Aug. 2011, Volume 5, No. 8 (Serial No. 45), pp. 670-678
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

A Case Study on Construction Dewatering-Induced Settlement Damage: Could This Have Been Avoided?

Robert L. Mokwa[1], Leonard P. Mokwa[2] and Timothy P. Mokwa[3]

1. Civil Engineering Department, Montana State University, Bozeman, MT 59717, USA

2. Consol Coal Company, Pittsburgh, PA, USA

3. Building Division Manager, Parametrics, Boise, ID 83714, USA

Abstract: A homeowner reported extensive settlement damage approximately two weeks after the groundwater in the vicinity of the home was lowered at a nearby construction project. The infrastructure improvement project consisted of installing a 27-inch-diameter sanitary sewer main with an invert elevation about 19 ft below existing grade. Groundwater was lowered 12 ft during construction, down to a depth of 23 ft below existing grade. This paper addresses the following key questions regarding settlement and potential structural damage as a result of a temporary drop in groundwater caused by construction dewatering: (1) How could a decrease in groundwater elevation cause settlement? (2) Is this a highly unusual or atypical phenomenon that cannot be explained or estimated using science and engineering techniques available to the engineering profession? (3) Based on the standard of care at the time, should these problems have been anticipated, or at least examined, by the engineering firms engaged on this project? Answers to these questions are addressed herein using results from geotechnical analyses and data obtained from laboratory and in-situ tests.

Key words: Consolidation, de-watering, construction claim, geotechnical uncertainties.

1. Background

A construction claim and follow-on lawsuit was filed by a homeowner in a city located in the Rocky Mountain region of the U.S. The homeowner claimed that nearby construction dewatering resulted in ground settlement of the residence and consequential damage to the house.

The description provided herein focuses on technical details of the lawsuit and the seemingly disparate and incongruous conclusions provided by experts involved with the case. The plaintiff in this case was the homeowner of the subject residence. The defendants of the lawsuit included the project owner, the general contractor, the lead civil engineer/designer of the project, and the geotechnical firm that was hired by the lead civil firm to conduct an investigation in support of the design. For privacy reasons, names of specific organizations and individuals involved in the case have been omitted from this paper.

Inspections and measurements of the residence conducted by various engineering firms and agents indicate that differential settlement damages likely exceeded one inch; possibly as much as two inches in some places. Reports prepared by representatives of the defendants indicate that settlement of the residence should have been less than one inch (about 0.75 in). In contrast, the plaintiff contended that settlement damage in the home was caused by construction dewatering and that settlement magnitudes were in the range of 1 to 2 inches. This paper explores these apparently conflicting positions using data that was available during the claim discovery period.

1.1 Project Details

The construction project consisted of the installation of a 27-inch-diameter sanitary sewer main with a bottom elevation about 19 ft below existing grade in the vicinity of the residence. The actual trench depth

Corresponding author: Robert L. Mokwa, associate professor, research field: civil engineering. E-mail: Rmokwa@ce.montana.edu.

was about 23 feet in this section to provide clearance for pipe bedding gravel. The construction plans and specifications required that all work in the trench be conducted in the dry, including placement of the pipe bedding gravel and installation of the sewer pipe. Consequently, because of the presence of groundwater, dewatering was required during trenching and pipe installation. As shown in Fig. 1, groundwater was lowered about 12 feet in the vicinity of the structure during the construction operation.

1.2 The Structure

The structure consisted of an approximately 2,200 ft^2 one-story wood house with a finished basement. The subject house was constructed in the 1990s in a middle-class residential neighborhood. This house was the closest structure to the trench and the contractor's primary dewatering well. The trench was excavated approximately parallel to the long axis of the house, about 50 feet from the back wall. The dewatering well was located about the same distance from the house.

The homeowner contacted the project owner and complained of settlement damage approximately two weeks after the contractor began dewatering. Dewatering, trench excavation, and pipe installation activities continued with no alteration in construction methods as a result of the homeowner claim.

