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Preliminary measurements of stress-dependent hydraulic conductivity of Santa Fe Group aquifer system sediments from the 98th St core hole, Albuquerque, New Mexico

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Abstract

Measurements made on undisturbed and recompacted samples from the 98th Street core hole in western Albuquerque show that the hydraulic conductivity of Santa Fe Group sediments is sensitive to the effective confining stress. The hydraulic conductivity of consolidated, undisturbed, and typically fine-grained sediments decreased two to three orders of magnitude between vertical effective stresses of about 50 and 1,000 kPa. That of unconsolidated, recompacted, and generally more sandy samples decreased by less than one to two orders of magnitude over about the same magnitude of effective stress change. Bulk density (and its surrogates, void ratio and porosity) appears to be the single most important controlling factor in the reduction of hydraulic conductivity. A simple regression model shows that changes in porosity can account for about three-fourths of the variability of hydraulic conductivity extrapolated at zero confining pressure. The results of our work imply that heavy ground water pumping may measurably reduce the hydraulic conductivity of the Santa Fe Group aquifer system in the vicinity of large water wells, and also that changes in effective stress (for example, due to burial and tectonic uplift over geologic time or heavy pumping over human time spans) may result in a nonlinear increase in the basin-scale hydraulic conductivity anisotropy.

Introduction

Purpose and scope

The City of Albuquerque, in collaboration with the U.S Geological Survey and the New Mexico Bureau of Mines & Mineral Resources, in late 1996 drilled a 457-m-deep core hole on 98th St north of I–40, about 6.5 km west of downtown Albuquerque. The lithology of the strata penetrated and geologic setting of the core hole are described in Allen et al. (this issue) and Stone et al. (1997), and the regional hydrogeologic setting is summarized in Connell et al. (this issue) and Hawley et al. (1995).

Core from the 98th St hole was obtained using a mud rotary drilling rig with a wireline innerbarrel core recovery system (B. D. Stone, 1997, written comm.). Cores were described in the field, wrapped in plastic film, and then placed in PVC pipe and sealed with duct tape. The depth to water upon completion of the borehole was 115.2 m (B. D. Stone, 1997, written comm.), and all but two of the samples that we tested came from the vadose zone. The hydraulic conductivity of samples taken from the core was measured using consolidation tests on undisturbed, primarily fine grained samples and constant head tests under confining pressure in a triaxial cell for recompacted, primarily coarse grained samples, in order to gain insight into the influence of changing effective stress on the magnitude of hydraulic conductivity. Values of hydraulic conductivity were measured for flow perpendicular to original stratification in the consolidation tests and perpendicular to recompacted lifts in the triaxial tests. Grain-size-distribution parameters were also calculated for the coarse-grained samples in order to investigate empirical relationships between grain size, porosity, and hydraulic conductivity. This paper describes our methods and summarizes our results; complete test results are available in Haneberg et al. (1998).

Understanding the relationship between hydraulic conductivity and effective stress will become increasingly important as computer models of ground-water flow in the basin become more sophisticated because the changes in effective stress, for example as induced by heavy ground-water pumping, may decrease hydraulic conductivity, porosity, and specific storage in much the same way as does burial and compaction of sediments (Haneberg, 1995; Helm, 1984). Although the data presented in this paper are preliminary, by virtue of the limited number of samples tested and the physical limitations of our laboratory equipment, they do suggest that the hydraulic conductivity of Albuquerque Basin sediments is strongly dependent on the level of effective stress to which they are subjected.

Previous work

The general relationship between effective stress or confining pressure and matrix hydraulic conductivity (or, in more general terms, permeability) has been observed in studies of modern-day accretionary prisms (e.g., Fisher and Zwart, 1996; Maltman and Bolton, 1996); in laboratory tests of fault gouge, sheared sediments, and sheared sedimentary rock (e.g., Morrow et al., 1984; Dewhurst et al., 1996; Zhu and Wong, 1997); and in petroleum reservoir development (e.g., Teufel, 1992; Rhett and Teufel, 1992). Fracture permeability, which is also highly stress dependent, has also been incorporated into ground-water flow models of faulted hydrogeologic systems (e.g., Roberts et al., 1996; Zhang and Sanderson, 1996). In most studies of ground-water flow, however, matrix hydraulic conductivity is considered to be independent of the state of stress, and the compressibility of aquifers is conventionally incorporated through the use of the specific storage term in the equations describing unsteady ground-water flow (e.g., Bear, 1972). Yeung et al. (1993) did, however, perform an analysis of the effects of pressure-sensitive permeability on ground-water flow in aquifer systems.

