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Forensic Engineering Evaluation of Excessive Differential Settlement on Compressible Clays

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Abstract

This forensic engineering (FE) study evaluated root cause errors associated with excessive differential settlements on a housing project constructed on top of a variable thickness layer of highly compressible clays. The structures were reported to have experienced differential settlements on the order of 2 to 10 in. across 40 ft. The FE study examined fundamental assumptions, granularity/resolution of the settlement and differential settlement analyses, and finalized grading plan vs. the conceptual grading plan used as a basis for the differential settlement predictions. The FE study found numerous discrepancies between the "idealized site" used as a basis of analysis and the "actual site" as constructed.

Keywords

Consolidation settlement, foundations, settlement, differential settlement, compressible clays, root cause errors, time-rate effects, geotechnical, site development, forensic engineering

Introduction

This FE study evaluated root cause errors associated with excessive differential settlements on a housing project constructed on top of a variable thickness layer of highly compressible clays. These compressible clays are subject to volumetric strain as a result of loads applied changing the stress distribution.

Soil deformations, manifested primarily through vertical displacements or "settlement," occur via changes in stress, water content, soil mass, or temperature. These soil deformations are classified[1] into the following types:

- *Elastic Deformations* — Small deformations that occur nearly immediately following changes in stress state;

- *Primary Consolidation* — Time-delayed settlement by volumetric reduction as a result of reduction in water content. Due to the very low permeability of fine-grained clayey soils, consolidation settlement can take a very long time to occur as a result of the very slow drainage of water out of the soil matrix. Excess pore pressures are dissipated by the gradual expulsion of fluid from voids in the soil leading to the associated compression of the soil skeleton. Excess pore pressure is pressure that exceeds the hydrostatic fluid pressure. The hydrostatic fluid pressure is the product of the unit weight of water and the difference between the given point and elevation of free water (phreatic surface);

- *Secondary Compression/Creep* — The compression and distortion at constant water content of compressible soils. This phenomenon occurs at a much slower rate than consolidation settlement.

- *Dynamic Forces* — Dynamic loads can cause settlement from rearrangement of particles, particularly in cohesionless soils (i.e., sands and gravels), resulting in a decrease of void space (air or water).

- *Expansive Soil* — Expansive soils contain colloidal clay minerals, such as montmorillonite, that experience heave and shrinkage with changes in the soil water content.

- *Collapsible Soil* — Typically cohesive silty sands with a loose structure or large void ratio. The cohesion is usually caused by the chemical bonding of particles with soluble compounds such as