1.3 Observed Damage in Residence

After a claim was filed against the contractor and project owner, the subject house and other nearby houses in the subdivision were inspected for damage by four different engineers or engineering firms as well as numerous representatives of law firms, constructions companies and insurance companies. Numerous irregularities in the interior of the subject home were documented, including drywall cracks in the ceiling, walls, and in many of the wall ceiling joists. Serviceability problems were observed, including: malfunctioning doors and windows, out of square door frames, and sloped and uneven floors and counters. Level measurements indicated the foundation and floor slabs appeared to have settled 2.16 and 1.60 inches, respectively. Independent measurements reported differential settlement of up to 1.38 inches.

1.4 Soil Conditions

A limited geotechnical investigation was conducted along the sewer line alignment during the design phase of the project. However, as typical with these types of cases, a considerably more detailed investigation was conducted in the vicinity of the residence subsequent to the construction claim. The post-claim investigation included five soil borings, geophysical testing, and laboratory testing of split spoon and Shelby tube soil samples.

Geotechnical reports compiled for the project site indicate that subsurface conditions in the vicinity of the residence consist of fine-grained alluvial soils underlain by coarse-grained alluvium over shale bedrock. Fig. 2 contains plots of field-corrected SPT N-values, laboratory water content measurements, and undrained shear strength estimates for soils encountered in five investigative borings labeled ST-1A through ST-5. Data points representing soils in boring ST-2 are shown as bold blue squares in Fig. 2. This boring was closest to the subject residence (approximately 300 ft from the house), and is probably most representative of the soil conditions at the house.

Undrained shear strength values shown in Fig. 2 were calculated using correlations with SPT N-values [1]. Field pocket penetrometer measurements are included in the plot for comparison purposes.

Data and information from the geotechnical reports indicate soils at the site generally consist of a stiff surficial crust underlain by soft compressible fine-grained soils to a depth of about 50 ft below the ground surface. Data from the five soil borings plotted in Fig. 2 show the presence of a stiff layer from the ground surface to a depth of about 5 ft. Corrected SPT N-values in this region generally range between 10 and 30, and the estimated average undrained shear strength

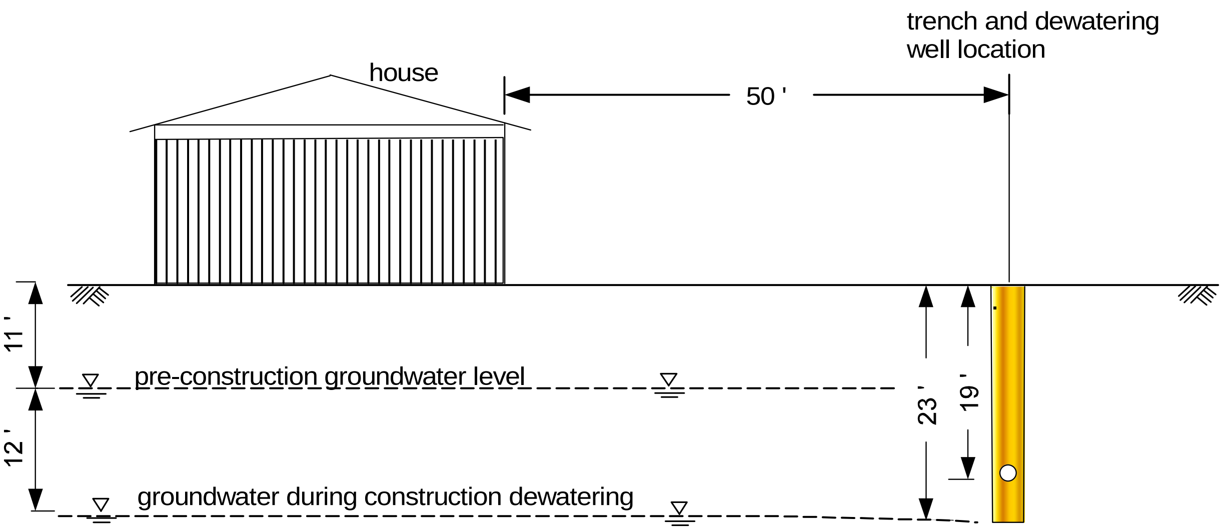


Fig. 1 **Subsurface cross-section at the site (Note: dimensions shown are to the nearest foot).**