We know of no previous studies of stress-dependent hydraulic conductivity of Albuquerque Basin sediments. Thorn et al. (1993) tabulated transmissivity values for City of Albuquerque water wells producing water from the Santa Fe Group and, by assuming that the screen length approximated the effective aquifer thickness, calculated effective horizontal hydraulic conductivity values that ranged from 1×10^{-7} to 4×10^{-4} m/s. Kernodle et al. (1995) later used these data along with qualitative geologic constraints to derive a detailed three-dimensional hydraulic conductivity distribution for a basin-wide ground-water flow model. Detmer (1995 a,b) and Davis et al. (1993) conducted extensive air permeameter studies of Santa Fe Group sediments and found strong empirical relationships between hydraulic conductivity and depositional environment. Detmer found strong empirical relationships between various measures of effective grain size and hydraulic conductivity, but not between porosity and hydraulic conductivity. Sigda et al. (1996) conducted air permeameter studies in the vicinity of small faults in the Santa Fe Group and reported significant permeability decreases and petrographic changes between deformed and undeformed sediments.

Undisturbed samples

Procedure

The consolidated-state hydraulic conductivity of undisturbed and primarily fine grained samples from the 98th St core was measured using a standard consolidation apparatus. Note that the term “consolidation" is used differently by geologists and soil mechanicists. Geologists typically use the term to denote the process by which loose, disaggregated sediment is compacted and cemented to form rock. In soil mechanics, however, consolidation is conventionally used to described the reduction in volume of sediments as a consequence of water expulsion during compaction. Thus, to say that a specimen is consolidated means in soil mechanics terms only that it has equilibrated its density to a specified load, not that it has been transformed into a rock. In geologic terms, the sediments that we tested would be described as unconsolidated to poorly consolidated.

Samples were selected by visually examining the core, removing sections that appeared to be representative of the fine-grained portions of the core, and then wrapping the samples in plastic film to reduce dehydration. Because the core diameter was slightly less than the standard consolidation-test sample diameter of 6.3 cm (2.5 inches), we modified the consolidation apparatus to accept 5.1-cm-diameter (2.0-inch-diameter) disks of soil and trimmed the samples accordingly. Although the samples were moist and plastic to semiplastic, they were not saturated, and each sample was resaturated in the laboratory before testing consolidation. Applied stress levels for the first five tests were 48, 145, 339, 726, and 1,500 kPa and 27, 75, 172, 365, 753, 1,140, and 1,914 kPa for the final four tests. Consolidation coefficients were calculated using one of two standard methods: the logarithm of time method (for clayey samples) and the square root of time method (for gritty or sandy samples). Both methods are described in soil mechanics texts (e.g., Das, 1983). Void ratios were calculated from the change in thickness of the sample over each load increment, measured using a dial gauge affixed to the consolidation apparatus, and the consolidated-state hydraulic conductivity for each load increment was calculated from the rate of consolidation and excess pore-water pressure dissipation using (Das, 1983; Terzaghi, 1943)

$$K = \frac{C_v \gamma_w a_v}{1+e} \qquad (1)$$

where C_v is the coefficient of consolidation, γ_w is the unit weight of water, and e is the void ratio. Because the samples that we tested came from a vertical borehole in flat-lying sediments, the value given by equation (1) represents the vertical component of the hydraulic conductivity tensor. The coefficient of compressibility, a_v, is the change in void ratio relative to the change in vertical effective stress

$$a_v = -\frac{\partial e}{\partial \sigma'} \qquad (2)$$

which can be obtained as the local slope of the consolidation curve. Because of the limited range of the consolidation apparatus available, we were not able to apply loads high enough to measure preconsolidation stresses for the samples or the inferred in situ vertical effective stresses, so the measured hydraulic conductivity values are representative of the recoverable or elastic range of deformation. The unconfined compressive strength and shear strength of the samples were also measured using a pocket penetrometer and pocket shear-vane apparatus.

TABLE 1—Geotechnical properties for undisturbed samples from the 98th Street core hole.

Drive	Depth (meters)	Lithology	Compressive strength (kPa)	Shear strength (kPa)	Specific gravity of grains
20	38.3	silt	306	49	2.75
24A	45.8	silty sand	>431	27	2.68
37A	72.4	silty clay	396	69	2.71
38A	74.2	sand	26	nm[*]	2.66
40A	76.5	very fine silt	>431	81	2.75
4[†]	78.1	silt	>431	56	2.71
5[†]	95.8	fine sand	>431	156	2.65
90C	154.6	clay/silt	>431	156	2.70
93B	159.2	fine sand	nm[*]	nm[*]	2.66

[*] not measured.

[†] Core drives 4 and 5 were obtained from a second borehole at the same site; therefore, the drive numbers do not correspond with the others in this table.

