Teaching Consolidation: Case Study of Preloading with Vertical Drains

Robb Eric S. Moss, *Associate Professor, Department of Civil and Environmental Engineering, Cal Poly, San Luis Obispo, CA; email: rmoss@calpoly.edu*
Judd King, *Senior Geotechnical Engineer, Yeh and Associates, Inc., Grover Beach, CA; email: jking@yeh-eng.com*
Gregg L. Fiegel, *Professor, Dept. Civil and Environmental Engineering, Cal Poly, San Luis Obispo, CA; email: gfiegel@calpoly.edu*

ABSTRACT: *This paper describes a ground improvement case study where preloading and prefabricated vertical drains (PVDs) were used to accelerate foundation settlements. The case study is used in a classroom setting with the learning objective of introducing engineering students to methods for estimating settlement of shallow foundations on compressible soils. The project site was developed for a corporate retail chain planning to open a new facility in San Luis Obispo, California. Up to 2.5 meters of fill were needed across much of the site to raise foundations and improvements above the flood elevation. Loads from the fill and the structure were expected to cause total and differential settlements that exceeded the allowable values established by the retailer. To mitigate settlement, the geotechnical engineer developed a preloading plan. Although the soil conditions were complex (e.g., interlayering, dipping strata, variable compressibility), the preloading plan was successful in achieving the desired settlement within 3 months, and subsequent site performance has been exemplary. This case study has been used for several years within a quarter-long shallow foundation design course to teach settlement performance. Learning outcomes from the assignment are summarized in the paper. Students are given the subsurface information and test results originally acquired by the geotechnical engineer. The students, working in teams, try to estimate how much primary consolidation settlement will occur due to the fill plus the preload, and the PVD spacing needed to achieve 90% of that settlement in 3 months. The assignment and relevant data are included herein along with the grading policy. The project culminates with the geotechnical engineer of record presenting in class the results of site monitoring during preloading and consolidation. These results include settlements across the 16,908 m^2 site, which were tracked up to three times a week at 20 locations. This project affords students a case study experience that is rich in the "messy" details of a complex and local (i.e. familiar) geotechnical project. Included is a discussion of lessons learned by the instructors who have taught several iterations of this case study.*

KEYWORDS: consolidation, settlement, wick drain, case study, learning outcomes

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

INTRODUCTION

Consolidation settlement is often the controlling design issue when constructing a shallow foundation at a site underlain by saturated, fine-grained soils. The additional load from the foundation and supported structure compresses the soil. This compression, or settlement, typically includes a small amount of elastic compression and secondary compression along with a larger amount of primary compression (a.k.a. consolidation) where the pore water is "squeezed out" of the soil (Terzaghi, 1943). Instructors often use case studies to teach important concepts related to the behavior of fine grained soils, consolidation theory, and settlement evaluation. This paper documents a local case study involving shallow foundation design, consolidation settlement, and settlement mitigation using preloading and prefabricated vertical drains (PVDs). In the paper, we document the case study, present field and laboratory test results, describe the details of the in-class lessons, and discuss the objectives and assessment of the assignment.

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PROJECT

The case study involves the design and construction of a corporate shopping center (Target) at a site located in San Luis Obispo, California. The project site is located on a previously undeveloped lot next to a primary thoroughfare (Los Osos Valley Road). Site improvements included the retail space, parking spaces roughly 5 times that area, two access roadways, and the associated drainage systems. The retail space consists of a single story reinforced concrete tilt-up structure that imposed a bearing stress up to 144 kPa (3,000 psf) immediately below the footings.

The project site was optimal from a business perspective, but far less optimal from a geotechnical perspective. Figure 1 shows a surficial geology map of the area. [Note: all figures in this paper are from the original report geotechnical report and are in English Units, whereas the discussion is in Metric (SI) Units. This is on purpose and is identical to the way it is presented in class.] Shown in the lower-right corner of Figure 1, the project site is located adjacent to Perfumo Creek, which is downstream from Laguna Lake. The geologic unit at the project site maps as Qa (Quaternary Alluvium), which is described as "surficial sediments, sands, and gravels of the valley areas." There is a nearby fault, the Los Osos Valley Fault, which controls seismicity for the site, but does not represent an inordinately large design issue. The site also lies within the 100-year flood plain, which represents the primary design constraint for this project.