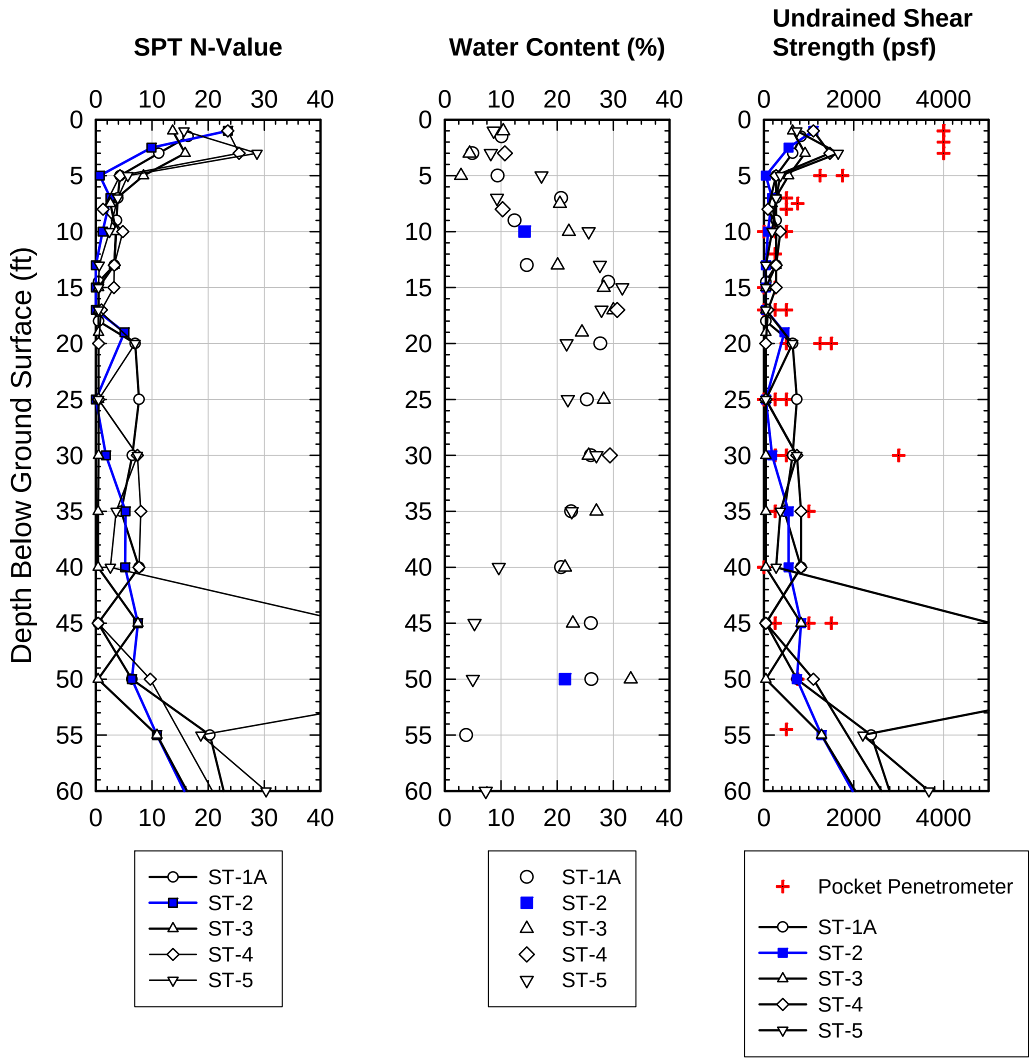


Fig. 2 **Soil parameters obtained from subsurface investigation.**

is about 1100 psf. The SPT N-values and estimated undrained shear strength values decrease markedly below this layer. The reported N-values are quite low from a depth of 5 ft down to the top of the sand and gravel layer, which was encountered at a depth of about 50 ft in soil boring ST-2. Static groundwater was reported at a depth of about 15 ft in soil boring ST-2 on the date of drilling.

