3.68E-3 / 2.78E-3 = 1.3.

Several examples of realistic error in Kh for Kings Bay data may be examined, again using the later data from well 11-3. Data previously given were: RW of 4 inches, adjusted RC of 2 inches (20 percent effective porosity of the sand pack), and Kh of 3.68E-3 cm/s. Suppose the RW is not the same radius of the auger, but collapsed (only slightly) to give an RW of 5 inches. Also, suppose the 20 percent porosity of the sand pack were actually 30 percent. The adjusted RC is then 2.35 inches and the computed Kh is 4.67 E-3 cm/s. The Kh ratio for this example is 4.67E-3 / 3.68E-3 = 1.3. The small difference, at least in part, is because errors are partially compensating. However, if the hole collapsed to 5 inches and the porosity were 10 percent instead of 20 percent (giving an adjusted RW of 1.58 inches) the Kh would be 2.11E-3 cm/s. The ratio of Kh values for this last case is therefore larger; 3.68E-3 / 2.11E-3 = 1.7.

Slug testing is probably a good method for obtaining Kh values at Kings Bay because it is rapid, and many tests can be done at low cost. The disposal of possibly contaminated water is not a concern in slug testing, as it would be with aquifer tests by pumping. Updated slug-test data to be included in the revised ABB report should be useful, but, considering the complications from drainage of the sand pack and inherent errors in the method of analysis relating to well construction, investigators should realize that Kh values from slug testing could easily be in error by a factor of about 2 to 3, and possibly more.

Bouwer, H., and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research v. 12, no. 3.

Bouwer, H., 1989, The Bouwer and Rice slug test - an update: Ground Water v. 27, no. 3.