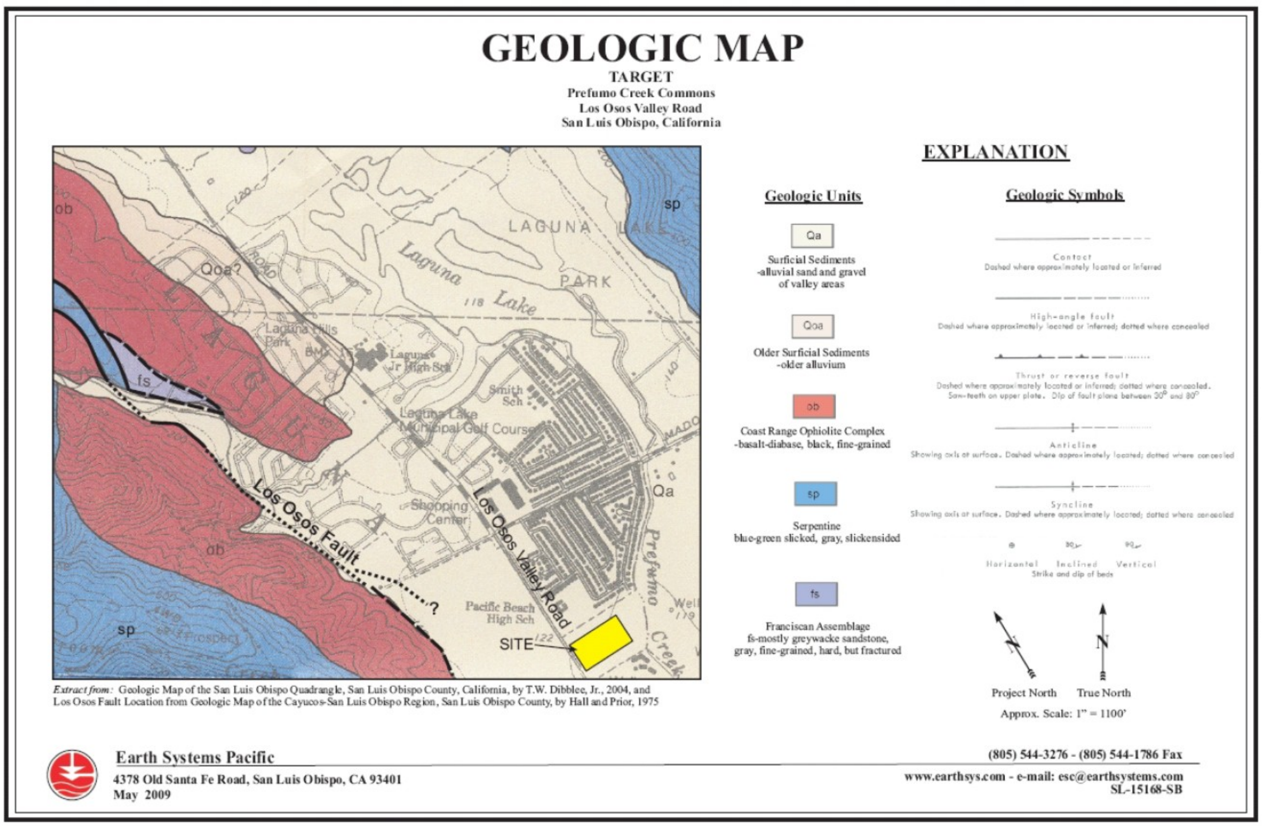

Figure 1. Map showing the local geology with respect to the site location and other surface features.

Local geotechnical knowledge of the area anticipated subsurface conditions consisting of soft, compressible soils deposited in prior geologic history when the site was located in a lake environment. Previous experience in the project area indicated that consolidation settlement would be a controlling design issue. With that in mind, a comprehensive subsurface investigation was planned, as illustrated in Figure 2. This figure shows the location of the retail space, associated parking, Los Osos Valley Road, and Perfumo creek, all relative to the completed site explorations. To fully characterize the soft soils encountered at the site, several rounds of subsurface exploration were planned and executed. Aspects of this exploration included SPTs (standard penetration tests), CPTs (cone penetration tests), subsurface sampling, and test pits (not presented in this paper).

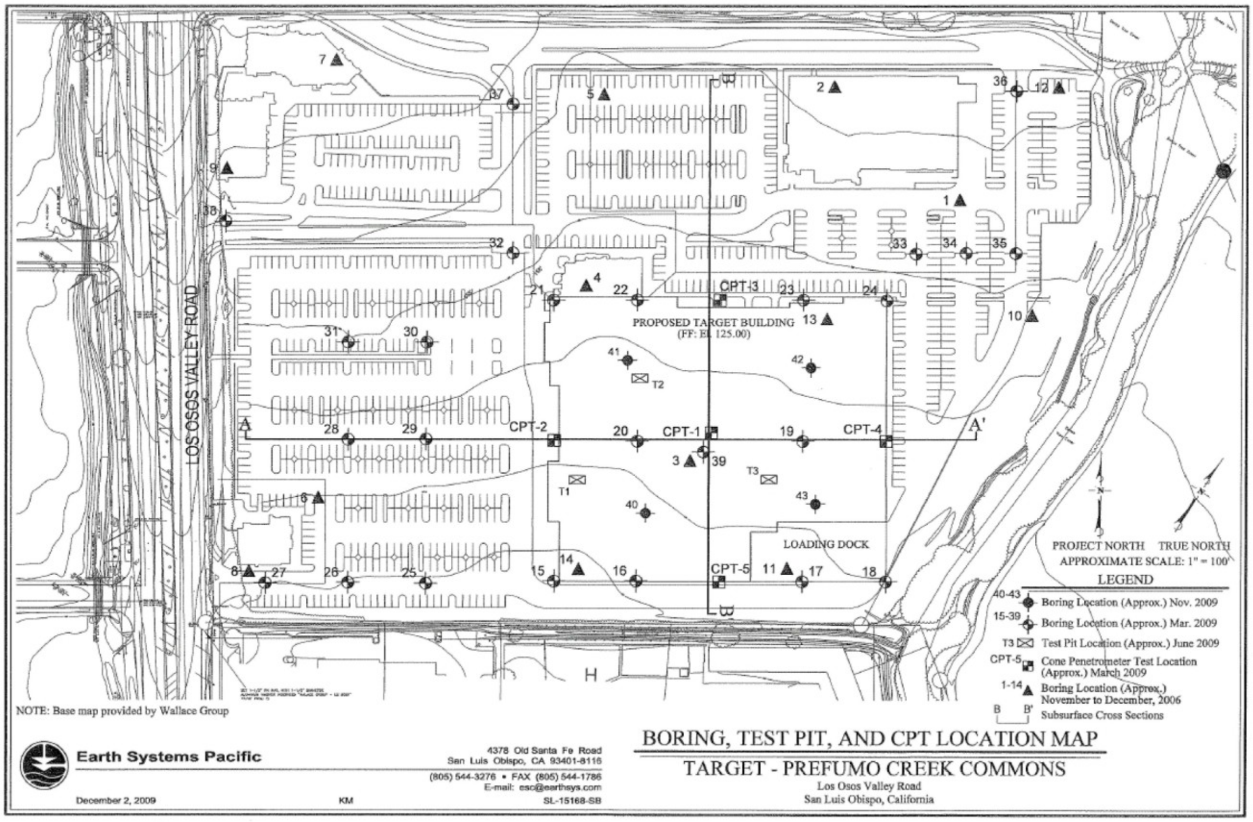

Figure 2. Site map showing the locations of borings with SPT, CPT soundings, and test pits.