Results

The basic geotechnical properties of the samples used for consolidation tests are in Table 1, and the corresponding hydraulic conductivity measurements are in Fig. 1. The drive numbers refer to the sequence of core runs or drives, with small numbers being closer to the surface than large numbers. Although there are some noticeable deviations, the logarithmic hydraulic conductivity and vertical effective stress data generally show strong linear relationships over the range of measurements, with goodness-of-fit values between 0.92 and 1.00. The slopes of the regression lines, which reflect the sensitivity of hydraulic conductivity to changing stress, vary between –1.21 and –1.90. Void ratio also decreased with increasing stress, and the relationships among void ratio, effective stress, and hydraulic conductivity for each of the nine samples are in Fig. 2.

Recompacted samples

Procedure

The unconsolidated-state hydraulic conductivity of recompacted samples from the 98th St core was measured in a triaxial cell using the constant-head method (e.g., Das, 1983). Samples that appeared to be visually representative of the sandy portions of the core were chosen for triaxial permeability testing, although we discovered that many of these samples had appreciable fine-grained components. Samples containing very coarse sand to granules were not selected in order to make sure that the typical grain size was much smaller than the diameter of the triaxial samples. We intended to use trimmed but undisturbed samples, but the sandy materials were brittle, and intact samples could not be removed from the core. Each sample was manually disaggregated and homogenized, then recompacted into a 7.6 cm long by 3.6 cm diameter cylindrical mold. Hydraulic conductivity was measured for flow parallel to the long axis of the sample (i.e., perpendicular to the direction of compaction).

Except for one sample from Drive 19, which will be discussed separately, the hydraulic conductivity was measured under confining pressures of approximately 69, 207, 345, 483, and 620 kPa. The head difference for all tests was 1.07 m, which produced an average pore-water pressure of approximately 10 kPa in the samples. We used tap water produced from wells on the New Mexico Tech campus as a permeant because we felt this tap water would be closer in chemical composition to Albuquerque Basin ground water than distilled water would be. Trials with smaller head differences produced infinitesimally small flow rates and would have resulted in unacceptably long test durations. Because the triaxial cell serves as a flexible walled permeameter in which the sample is encased in only a thin latex membrane, attempts to saturate the sample in an empty cell and a head difference in excess of a meter resulted in liquefaction of the sample. Therefore, we could not measure hydraulic conductivity values for zero confining pressure using the triaxial cell. Each confining pressure was maintained for only a short time, generally less than an hour, so the results obtained represent values for the unconsolidated state except for the sample from Drive 19. For the sample from Drive 19, hydraulic conductivity was repeatedly measured under a constant confining pressure of 483 kPa over a period of six days.