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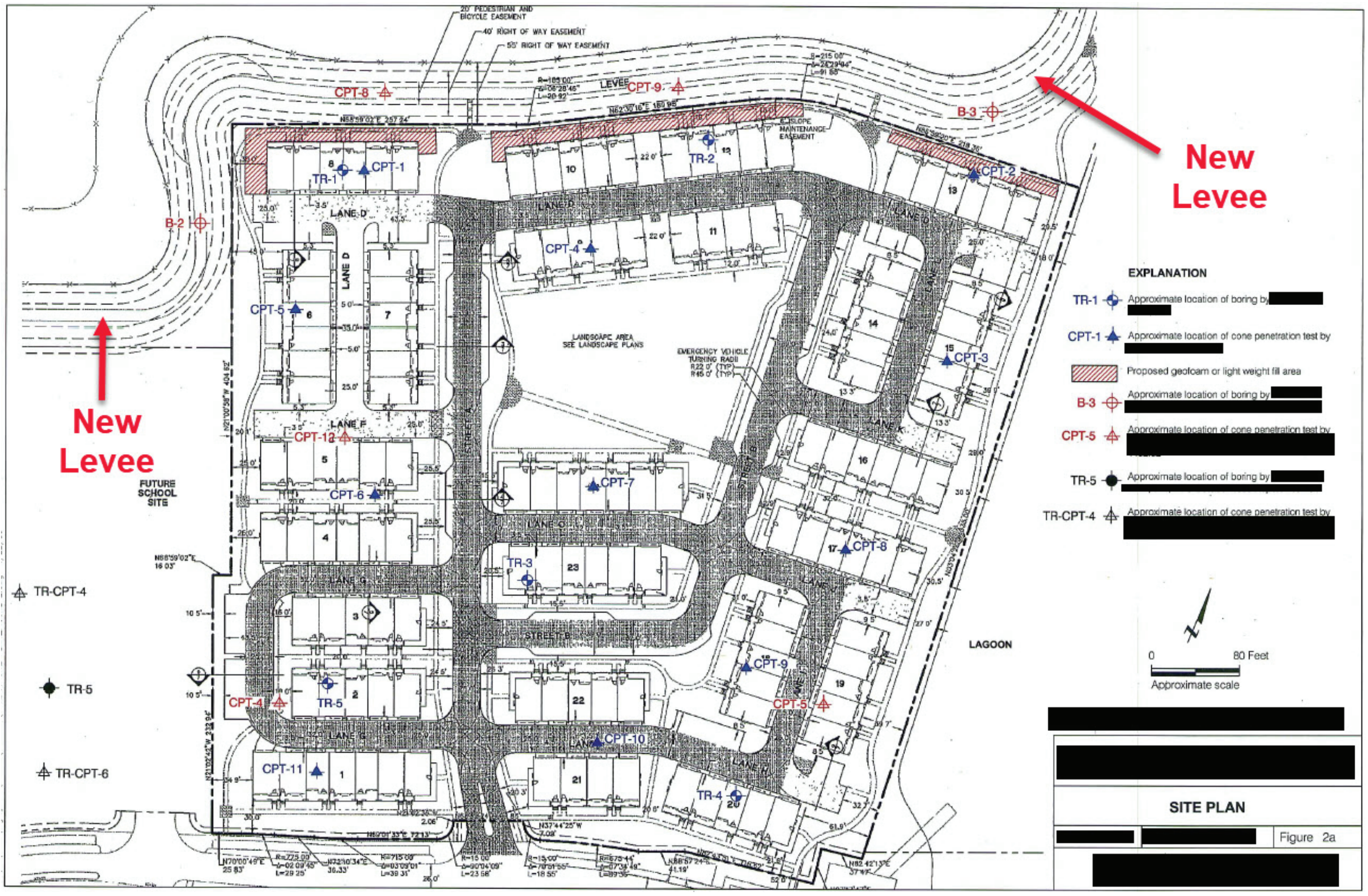


Figure 1
Overview of development features, which included a perimeter levee, site grading, multi-unit structures, and streets/utilities. Source: Discovery Docs.

cancerous or ferrous salts. Collapse occurs when the bonds between particles are dissolved.

The soil deformation mode being address in this paper is consolidation and the heterogeneity of vertical settlements across a spatially diverse deposit of highly compressible clays.

The authors were retained as experts by the plaintiffs. The case settled during mediation. The findings and opinions were subject to critique by defense experts as well as experts for both the plaintiff and defense being subject to depositions by opposing counsel. The mediation concluded in a settlement offer to the plaintiffs, which was accepted. The settlement was of a sufficient magnitude to compensate the plaintiffs for damages and fund mitigation efforts.

Project Overview

This project comprised the construction of a residential development and perimeter levee on a highly compressible non-uniform clay deposit with variable thickness (**Figure 1**). The potential for large and variable settlements were identified early in the planning process. **Figure 2** shows an overlay of an aerial image of the project area before initiation of construction. The area is situated in a bay margin with wetlands and sloughs. Interpolated contours of compressible clay thickness are shown. The clay thickness varies

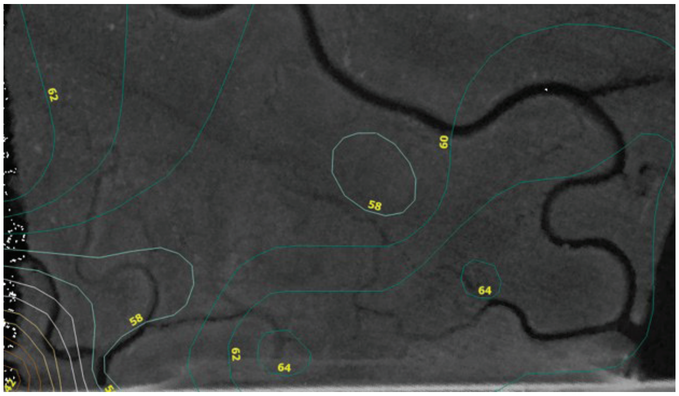


Figure 2
Overlay of compressible clay thickness and aerial image showing sloughs traversing the project area. Source: Author.