Figure 3 shows a simplified profile of the site based on the subsurface investigation. As noted, groundwater was encountered near the ground surface in what is locally called "Younger Alluvium." This Younger Alluvium overlies a dipping contact with "Older Alluvium." The Younger Alluvium at this site consists of fat (CH) and lean (CL) clays of varying compressibility, and each were sampled and tested in the laboratory. Laboratory testing included measurements of water content, initial void ratio, particle size distribution, unit weight, Atterberg limits, shear strength, and compressibility. One-dimensional, incremental oedometer tests were performed to investigate the compressibility and consolidation characteristics of the soils. These tests were performed on typical Cal-Mod ring samples and thin-walled Shelby tube samples, common subsurface sampling techniques in this part of the U.S.

Typical consolidation test results are shown in Figures 4 and 5. Figure 4 presents a consolidation curve generally representative of the behavior observed in the Younger Alluvium at the site. This consolidation test was performed on a driven ring sample. Figure 5 shows settlement versus time data for a specific load increment during a different consolidation test, also performed on a driven ring sample. A total of 10 consolidation tests were performed on specimens of this material. The consolidation or "*e-log p*" curves were highly variable, both across the site and with depth. Assessment of stress history indicated the Younger Alluvium was normally (NC) to slightly overconsolidated (OC). The "*e-log p*" curves are not the "textbook" curves students are often presented with during class instruction on settlement. Indeed, for many of these curves the evaluation of the preconsolidation stress (σ_p') and the slopes of the virgin and recompression limbs present a challenge (an electronic supplement containing the lab curves is provided). The consolidation curves, measured by testing both driven ring and thin-walled tube samples, provided the unique opportunity to assess consolidation characteristics as well as sample disturbance. Having the students interpret real consolidation test results provides opportunities for the instructors to discuss soil sampling and disturbance effects, potential errors associated with field and laboratory testing, data interpretation concepts, and the use of judgment and experience in geotechnical engineering.

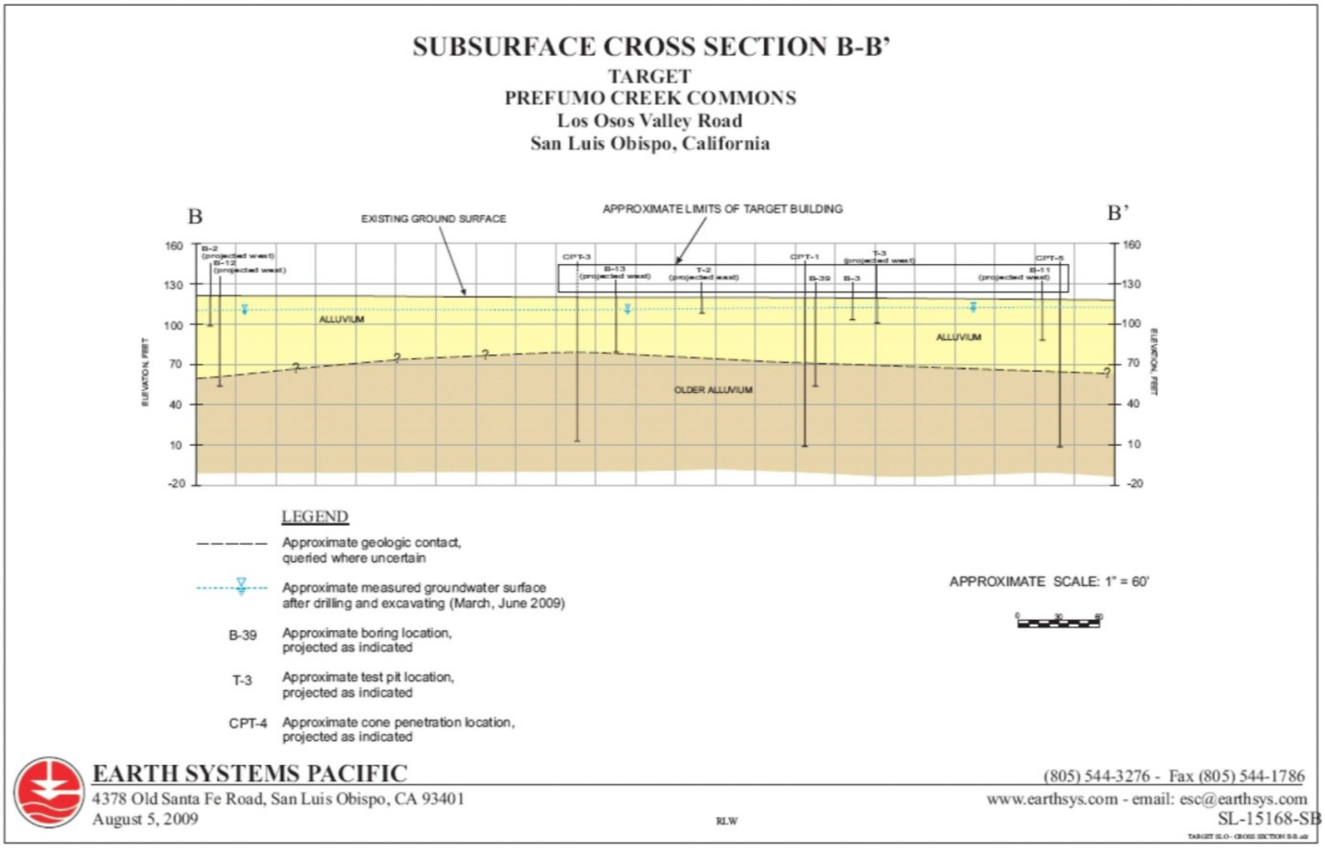

Figure 3. Simplified cross-section profile of the soil conditions at the site.