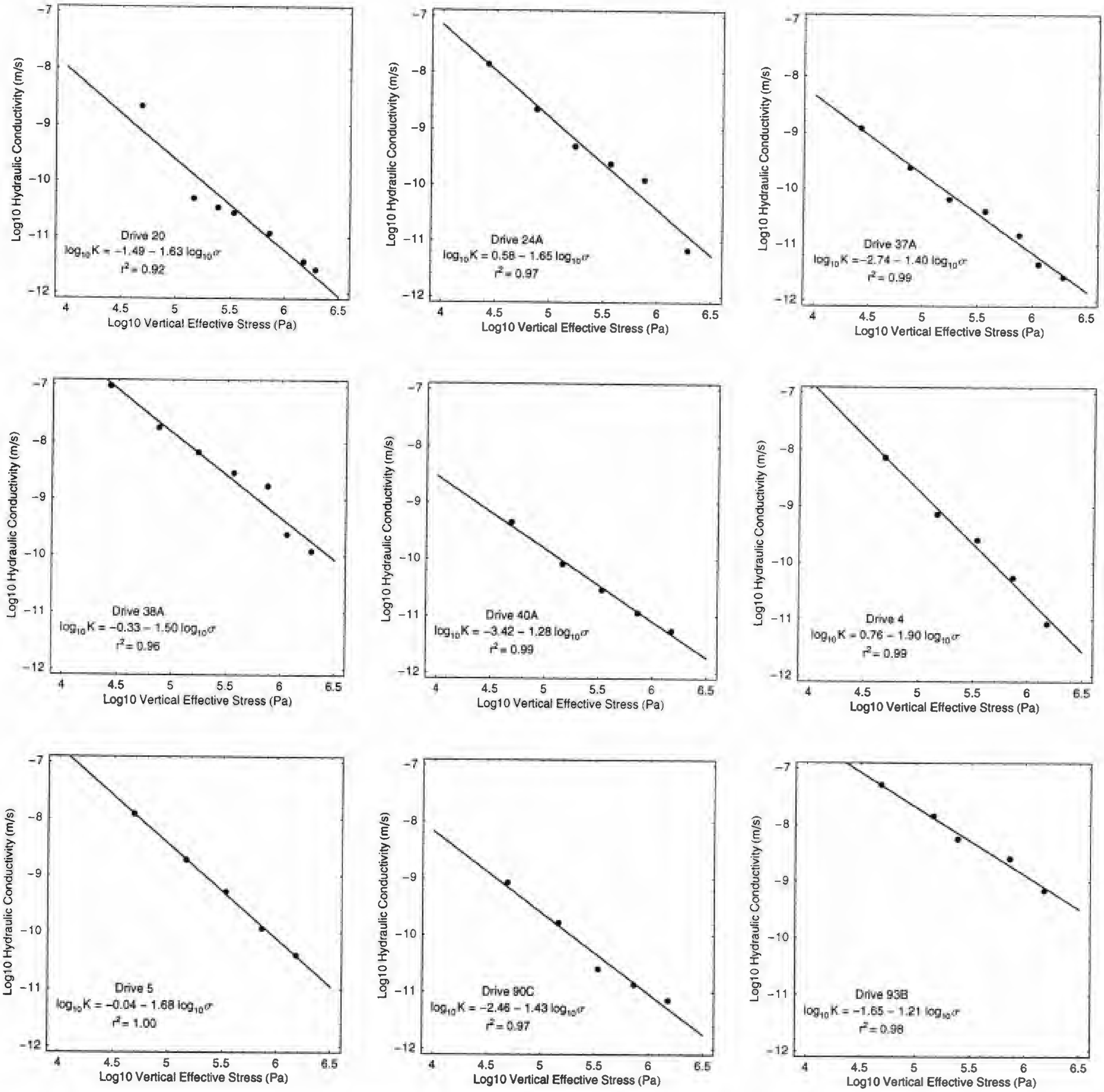

FIGURE 1—Changes in consolidated hydraulic conductivity as a function of vertical effective stress for nine undisturbed samples from the 98th St core obtained from pore pressure dissipation rates during consolidation tests. Geotechnical data for the samples are summarized in Table 1.

After the hydraulic conductivities of each sample were measured, the samples were dried and sieved to obtain its grain-size distribution, using sieves ranging from 0.075 mm (200 mesh) to 0.85 mm (20 mesh). The fraction passing the 200 mesh sieve was not differentiated into silt and clay fractions. On the basis of the results of the grain-size analysis, each sample was classified according to the Unified Soil Classification System (e.g., Hunt, 1986). We did not conduct Atterberg limit tests, and therefore USCS classes SM and SC (silty sand and clayey sand) were combined because liquid limits and liquidity indices are required to distinguish between them. Standard-grain-size distribution parameters calculated were: d_{10}, d_{30}, d_{60}, the coefficient of uniformity (Hunt, 1986)

$$C_u = \frac{d_{60}}{d_{10}} \qquad (3)$$

and the coefficient of gradation (Hunt, 1986)

$$C_c = \frac{d_{30}^2}{d_{60}\, d_{10}} \qquad (4)$$

The subscripted d values represent the grain diameter, in millimeters, that is coarser than all but the subscripted weight percent of the grains sampled. Another, nonstandard, grain-size-distribution parameter that Detmer (1995a,b) found a useful predictive variable in his study of permeability of Albuquerque Basin sediments is the Kruger effective grain diameter (Vukovic and Soro, 1992)