Figure 3
Overlay of compressible clay thickness and planned rough grading for the residential development and perimeter levee within the project area.
Source: Discovery Docs; contours by author.

from about 58 ft to 64 ft, based on the available subsurface information. **Figure 3** shows the same overlay, but with the planned site rough grading.

Several approaches to confront the potential settlement were identified and evaluated prior to initiation of construction. These approaches included: deep foundations for the structures bypassing the compressible soils; conventional surcharge loading by placing soil stockpiles and waiting for the site to realize the expected settlements prior to construction of the structures; and use of wick drains to increase the rate of consolidation and reduce the waiting period between site loading and realization of the full magnitude of anticipated settlements.

Deep foundations were eliminated as a feasible foundation type due to the very high costs associated with the quantity and length of foundation elements required. The long wait time required for conventional surcharge loading precluded that as an option to mitigate projected consolidation settlements within the desired development time period.

To accomplish the project in a shortened construction period, wick drains were used along with staged fill placement to accelerate consolidation settlement (**Figure 4**).

Figure 4
Installation of wick drains at select locations to facilitate "rapid" consolidation settlement. Source: Discovery Docs.

Wick drains facilitate acceleration of the consolidation settlement process by reducing the drainage path of the water to evacuate the soil skeleton. By reducing the distance, the water has to travel before evacuating the soil mass, the time rate of consolidation is accelerated.

For example, without wick drains and a clay thickness of 60 ft, the water may have to travel a distance of 30 ft before it can be fully evacuated from the soil mass. With wick drains installed at a spacing of 6 ft (and driven the full depth of the clay layer thickness), the water now only needs to travel 6 ft before being evacuated. Thus, the reduced travel distance directly reduces the time required to achieve the anticipated settlement magnitude.

Figure 5 shows an overview of the wick drains installed in the slough areas (yellow highlight) that traverse the residential development. This limited treatment zone resulted in some buildings having wick drains installed in portion of the building pad area and no wick drains in the other areas. It is inferred that the design assumption was the majority of settlement would occur during the rough grading and phased fill placement stage of the project and after construction of the building pads, the magnitude of remaining settlement would be negligible, and thus the use of wick drains in limited areas would have insignificant impact on differential settlements.

The use of wick drains was selected for the areas of the project to receive the greatest quantities of import fill. These areas included the new levee as well as the historic sloughs. Settlement plates and pore pressure transducers were installed at select locations to allow the engineering team to evaluate the degree of pore pressure dissipation following placement of the fill. Once the magnitude of pore pressure dissipation reached the calculated stress from fill placement, it was assumed that the consolidation settlement was complete — and site work could continue with minor future settlements as a majority of the settlements had already occurred.

Figure 6 shows a conceptual rendering of the proposed residential units. The units were anticipated to be