The site, prior to construction, was generally level with a MSL elevation of approximately 38 meters (125 feet). Design constraints related primarily to site drainage and flood mitigation required extensive grading during construction. To raise the site and subsequent foundations and improvements above the 100-year flood elevation, up to 2.5 meters (8 feet) of fill were required. Site excavation and fill requirements are shown in Figure 6 and include the native material, the desired level of excavation depth, the native backfill, structural fill, and granular fill. Because of the added load of the fill, the consolidation settlement was forecast to be excessive for satisfactory foundation/building performance, as set by the project owners' in-house structural engineers. This anticipated poor site performance is what led to preconsolidation using PVDs as the design solution to mitigate the excessive consolidation settlement. Other mitigation options were considered (piles, piers, overexcavation, micro-piles, soil mixing) but PVDs were selected by the client and the engineer as the preferred means of mitigating the excessive settlement while considering cost and timeline.

Project timeline and constraints called for achieving desired preconsolidation settlement within 3 months to accommodate an overall project completion schedule of 14 months. The desired preconsolidation settlement was based on the loads from the required fill and subsequent building foundation, and needed to be sufficient to limit future settlement to less than 1.3 cm (1/2 in) differential over 9 m (30 ft), 2.5 cm (1 in) over 30.5 m (100 ft), and no more than 7.6 cm (3 in) over the length of the building which is approximately 140 m (460 ft). This required the installation of a field of PVDs below the structural pad fill and an additional minimum 1.3 m (4 ft) of temporary surchage fill to preconsolidate the soft soils (Figure 6).

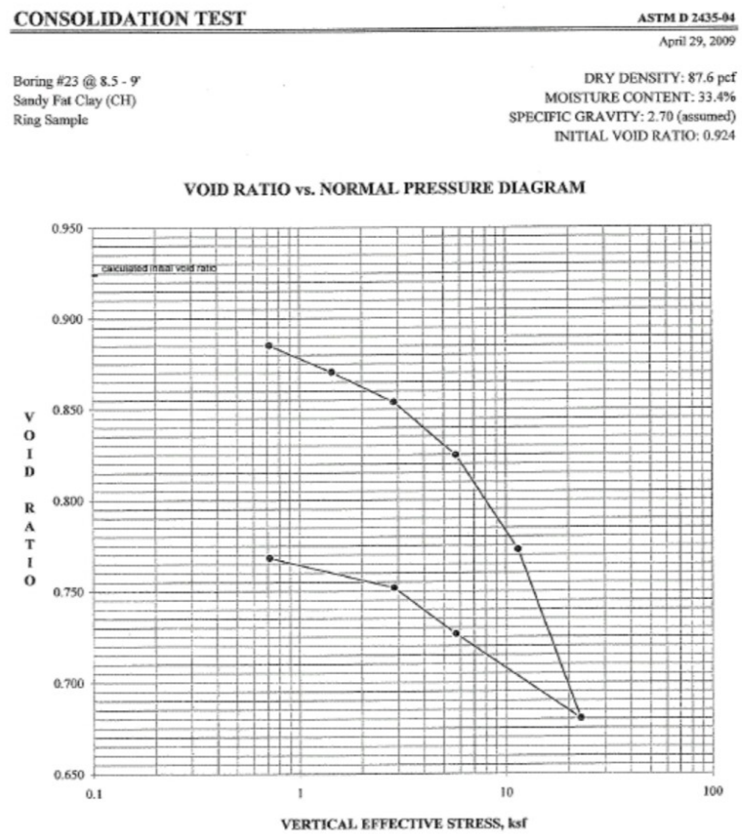

Figure 4. Typical 1D incremental oedometer lab test results from the CH soils at the site.

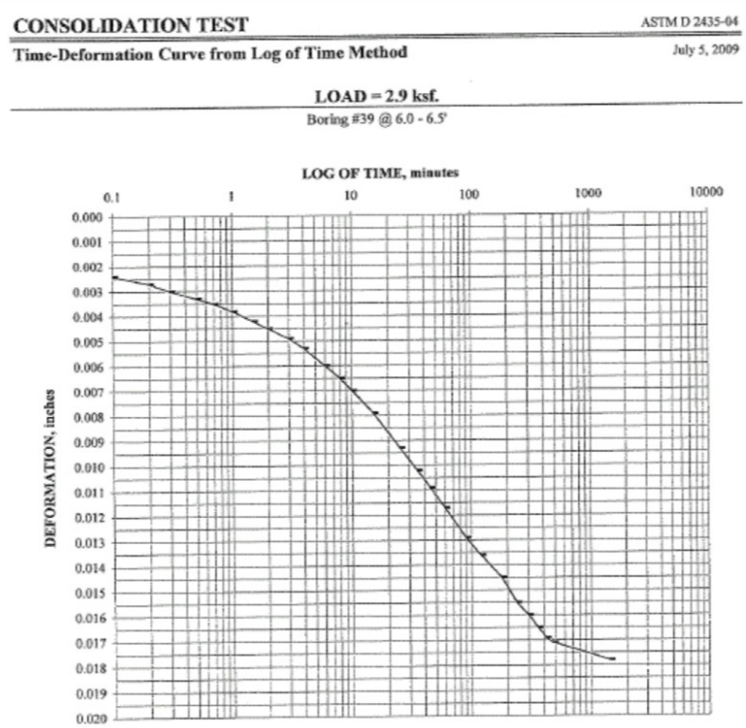

Figure 5. Typical log of time consolidation lab test results from the CH soils at the site.