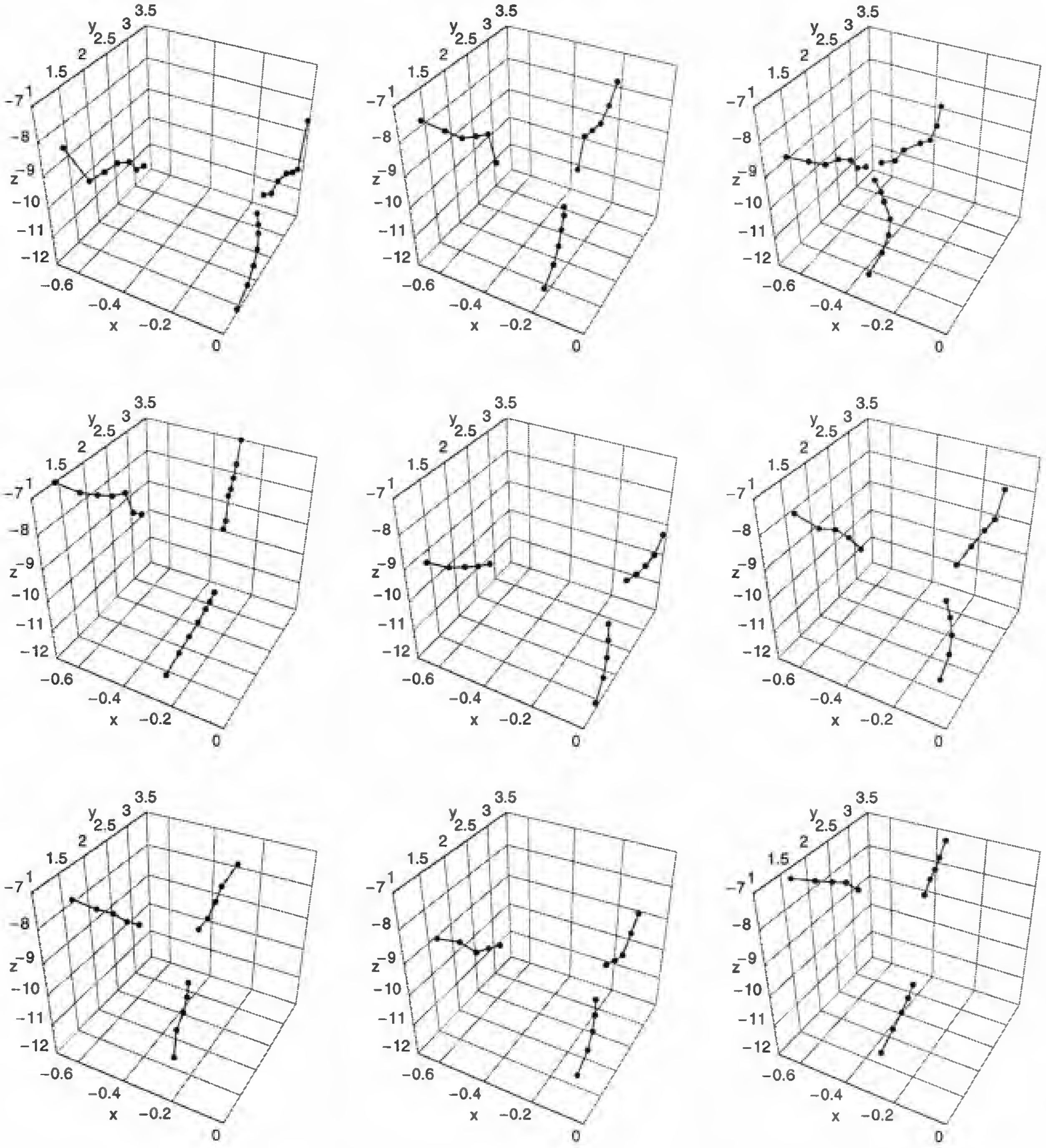

FIGURE 2—Relationships among hydraulic conductivity, void ratio, and vertical effective stress for the nine undisturbed samples. The x axes show $\log_{10}$ void ratio, the y axes show $\log_{10}$ vertical effective stress (kPa), and the z axes show $\log_{10}$ hydraulic conductivity (m/s). Each of the lines shown in each plot is a two-dimensional projection of the three-dimensional conductivity-void ratio-effective stress curve for that sample. The order in which the plots are presented is the same as in Fig. 1.

$$\frac{1}{d_e} = \sum_{i=1}^{N} \frac{g_i}{d_i} \qquad (5)$$

where g_i is the weight percentage of grains retained on the ith sieve, d_i is the mean grain diameter (in millimeters) of the corresponding fraction, and N is the number of sieves.

Results

Geotechnical properties for the sandy samples are in Table 2. All samples fell into either the Unified Soil Classification System SM/SC classes (silty sand and clayey sand) or were borderline between SM/SC and SP (poorly graded sand). Recompacted densities ranged from 1,726 to 2,023 kg/m^3, and the weight percentage of fines (< 200 mesh sieve or 0.075 mm) ranged from less than 8 to more than 35%. For samples in which the weight percentage of fines exceeded 10%, values of d_{10} had to be estimated by visual extrapolation of the grain-size-distribution curve. The Kruger effective grain diameters are all on the order of a tenth of a millimeter, and for the samples that we tested, the Kruger effective diameter was very close

TABLE 2—Geotechnical index properties for recompacted samples from the 98th St core hole.