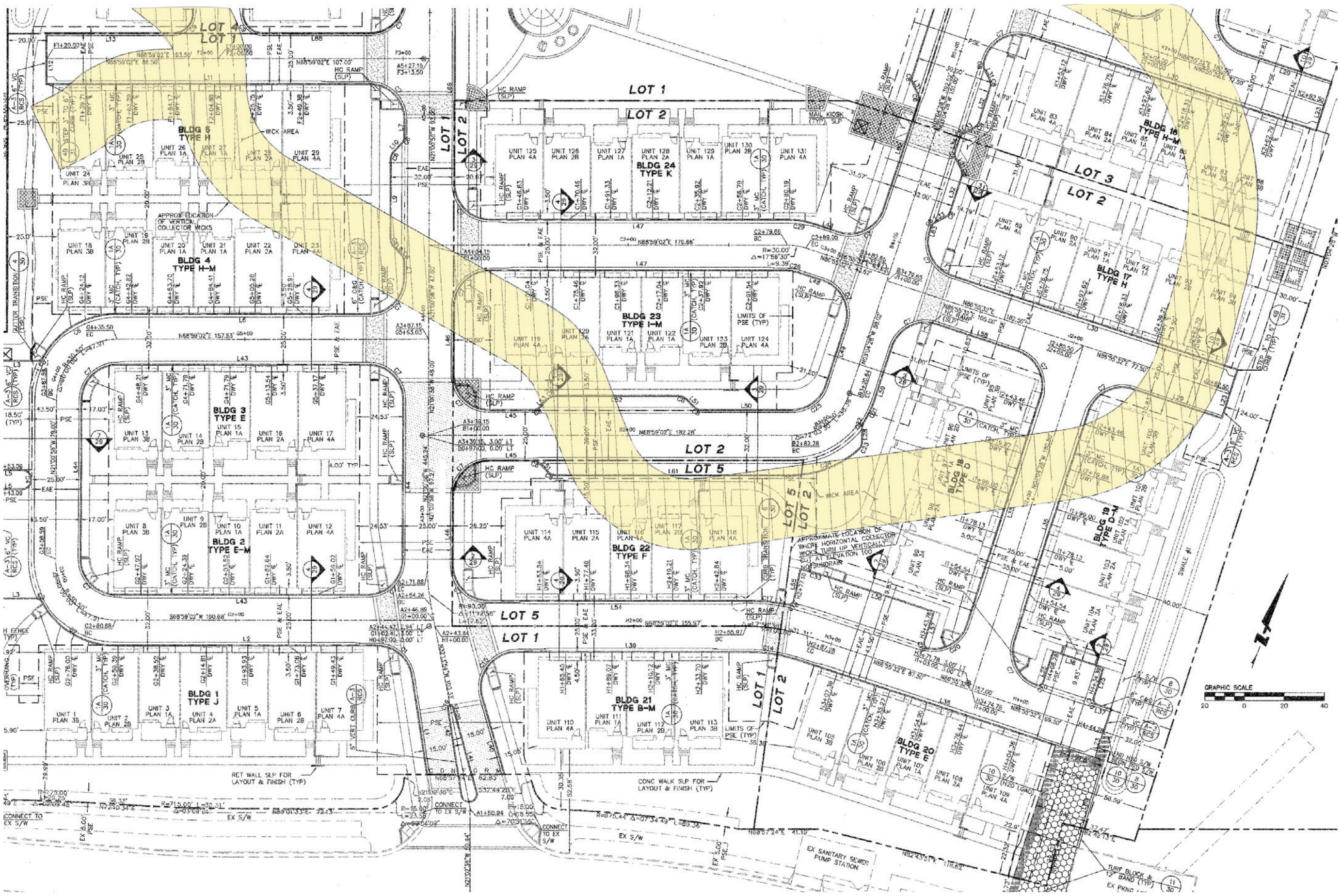


Figure 5
Location of historic slough relative to new building footprints. Source: Discovery Docs.

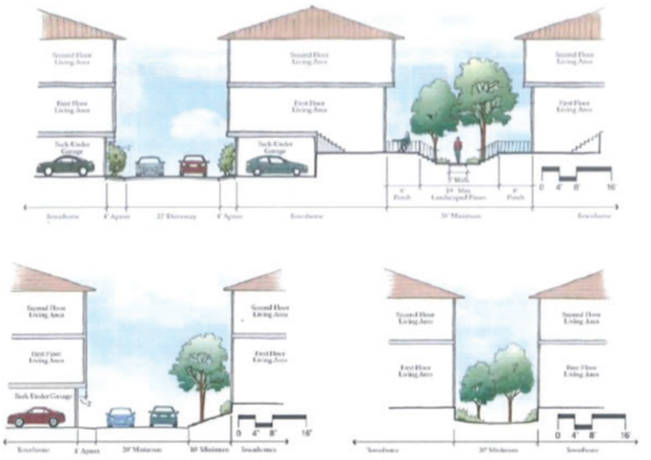


Figure 6
Architectural rendering of the multi-unit structures showing the micro-topography and variable site grade elevations across the project area. Source: Discovery Docs.