2. Consolidation Settlement Analysis

The alluvial deposit encountered at this site is quite variable in both vertical and lateral extents as can be observed in the five soil borings. The heterogeneous soils at the site are typical of the alluvial deposits in the area because of the random nature of deposition that occurs as soil particles are transported and deposited in a flowing water environment. The simple representative soil model shown in Fig. 3a was developed using test data and boring logs from the geotechnical and hydrological reports. The vertical pressure distribution shown in Fig. 3b was calculated using measured soil unit weights and water contents. The change in vertical stress ($\Delta\sigma_v$) is based on a 12 ft drop in groundwater at the subject property as a result of construction dewatering. The calculated final vertical stress, during drawdown, is shown as a dashed line in Fig. 3b.

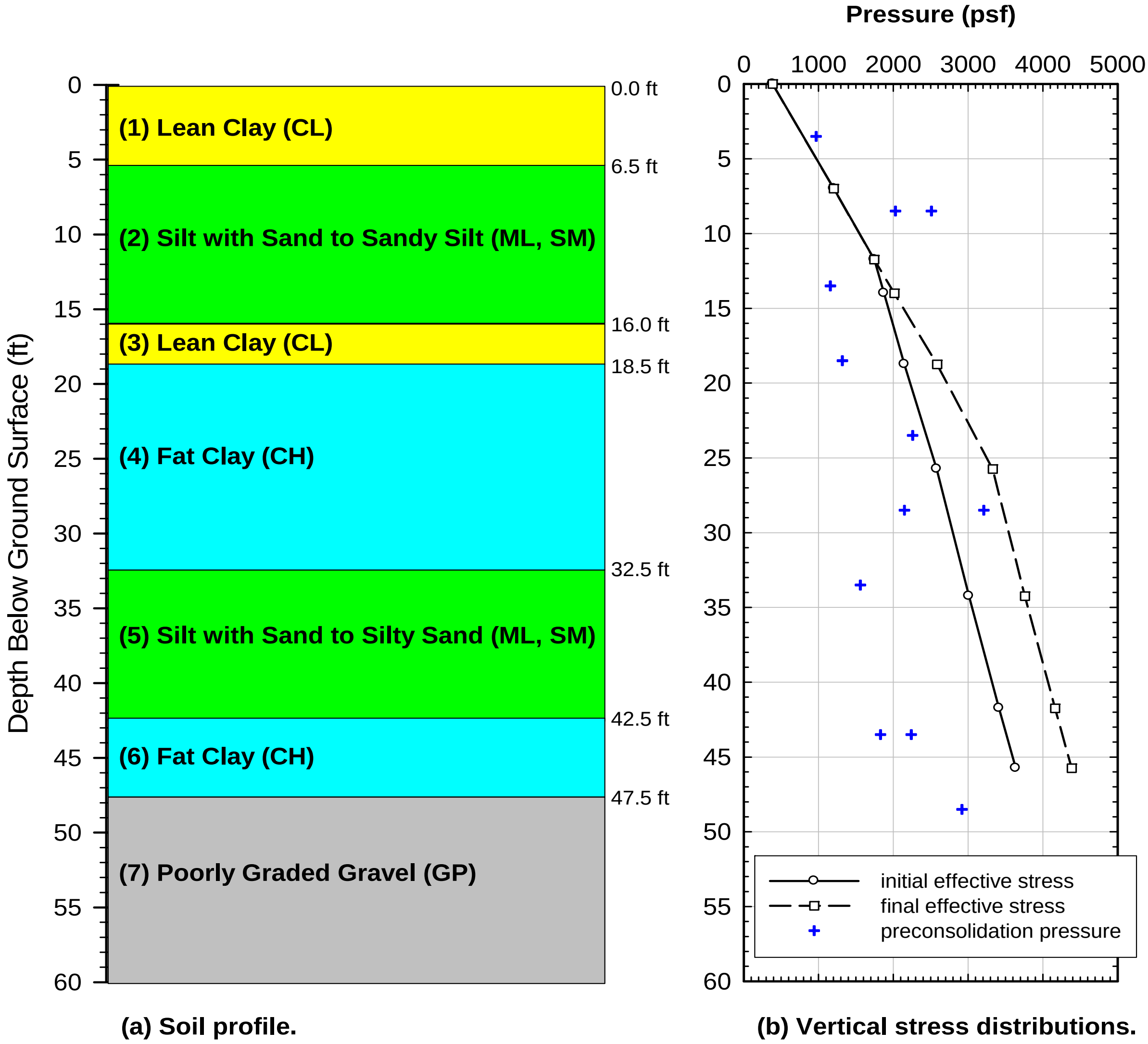
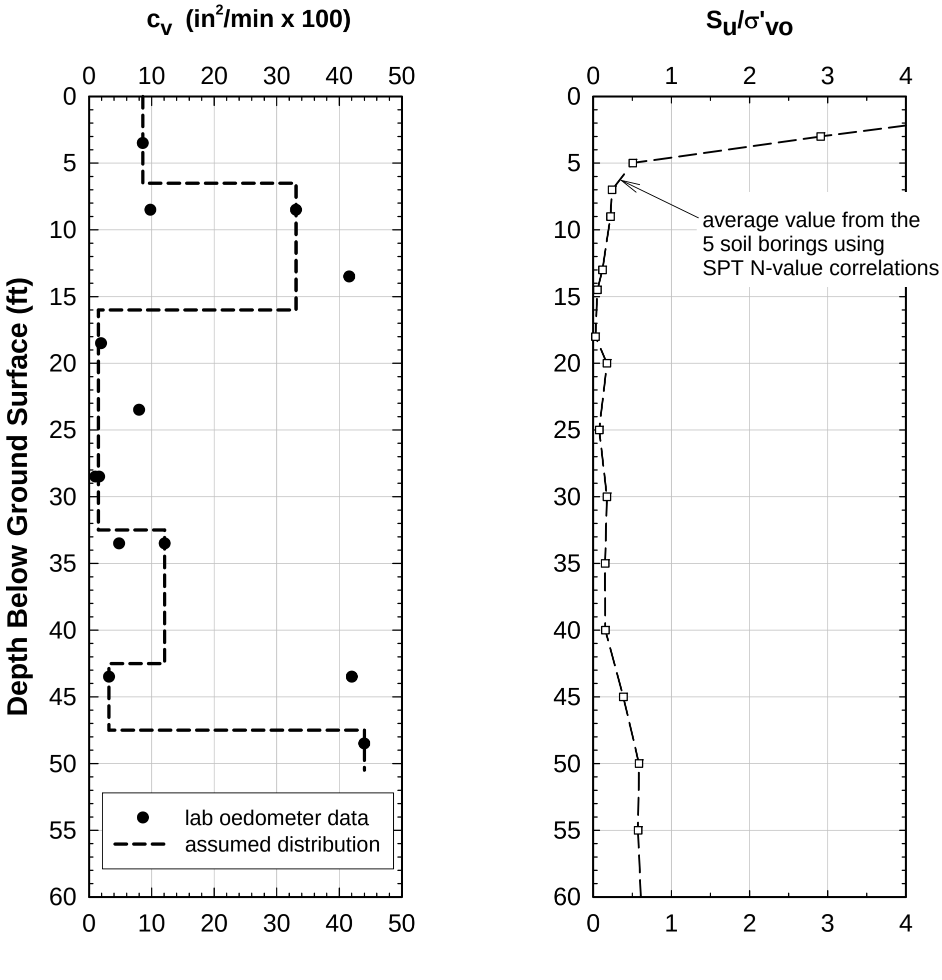