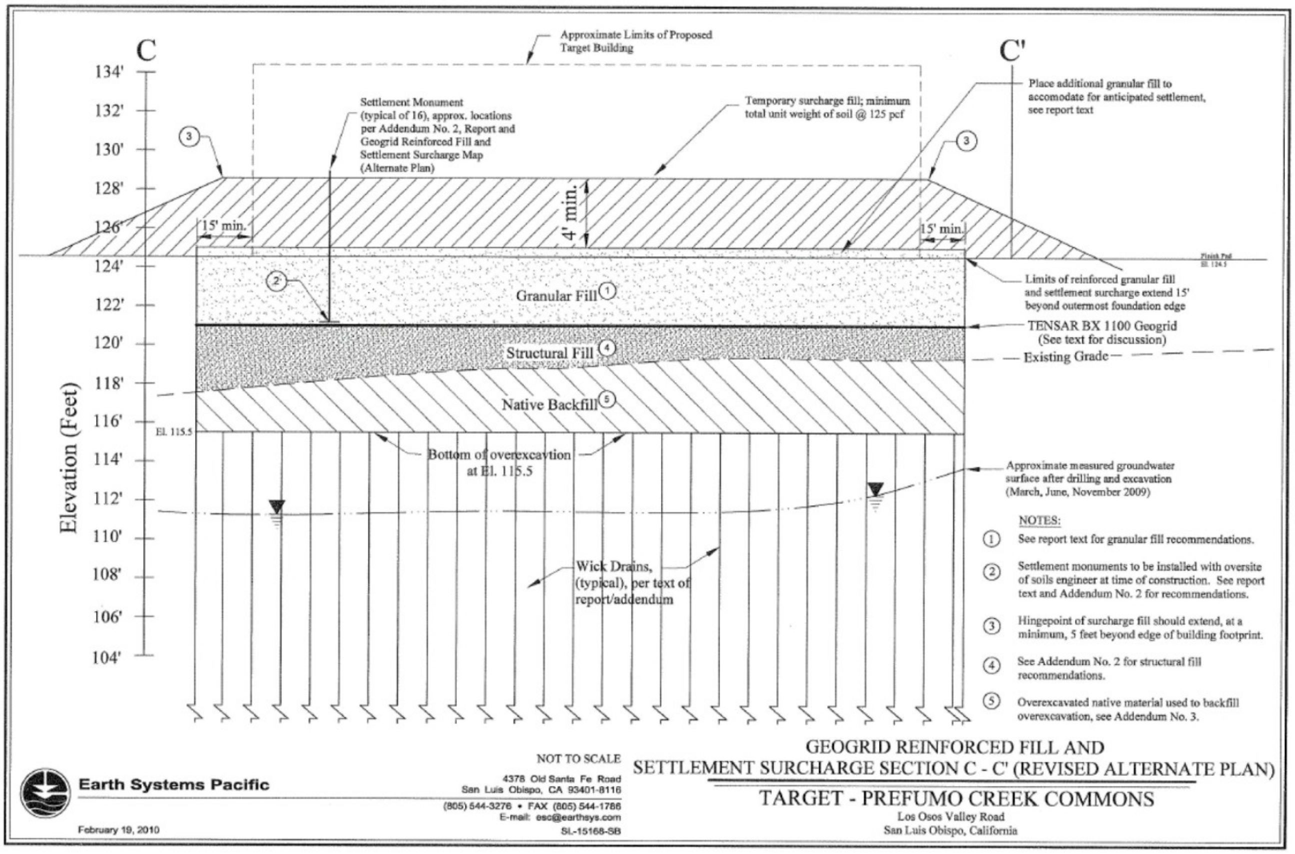

Figure 6. Cross section showing the fill needed to bring the foundation above the flood plain as well as surcharge fill and prefabricated vertical wick drains installed to preconsolidate the site within the project timeline of 3 months.

During construction, 20 settlement monuments (Figure 7) were surveyed up to 3 times per week by the project surveyor (Wallace Group) to within 3 mm accuracy. A monument consisted of a steel pipe welded to a steel base plate arranged such that steel pipe sections could be added as the fill height increased. A benchmark was established at the corner of the site using a small drilled shaft; its elevation was tied to a local city survey monument. The locations of the settlement monuments are noted on Figure 7 relative to the site improvements. The total amount of measured settlement was close to the predicted 10 to 15.5 cm (4 to 6 in) settlement, as presented in the geotechnical report (Earth Systems Pacific 2009). Figure 8 is a plot of the settlement for each of the monuments within the fill (an electronic supplement containing Figure 8 data is provided). The rate of settlement increased as the loads on the pad moved past the maximum past effective pressures. The total measured settlement ranged from just under 2.5 cm (1 in) to over 16.5 cm (6.5 in). King (2013) describes important geotechnical aspects of the project in a separate publication.