Drive	USCS class	Recompacted density (kg/m^3)	Percent fines (by weight)	d_e (mm)	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	C_u	C_c
14B	SP-SM/SC	2023	7.9	0.14	0.09	0.14	0.22	2.44	0.99
17D	SP-SM/SC	1803	7.7	0.13	0.08	0.13	0.18	2.25	1.00
19	SM/SC	1910	12.5	0.12	0.07	0.12	0.18	2.57	1.14
23A	SM/SC	1773	14.6	0.10	0.06	0.11	0.16	2.67	1.26
25B	SM/SC	2020	35.6	0.07	0.04	0.09	0.13	3.25	1.56
27B	SP-SM/SC	1828	8.8	0.13	0.08	0.12	0.19	2.38	1.50
31B	SP-SM/SC	1840	9.9	0.14	0.07	0.15	0.21	3.00	1.53
33A	SM/SC	1944	12.2	0.13	0.07	0.14	0.21	3.00	1.33
38A	SM/SC	1726	24.0	0.09	0.05	0.09	0.19	3.80	0.85
55B	SP-SM/SC	1822	8.8	0.13	0.08	0.13	0.19	2.38	1.11

to d_{30}. Results of the permeability tests and best-fit trends for all sandy samples except that from Drive 19 are in Fig. 3. There is a well-developed linear relationship between confining pressure and hydraulic conductivity in log-log space, although the magnitude of hydraulic conductivity and sensitivity to confining pressure varies substantially among the samples. The hydraulic conductivity of the predominantly sandy samples tested in the triaxial cell were less sensitive to changes in stress than were the clayey samples tested in the consolidometer. With the exception of the sample from Drive 38A, which had a slope of –1.46, the slopes of the log–log regression lines ranged from –0.10 to –0.64.

The characteristic time for two-way drainage, which reflects the rate at which excess pore-water pressures generated by loading are dissipated, is (Helm, 1984)

$$t_c = \frac{S_{skv} H^2}{4K} \tag{6}$$

in which H is the height of the sample, S_{skv} is the virgin specific storage of the material, and K is the hydraulic conductivity. Haneberg (1995) estimated the virgin specific storage of Santa Fe Group sediments to be on the order of 10^{-4} m^{-1}, the sample thickness is approximately 0.08 m, and the measured hydraulic conductivity of the recompacted samples ranged from 10^{-5} to 10^{-7} m/s. The characteristic time for the recompacted samples should therefore be in the range of 0.02 to 2 s, which is much less than the time over which hydraulic conductivity was measured and indicates that the values are for drained but unconsolidated conditions.

Using the principle of effective stress, the hydraulic conductivity for an effective confining pressure of zero can be extrapolated by solving the regression equations in Fig. 3 for a confining pressure that is equal to the average fluid pressure in the sample (i.e., 10.1 kPa). We denote this extrapolated hydraulic conductivity as K_0. It provides a pressure datum, albeit somewhat subjective, for which hydraulic conductivities can be calculated and empirically compared to geotechnical parameters measured at atmospheric pressures.

Empirical density and hydraulic conductivity relationships

Exploratory data analysis showed that, except for recompacted sample density, there is no apparent relationship between hydraulic conductivity and any of the geotechnical properties in the samples that we tested. In Fig. 4, the least-squares best fit equation

$$\log_{10} K_0 = 52.5 - 0.0573\rho + 1.41\times10^{-5}\rho^2 \tag{7}$$

where ρ is the recompacted bulk density in kg/m^3, has a goodness of fit of $r^2 = 0.76$; in other words, the regression model accounts for 76% of the variability of $\log_{10} K_0$. We explored other multivariate models that incorporated additional variables, such as the effective grain size and weight percentage of fines, and found that inclusion of these terms increased the goodness of fit approximately 10%. For example, the model

$$\begin{aligned}\log_{10} K_0 &= 2.21\times10^{-3} - 2.31\times10^{-6}\rho \\ &+5.92\times10^{-10}\rho^2 + 8.11\times10^{-7} f \\ &+4.77\times10^{-4} d_e - 2.82\times10^{-4} d_{10} \\ &+2.12\times10^{-6} C_u - 1.21\times10^{-5} C_c\end{aligned} \tag{8}$$

where f is the weight percentage of fines and the other parameters are as defined above, has a goodness of fit of $r^2 = 0.96$. Although this kind of elaborate model accounts for almost all of the variability of the hydraulic conductivity, it is not likely to be of general applicability because the regression coefficients are fine tuned to our small data set.

Time-dependent hydraulic conductivity

The constant-head test on the sample from Drive 19 was allowed to run for 149 hrs to examine changes in hydraulic conductivity over time. Hydraulic conductivity decreased about an order of magnitude during the test, with values decreasing exponentially as a function of time (Fig. 5). Although our experimental setup did not allow measurements of changes in sample volume during the permeability test, the exponential decrease in hydraulic conductivity suggests that the decrease in permeability occurred as a result of secondary consolidation of the sample over time and under drained conditions.