Fig. 3 Representative soil model for settlement analyses.

A consolidation analysis was conducted using laboratory test results generated during the claim investigation in conjunction with the subsurface model shown in Fig. 3. A computer program that uses a numerical analysis procedure was employed to calculate the magnitude and rate of consolidation settlement. Conventional Terzaghi consolidation equations were used to determine the magnitude of the ultimate consolidation settlement, after the excess pore pressures are dissipated. A finite difference approximation was used to calculate the rate of consolidation settlement and the rate of dissipation of excess pore pressures. Time rate values of soil consolidation are represented by the coefficient of consolidation, c_v. Values of c_v obtained from consolidation tests are plotted in Fig. 4a. The assumed distribution of c_v used in the analyses is shown as a dashed line in the plot.

Laboratory consolidation tests indicate the soils are likely normally consolidated. This observation is further supported by the estimated distribution of S_u/σ'_{vo} with depth that is shown in Fig. 4b. Published data in the technical literature [2-4] indicates that S_u/σ'_{vo} ratios less than about 0.45 are indicative of normally consolidated soils. As shown in Fig. 4b, the fine-grained soils underlying the desiccated crust would be considered normally consolidated based on the calculated S_u/σ'_{vo} distribution, which is generally less than 0.2 from about 6 to 40 ft below the ground surface.



(a) Data for time-rate analyses. **(b) Strength versus effective stress.**

Fig. 4 Soil compressibility and strength data.

Consequently, the available geotechnical data (including both consolidation and strength tests) indicates the soil deposit is normally consolidated. Using measured data from the defendant's geotechnical report, the calculated primary consolidation settlement amounts range from about 3 to 3.5 inches, as shown in Fig. 5. The solid line in Fig. 5 was calculated using a constant groundwater drawdown level of 12 ft, while the dashed line was calculated using the drawdown and recovery curve obtained from a dewatering test adjacent to the site. The magnitudes of settlement shown in Fig. 5 are consistent with the settlement damage that was observed and documented at the residence.

A report produced by the defendants presents a calculated settlement estimate approximately 75% less than the amount shown in Fig. 5. The discrepancy is believed to occur in the assumptions used to evaluate the data and inconsistencies in the data itself. As with most analyses involving the prediction of soil response, there is seldom a single "correct" answer, but rather a predictive range or probable outcome. Variability introduced in calculations as a result of inaccurate assumptions or erroneous data can decrease the reliability and precision of calculated settlements. The following section further explores potential reasons behind the apparent discrepancies in calculated settlements in terms of possible margins of error, which include assumptions regarding in-situ physical conditions, both past and present, and inaccuracies in soil test data.

3. Margin of Error in the Settlement Calculations

3.1 Overconsolidation Ratio

Interestingly, eight of twelve samples tested by the defendants had overconsolidation ratios (OCR) less than one, indicating an underconsolidated deposit. This would indicate the layer has not yet come to equilibrium under the weight of the overburden load. If pore water pressures were measured under these conditions, the pressures would be in excess of hydrostatic [5]. If the soils were truly underconsolidated, they would be highly compressible and would continually settle until a stress-equilibrium condition was reached. Any additional load or stress increase would result in comparably large settlements.

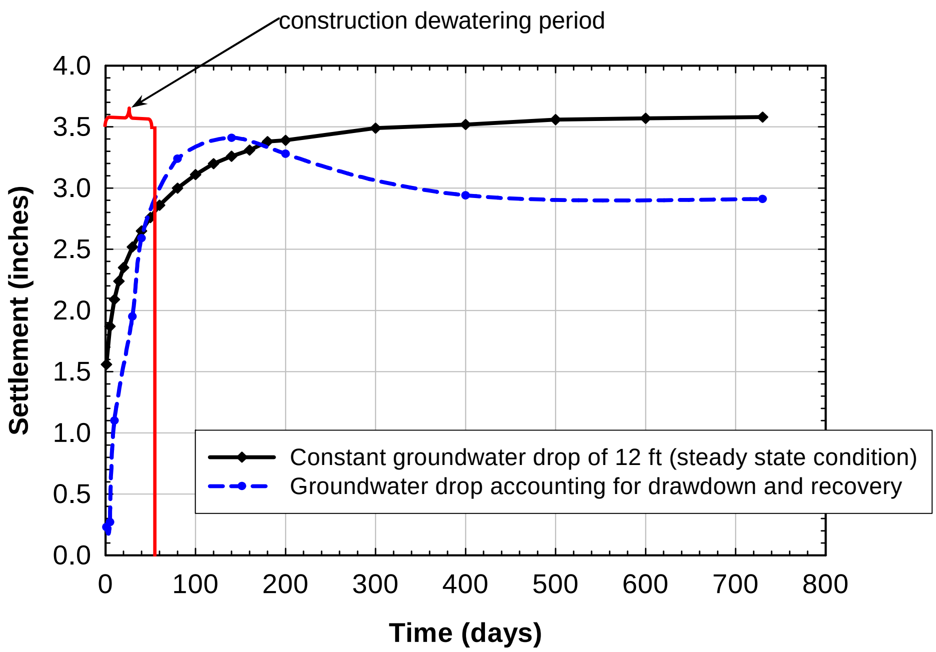


Fig. 5 Calculated settlement assuming soil is normally consolidated.