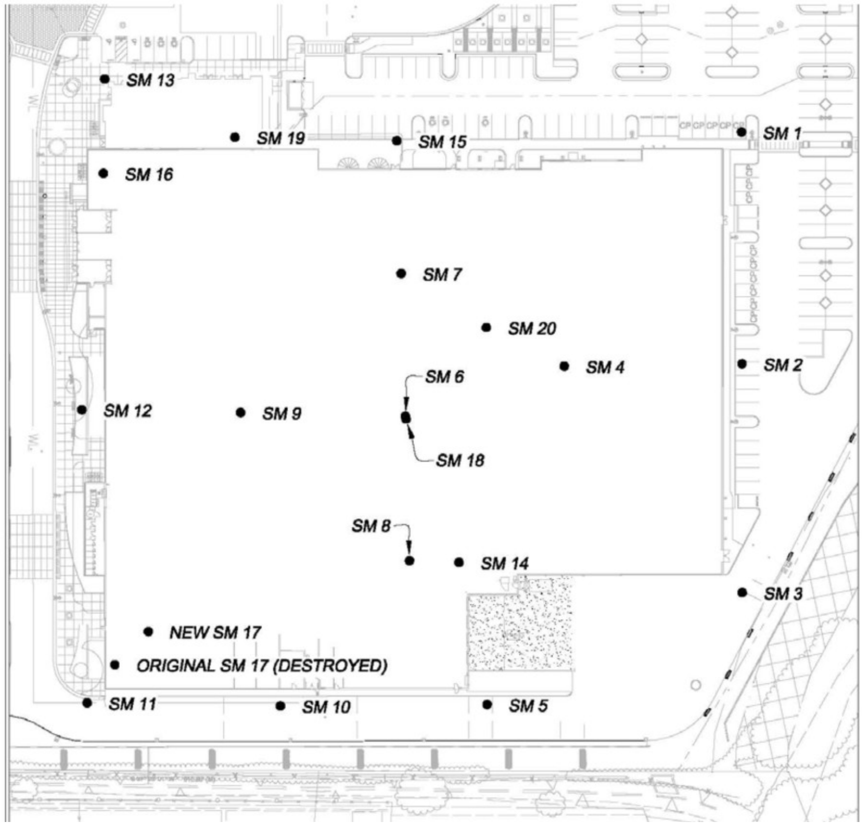

Figure 7. Site plan showing locations of the survey monuments that were measured 3 times per week.

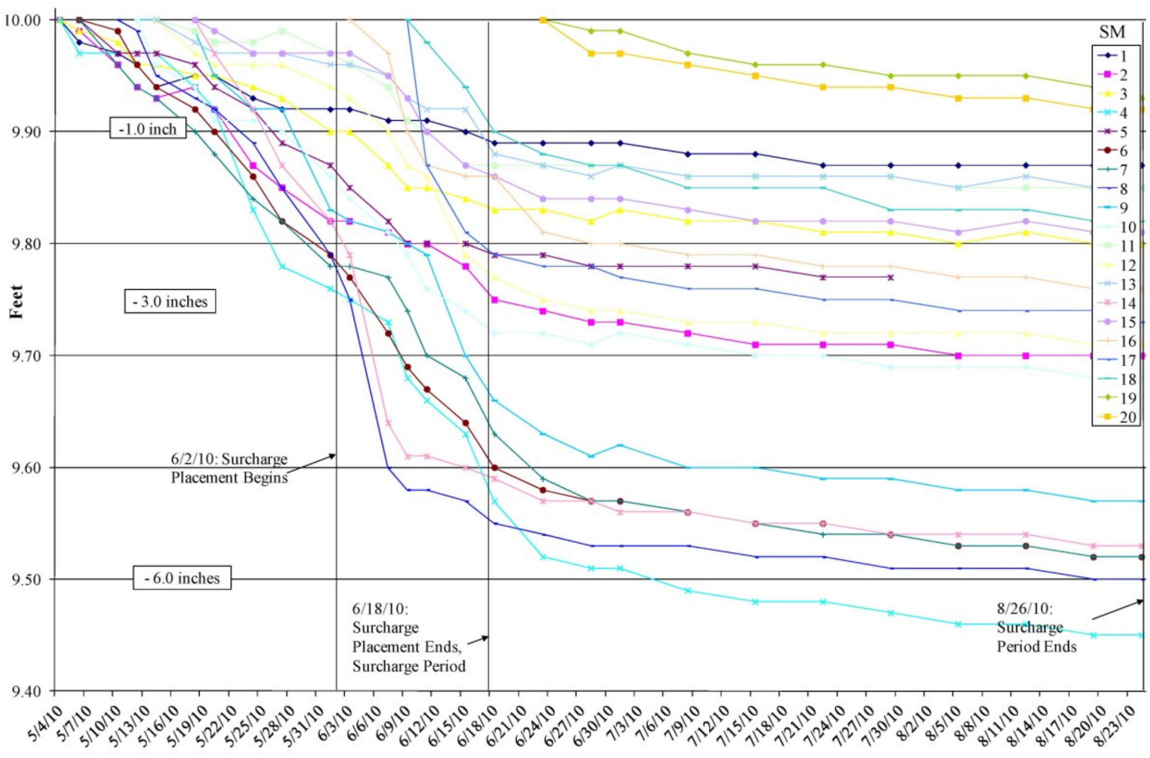

Figure 8. Measured settlement (y-axis) as a function of time (x-axis) for each monument shown in Figure 7.

CLASS ASSIGNMENT

Foundation Design Course

The presented settlement case study is introduced as a class assignment near the end of the quarter in Cal Poly's shallow foundation design course. This course is taught primarily to undergraduates who have already completed an introduction to soil mechanics in a previous quarter. Shallow foundation design is offered once every quarter and typically seats between 30 and 40 students per quarter. It is a prerequisite for all subsequent geotechnical courses, including deep foundation design, retaining structures, slope stability, in-situ testing, geoenvironmental engineering, ground improvement, and geotechnical earthquake engineering. The course has two main design components that share equal time during the quarter: design against ultimate limit state failure (i.e., bearing capacity analysis), and design for service limits (i.e., settlement analysis). These two design components are supported by modules on planning a site investigation, subsurface index testing and data analysis, lab testing procedures and data analysis, critical state soil mechanics, Mohr's circle and soil failure criteria, elastic stress distribution methods, bearing capacity theory, bearing capacity methods, shallow foundation types and foundation constructability, consolidation theory, calculation methods for immediate settlement, primary consolidation settlement, secondary compression, total and differential settlement issues, and other related sub-topics.

Learning Outcomes

One of the first steps in developing this class assignment was the articulation of learning outcomes. In this context, learning outcomes define what the students should know and be able to do upon completion of a course, course subject, or assignment. Outcomes are typically linked with an action verb, which is representative of a particular level of achievement in the cognitive domain (Fiegel, 2013). Outcomes should be specific and measurable. If posed carefully, outcomes can provide a useful tool for developing curricula and assessing student learning.

We identified the following learning outcomes for the case study described in this paper:

- Outline the procedure for performing a consolidation test and describe what data is collected;
- Interpret consolidation test results for the evaluation of compressibility and stress history;
- Describe how sample disturbance affects consolidation test results;
- Estimate primary consolidation settlement beneath a fill and a shallow foundation;
- Describe how preloading and vertical drains accelerate settlement in clayey soils; and
- Evaluate the accuracy of your solution based on different sources of information.