Discussion

The preliminary results presented in this paper suggest that the hydraulic conductivity of sediments making up the upper Santa Fe Group aquifer system, from which the City of Albuquerque currently draws its water, are sensitive to the magnitude of effective confining stress. It is impossible to rigorously compare the hydraulic conductivity of the undisturbed and recompacted sediments because two test methods were used and two kinds of hydraulic conductivity were measured (consolidated state for undisturbed, primarily fine-grained sediments and unconsolidated state for recompacted, sandy sediments). Nonetheless, if the results from our single extended triaxial test can be extended to the other sandy samples, it appears that consolidation will decrease the hydraulic conductivity by about an order of magnitude, thus leaving the sandy samples more conductive than the clayey samples at a given effective stress level.

The relatively strong correlation between hydraulic conductivity and bulk density (which is directly related to porosity) and the essentially nonexistent correlations between hydraulic conductivity and grain size contradict the results obtained by Detmer (1995 a,b). One possible explanation is that Detmer sampled outcrops from a relatively small range of elevations, over which the small-scale stratigraphic variability of porosity may have manifested itself as statistical noise, but a wide range of representative grain sizes. In the present study, however, the opposite is true: there were a relatively wide range of initial recompacted bulk densities but a relatively small range of

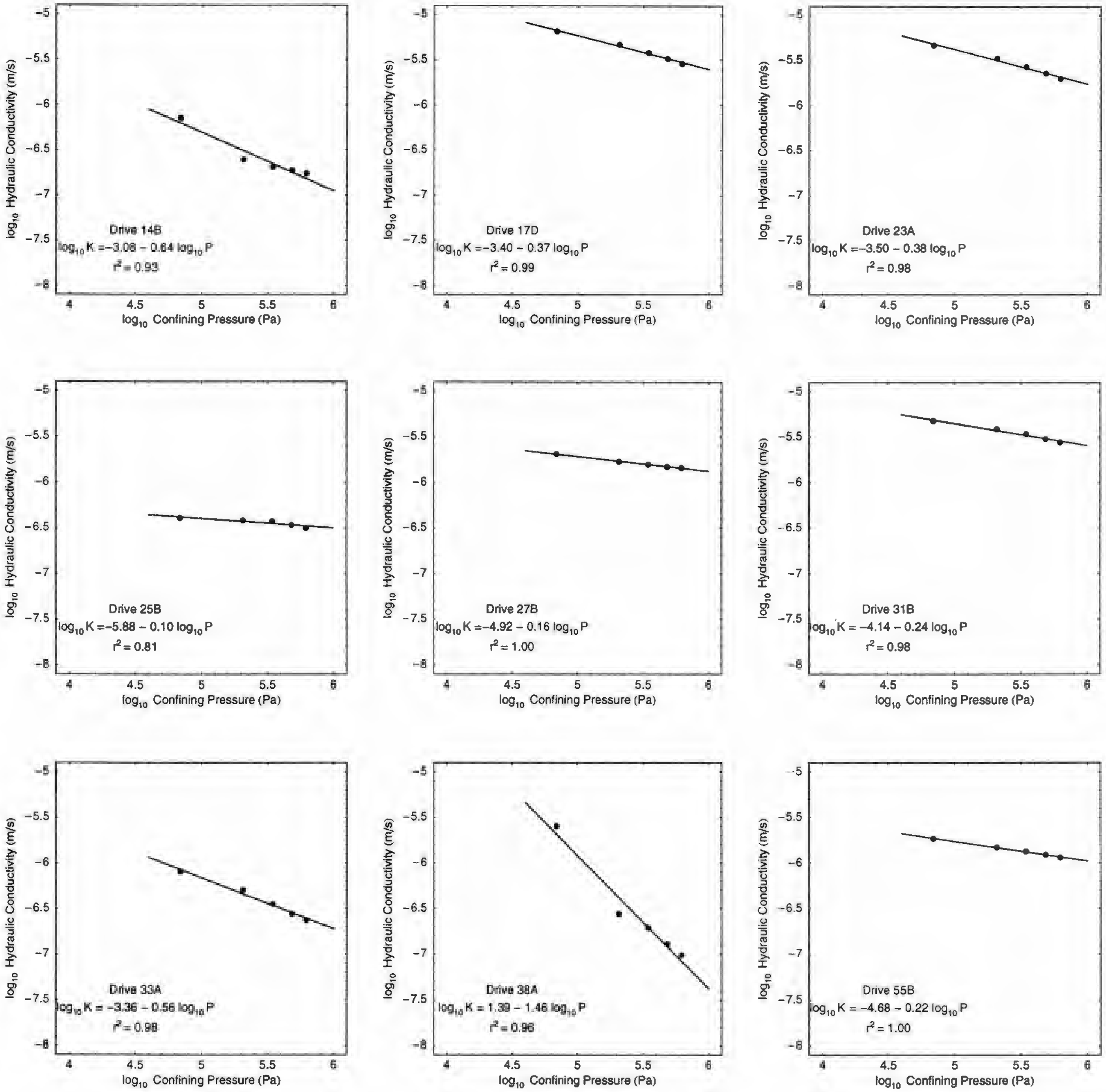

FIGURE 3—Changes in unconsolidated hydraulic conductivity as a function of vertical effective stress for nine recompacted samples from the 98th St core obtained from constant-head tests with samples in a triaxial cell. Geotechnical data for the samples are summarized in Table 2.

representative grain sizes.

The regression equations presented in this paper were developed for low magnitudes of effective stress, corresponding to those in the upper 50 to 100 m of the Earth's crust. If the trends that we observed at low pressures continue into the range of effective stresses existing in the productive zones of the aquifer system, we speculate that the magnitudes of head decline associated with widespread ground-water overdraft may lead to significant decreases in the hydraulic conductivity of the aquifer around pumping wells. This would in turn decrease the specific capacity of those wells and produce larger drawdowns per unit of water removed. The exponential nature of our empirical relationships means that the exact amounts of change will depend on the type of sediment, the depth of burial, and the magnitude of the effective stress change. It is also possible that in a stratified sequence, differences in sensitivity to changing stress among different strata may effectively increase the basin-scale anisotropy of the aquifer system. As above, however, our data do not permit us to reliably calculate the degree to which this might occur.