Based on the geologic setting and past land use practices in the area, there is no evidence indicating the soils at the site are underconsolidated. Rather, it is more likely that some of the consolidation test data may not be accurate. The defendant's report attributes inconsistencies in their consolidation test data to sample disturbance. As discussed in their report, it is very difficult to obtain high-quality undisturbed samples in soft compressible clay deposits. The amount of disturbance is proportional to the strength and compressibility of the deposit and the care used in obtaining and testing the samples. Even if the highest standards of practice are followed in the drilling, sampling, and testing methods, some disturbance will occur, and this disturbance will have adverse effects on the data obtained from laboratory consolidation tests. Based on the soft compressible nature of this soil deposit, as illustrated in the low SPT blow counts and the low values of undrained shear strength shown in Fig. 2, it is not surprising that the geotechnical firm had difficulties obtaining accurate laboratory consolidation test results.

Past and present groundwater levels will influence the consolidation calculations because groundwater directly affects the soil stress state and the relationship between stress increase and strain. Surprisingly, the defendants assumed in their calculations that the soils were not underconsolidated, as their data suggested, but were actually overconsolidated (OC). They based this assumption on approximations and estimates described in a hydrology report, which inferred that historic groundwater levels prior to irrigation were lower than at present.

The defendants predicted about ¾-inches of settlement at the residence, assuming pre-irrigation water levels were 33 ft lower than at present (about 48 ft below the ground surface). This value is based on a simple gross calculation based on estimated (not measured) porosity values for the soils at the site. They used data from their consolidation tests to estimate recompression indices for the analyses. This was the same data that they deemed inaccurate because of sample disturbance. In addition, the values of P_c used in the defendant's analyses were determined to be off by a factor of about three. Even with the assumption of historically lower groundwater levels, the sample in boring ST-4 at a depth of 18 to 19 ft still has an OCR less than one.

3.2 Settlement Calculations

The defendants' settlement estimate is based on the premise that the soils are overconsolidated, in which case the calculated settlement will be directly proportional to the slope of the recompression curve (C_r). The accuracy or margin of error in the C_r values presented in the geotechnical report is unknown. Error factors as large as 2.67 and 3.10 were observed in the P_c data. If the variability in C_r is as large as the apparent variability in the P_c parameter, than the calculated range of settlement could vary by 200% (0.6 to 1.8 in).

Fig. 6 shows the variation in calculated settlement in relation to the assumed historic water level. Uncertainty in the settlement prediction increases as additional variables are examined. In this case, the assumption regarding historic water levels is superimposed with the error factor in the C_r soil parameter. Considering these two parameters, the variability in the settlement prediction (or margin of error) now increases from 1.2 in to 3.4 in. The high end of this range corresponds to a condition in which the pre-irrigation groundwater level is similar to the current groundwater level, in which case the soil deposit would be normally consolidated.

This parametric analysis indicates that damaging settlements would have been possible whether the historic pre-irrigation groundwater level was 33 ft or 46 ft below current levels.

4. Summary

As with any analysis that involves approximations and assumptions, there is seldom a single absolute