Student Activities

For this class assignment students are presented with an introduction to the case study and the identified learning outcomes. The assignment requires both magnitude and time-rate of settlement predictions. Students are asked specifically:

1. What is the magnitude of primary consolidation settlement due to the fill plus surchage load?
2. What is the appropriate wick-drain spacing to achieve 90% primary consolidation settlement within the alloted 3-month time frame?

Class discussions introduce the students to simple magnitude and time rate settlement calculations. The instructors typically follow methods presented in Holtz and Kovacs (1981), although the 2nd edition is used so the students aren't younger than the text (Holtz, Kovacs, and Sheahan; 2011). Terzaghi's 1D theory of consolidation is introduced, describing the Laplace equation and the graphical solution that is typically used to map the second order change of excess pore pressure with time and space. A demo using a bag of pretzels (Elton, 2001) presents an analog of the time rate effect of settlement in a two-phase system. A single layer example is presented on the board. Here the students work through the calculations on their own, and then together with the instructor to practice performing magnitude and time rate calculations for primary consolidation. The nuances of vertical versus horizontal (k_v vs. k_h) permeability are also discussed as this pertains directly to the vertical drains and the horizontal drainage path that they create (e.g., FHWA, 1986).

The students work in pairs on this assignment and are given all the consolidation test results that were available to the consultant during the original design (see electronic supplement). Working in pairs provides for a collaborative work environment. The students must coordinate their own internal review process prior to submitting their finished work. They have a week and a half to work on the assignment and ample opportunity to ask questions both in class and office hours prior to the deadline. Pairs can work with other pairs, but each pair must submit a unique report. In solving this foundation design problem and addressing the questions of "how much" and "how fast", the students must develop a three-dimensional understanding of the subsurface conditions across the site, reduce the lab data into usable consolidation parameters, and develop a spreadsheet for calculating magnitude and time rate of primary consolidation.

Letter Report Format

Students must present their findings and recommendations in a letter report, which is an informal report format that allows for efficient information transfer. The goal of this format is to push the students to be efficient and direct in communicating their engineering analyses and recommendations. The authors believe that clear and concise communication is key to being a good engineer and this format requirement provides a valuable practice opportunity.

As stipulated in the class assigment, each group letter report should include the following:

1. Header with the client's name, the names of the consultants (students) submitting the report, and the date;
2. Introductory paragraph stating the objective of the letter report and/or reiterating the client's request;
3. Description of the tests, procedures, analyses used to arrive at the information being presented in the report;
4. Results presented in a clear and concise manner;
5. Discussion of possible sources of error, data interpretation, and reasonableness of results;
6. Recommendations to the client based on the results;
7. References cited in the report; and
8. Appendices summarizing raw data sheets, sample calculations, additional plots or graphs, and other pertinent information.

In preparing their letter reports, students are instructed to prepare text and graphics using a computer. Sample calculations must be properly referenced and included in an appendix, but they may be handwritten. All values must be reported in SI units. American units may be included in parentheses, as they are in this paper. Overall, clarity, brevity, organization, and professional presentation all figure prominently in report assessment.

Grading Policy

Instructors use the following grading policy when assessing student performance on this project. Typical homework assignments in this class are worth 10 points. This assignment is worth two homeworks, or 20 points. Shown below is a typical grading sheet for this assignment.

Grading Policy for Settlement Project

5 pts	Report is submitted on time
5 pts	Report follows the required format
2 pts	Design package is organized and professionally presented
2 pts	Calculations are easy to follow and reviewed for quality assurance
3 pts	Calculated settlements answer are within 7 to 23 cm (range of field measurements)
3 pts	Recommended wick-drain spacing is within 1.5 to 2.5 m (acceptable range of calculations)
20 pts	TOTAL

Specific Comments:

Figure 9. Typical grading sheet.

Presentation of Measured Field Settlement

Once the students complete and submit their letter reports, the geotechnical engineer of record on this project (second author) presents an in-class summary of the analyses, construction, and field measurements of the preconsolidation settlement. The students are fully vested in the project at this point, having spent at least a week and a half working and struggling with the consolidation curves and wrapping their heads around the nuances of primary consolidation and time-rate calculations. Anticipation and enthusiasm are high because the students know a portion of their grade is riding on an accurate prediction.

The presentation itself is interactive; students are encouraged to ask questions throughout. An open discussion follows the presentation allowing the students, instructor, and presenter to delve into project details, analyses, and/or results. Finally a guided discussion rounds out the meeting where the class reviews each of the learning outcomes point by point to reinforce the key elements of this project.

LESSONS LEARNED BY THE INSTRUCTORS

Working on this project usually represents the first time students have been asked to deal with real "messy" geotechnical data, the type that they will encounter often in their future consulting careers. The experience provides an excellent mentoring opportunity; the instructor can assist the students in determining what is important and what is not important when performing settlement analyses. Listed below are common project-related questions by the students in class, during office hours, and during the final presentation by the practicing professional:

- What do I use for unit weight (γ) if it is not given?
- How do the samples at different depths and locations relate to each other?
- Why aren't there more borings and samples at the site?
- What are reasonable virgin (C_c) and recompression (C_r) indices?
- How do I assess stress history for consolidation curves exhibiting significant disturbance?
- Should I use average or lower bound indices?
- Is the fill compressible and should it be included in the settlement calculations?
- In my settlement spreadsheet, how thick should the sublayers be?
- How do I know if my results are reasonable?