three stories tall, with the parking garage situated facing the street and the main entrance on the opposite side of the structure. All units had a stepped entrance with staircases to the front door elevated several feet above the surrounding grade. Some units were configured to have an elevated walkway (called a paseo), some units had slightly elevated landscaping area, and some units had porches with steps leading up from street level.

The project construction timeline spanned a period of approximately three years and consisted of the following :

- Month 0: Start construction/clear and grub.
- Month 1: Rough grade and wick drain installation.
- Month 3: Start Phase 1 rough grading fill placement.
- Month 5: End of Phase 1 rough grading fill placement; start consolidation wait period #1.
- Month 9: Start Phase 2 rough grading fill placement.
- Month 10. End Phase 2 rough grading fill placement, start consolidation wait period #2.
- Month 13: Start Phase 3 rough grading fill placement.
- Month 15: End Phase 3 rough grading fill placement; start consolidation wait period #3.
- Month 18: Start finish grading, streets/sidewalks, utilities.
- Month 20: Building Group 1 construction starts.
- Month 30: Building Group 1 construction complete, start Building Group 2.
- Month 34: Building Group 2 construction complete; start Building Group 3.
- Month 36: Building Group 4 initiated.
- Month 40: Construction complete.
- Month 64: Approximately two years following completion of construction, first complaints were submitted to builder about difficulty closing doors/windows.

There were no deviations or problems flagged during the course of construction and all as-built documentation indicated that the project had been constructed as specified and within the delineated tolerances.

Documented Structure Distress

The triggering of structure distress conversations between the homeowners and the builders initiated a couple years after completion of construction when the homeowners had problems opening/closing doors and windows.

Floor level surveys were commissioned by the Homeowners Association (HOA) to document the distribution of elevation differences across the structures. **Figure 7** shows an example floor level survey within a structure. Note that each structure has a number of sub-units. Typically, each structure associated with this project had five to seven sub-units.

The magnitude and distribution of realized differential settlements launched a development-wide inquiry (and subsequent litigation) as to the cause of these differential settlements, the acceptability thresholds of differential settlement for the structures and individual units, and ultimately identification of solution(s) available to mitigate the unacceptable realized settlements.

FE Evaluation

The FE study presented in this paper is focused on identification of root causes for the excessive differential settlements as well as an understanding of the potential