Clearly, there is a need for additional work to investigate several important aspects of the stress-dependent hydraulic conductivity described in this paper. First, tests should be conducted at more realistic levels of effective stress corresponding to in situ effective stresses at the depths from which the city pumps water from the aquifer. The in situ effective stresses near pumping wells will be determined by the depth at which water is pumped (which in turn depends mostly on the location of a

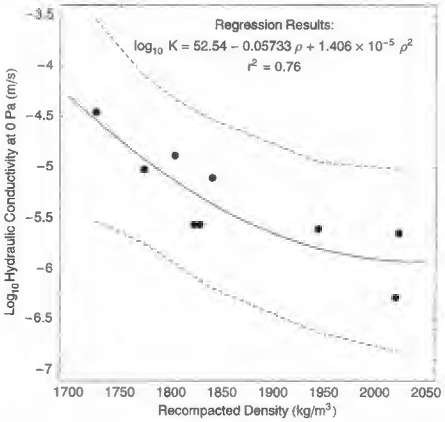

FIGURE 4—Polynomial regression model of extrapolated zero-confining-pressure hydraulic conductivity as a function of recompacted density for recompacted samples used in the triaxial constant-head tests. The dashed lines represent the 95% confidence interval.

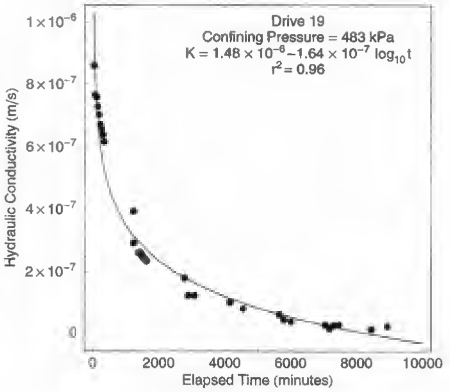

FIGURE 5—Changes in hydraulic conductivity as a function of time for a recompacted sample from Drive 19. The decrease in hydraulic conductivity is inferred to reflect consolidation of the sample.

particular well) and distance beneath the water table from which water is pumped. Heavy pumping may also induce hydrodynamic, as opposed to hydrostatic, changes in effective stress that we are not currently able to evaluate. In particular, attention should be paid to differences in compressibility and hydraulic conductivity above and below the preconsolidation stress of the sample if the results of laboratory testing are to be used in mathematical models of ground-water flow, contaminant transport, and aquifer- system compaction. Second, understanding the relationship between short-period (unconsolidated) and long-period (consolidated) results is critical when dealing with unlithified sediments. Third, the number of tests run to date is very small and needs to be increased substantially. Fourth, coring should be continued when possible, and future work should investigate the relationships between hydraulic conductivity and petrophysical parameters such as bulk density, electrical resistivity, and perhaps grain size to develop regionally useful predictive models. Fifth, hydraulic conductivity is a tensor quantity, and it is possible that hydraulic conductivity anisotropy, like hydraulic conductivity itself, is stress dependent.

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