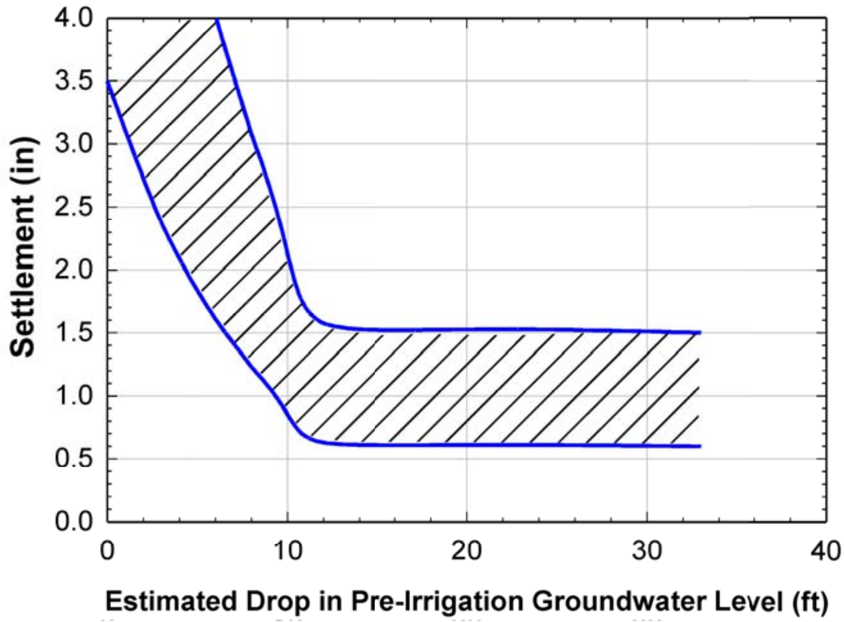


Fig. 6 Variation in calculated settlement as a function of historic groundwater levels.

solution, but rather a range of possible outcomes. There can often be more than one answer even when analyses are conducted using proper mechanics because there will always be some margin of error and potential contentious issues. Following is a summary of key technical issues associated with this case:

(1) The soils beneath the residence consist of very soft, compressible, saturated clayey and silty soils.

(2) Groundwater beneath the residence was lowered by as much as 12 ft during the dewatering operation.

(3) A drop in the groundwater level (at any site) will result in a stress increase within the soil deposit because of the reduction in buoyancy (Archimedes principle). A stress increase will be accompanied by strain (Hooke's Law). Settlement (or deformation) is the integration of strain over the effected volume of material. The amount of settlement depends on the stiffness (or modulus) of the soil and the soil stress history. In other words, consolidation settlement due to an increase in effective stress will occur when groundwater is lowered in compressible soils.

(4) Saturated clayey and silty soils experience stress-strain-time-dependent settlement known as consolidation settlement.

(5) The subject residence experienced obvious settlement damage, and the homeowner first filed damage reports about two weeks after the contractor began construction dewatering adjacent to the residence.

(6) There are two possible scenarios regarding the defendants geotechnical test data: (a) the data is correct or mostly correct, in which case the soil is normally consolidated; or (b) the data is erroneous, in which case a specific value of settlement cannot be calculated with any degree of reliability.

(7) Based on the authors' analyses, both consolidation and strength data indicate the soils are normally consolidated. Settlement of about 3 inches would be predicted using state-of-the-practice conventional geotechnical engineering procedures.

5. Conclusions

Based on analyses of soil data from the site, it can reasonably be concluded that anywhere from one to three inches of settlement could have occurred during the construction dewatering operation. Based on conventionally accepted engineering methods, the margin of error in the settlement estimates provided by the defendants' could easily exceed one inch.

Paraphrasing Ralph Peck: our ability to analyze far exceeds our ability to accurately characterize soil conditions. This adage is quite relevant for the circumstances at this site and should be kept in mind when evaluating the engineering reports that were prepared for this case. In conclusion, there will always be uncertainties associated with geotechnical analyses, and these uncertainties will be proportional to the complexities and the unknowns of the site and the underlying soils. Currently available scientific methodologies and analytical methods indicate the subject residence experienced damaging settlement as a result of groundwater lowering caused by nearby construction dewatering.

References

[1] Das, Principles of Foundation Engineering (6th ed.), Brooks/Cole Thomson Publishing, Pacific Grove, CA, 2007.

[2] F. H. Kulhawy and P. W. Mayne, Manual on estimating soil properties for foundation design, EPRI Report EL-6800, Electric Power Research Institute, Palo Alto, CA, 1990.

[3] C. C. Ladd, R. Foote, K. Ishihara, F. Schlosser and H. G. Poulos, Stress-deformation and strength characteristics, in: Proceedings of 9th International Conference on Soil Mechanics and Foundation Engineering, Vol. 2, Tokyo, 1977, pp. 421-494.

[4] P. W. Mayne, Determining OCR in clays from laboratory strength, Journal of Geotechnical Engineering 114 (1) (1988) 76-92.

[5] R. D. Holtz, W. D. Kovacs and T. C. Sheahan, An Introduction to Geotechnical Engineering, Prentice-Hall, New Jersey, 2011.