The notion of uncertainty in performing geotechnical calculations is unfamiliar for most students and they must be coached through the reality of estimating consolidation in the face of data paucity. Students at this stage of their academic careers are highly adept at performing precise calculations, but not well versed in achieving accurate calculations. (Note: precision is repeatability, accuracy is correctness.) Listed below are guidelines offered by the instructor for improving accuracy:

- Run a sensitivity study on your calculations to determine which input variables have the largest influence on the results, and then focus on "pinning down" the most sensitive input variables.
- Research other consolidation projects in the literature/text and use available information to calibrate your analyses.
- Check your input variables against typical values found in textbooks to confirm you are "in the ballpark" with your own recommendations and results.
- Have each project partner perform the calculations independently and then compare results. When differences are encountered, determine the basis of the differences and a best path forward.
- Decrease the sublayer thickness in your spreadsheet until the change in the results reaches a plateau or acceptable level of tolerance (e.g., 5%).

The students submit anonymous teaching evaluations at the end of every quarter. They evaluate the course and the instructor both in qualitative comments and in quantitative scoring. Since implementing this case study, the students have provided written feedback specifically identifying this assignment as a "worthwhile" learning process. In addition, instructor evaluation scores for the class have gone up roughly 10% compared to quarters when the project has not been used. A typical student comment is "so glad we got to work on a real settlement project." Students who have graduated and moved on to practice often reflect on this project and provide feedback that this assignment in particular prepared them well for dealing with settlement problems.

CONCLUSIONS

Presented herein is an example of a ground improvement case study that has proven instructive in Cal Poly's undergraduate shallow foundation design course. Use of real data in the classroom gives students the "messy" details they will often encounter in practice. While developing engineering judgment requires years of experience, the exposure to such a concept in the classroom is a first step in grappling with this important non-technical skill. Collaboration between consulting engineers and university engineering professors has been a rewarding experience that affords the students a challenging, comprehensive, and interesting educational experience. This settlement case study provides a useful vehicle for defining specific learning outcomes that enable students to tackle complex foundation performance issues when they graduate and enter geotechnical practice.

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- Target Corporation Target Stores, Target Executive Offices, PO Box 9350, Minneapolis MN 55440
- Wallace Group, 612 Clarion Ct., San Luis Obispo, CA 93401

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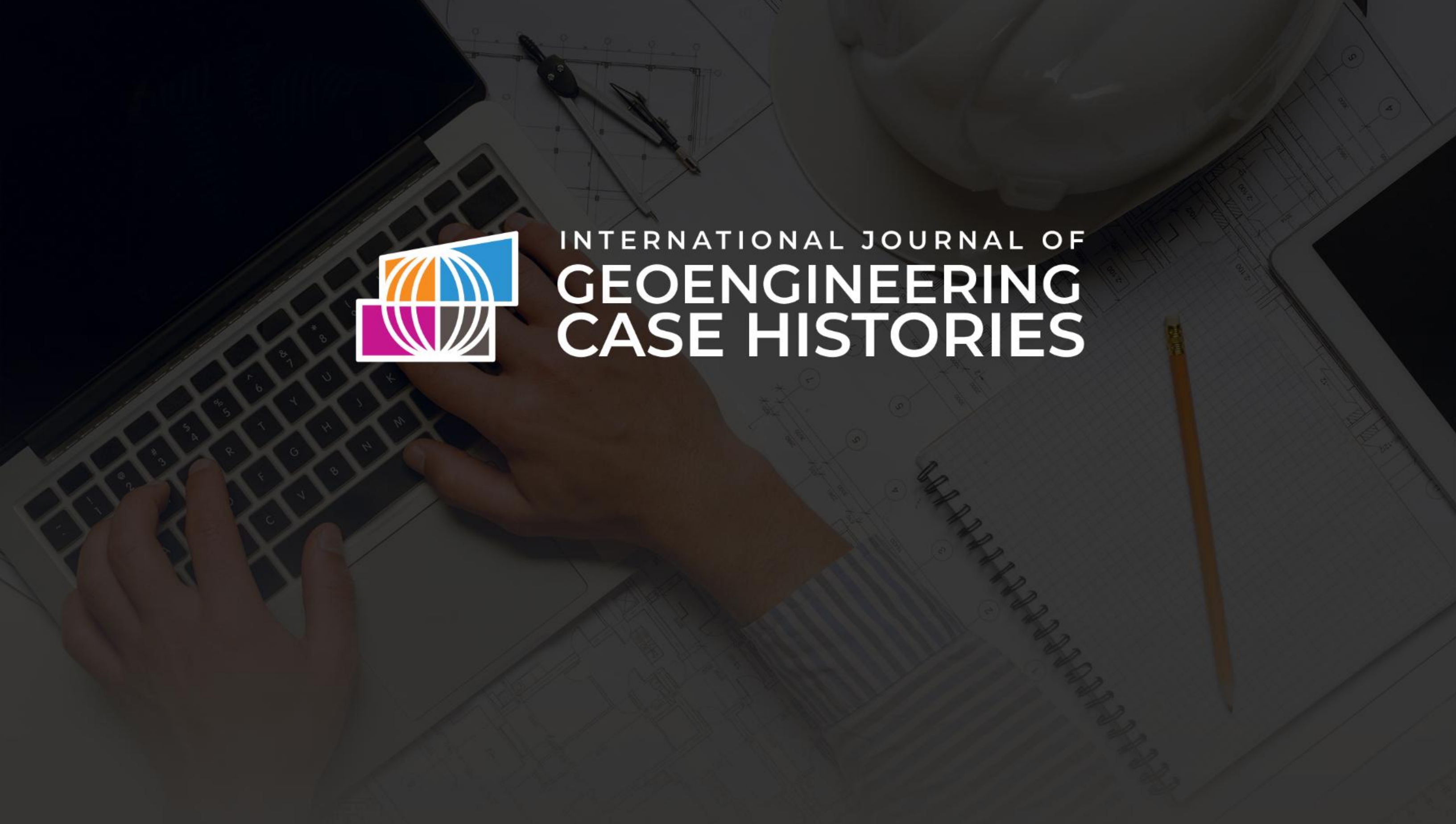
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