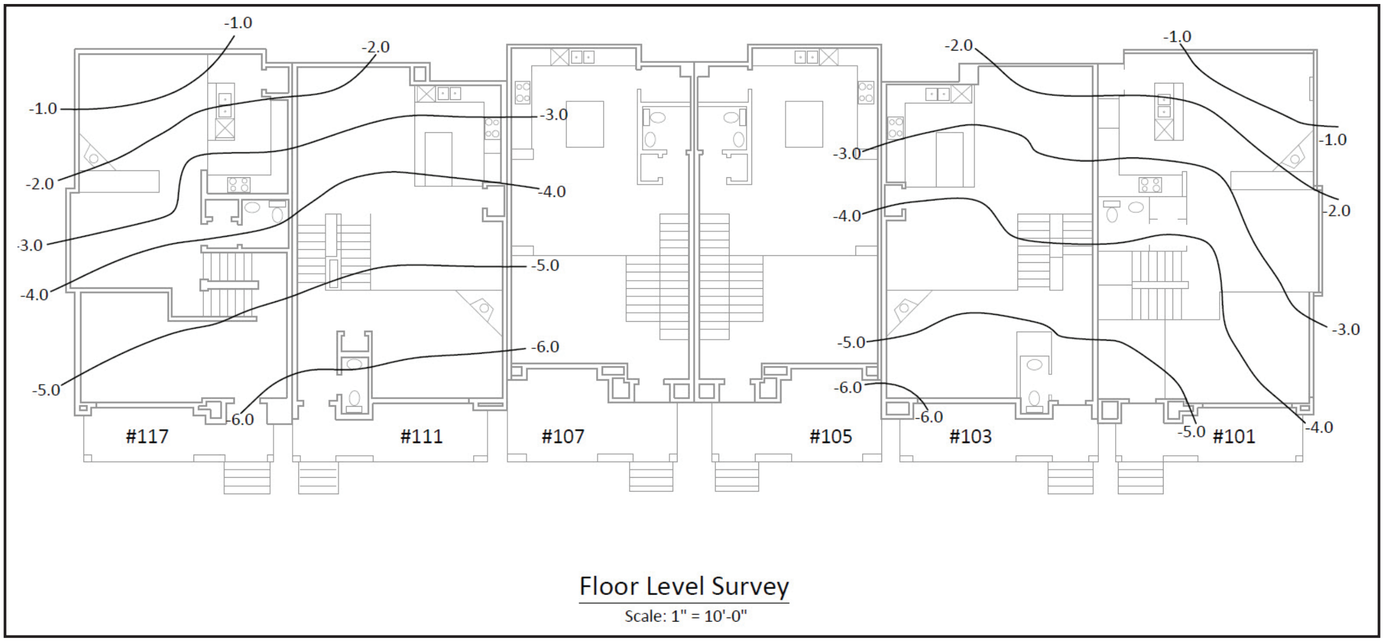


Figure 7
Example floor level survey showing differential settlement trends across the multi-unit structure. Source: Discovery Docs.

for additional differential settlement in the future. The FE study does not address mitigation efforts. The FE approach used to ascertain the root causes of the unintended differential settlements consisted of the following steps:

1. Review design calculations and associated assumptions;
2. Review project plans and specifications (construction bid package);
3. Review available construction documents; and
4. Compare/contrast the design details communicated via the construction bid package with the as-constructed conditions.

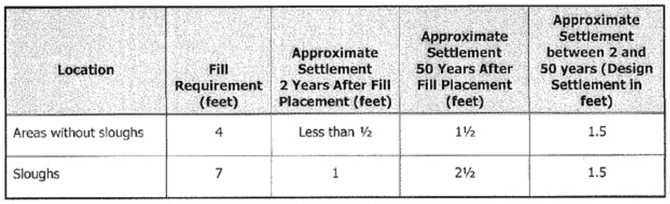
The discovery documentation made available for this case was fairly comprehensive, thus allowing for a reasonable evaluation of both the design calculations and the as-constructed conditions.

Idealized Conditions

The engineering analyses were centered about settlements for the perimeter levee. Few calculations were developed for the interior rough/finish grading associated with the building pads. In the building pad areas, analyses were performed assuming uniform fill. The placed fill was assumed to have a representative unit weight of 120 lb per cubic ft (pcf).

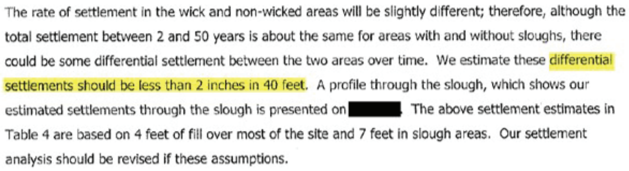
Based on these design assumptions, estimates were developed for total settlement, differential settlement, as well as settlement time-rate curves. The maximum settlement was anticipated to be approximately 2 ft over a 50-year period, with about ½ to 1 ft occurring in the first two years following completion of fill placement and the remaining 1.5 ft occurring fairly slowly over a 48-year period (**Figure 8**).

The maximum design differential settlement was documented by the project geotechnical engineer[2] to be "less than 2 in. in 40 ft," as shown in **Figure 9**.



Location	Fill Requirement (feet)	Approximate Settlement 2 Years After Fill Placement (feet)	Approximate Settlement 50 Years After Fill Placement (feet)	Approximate Settlement between 2 and 50 years (Design Settlement in feet)
Areas without sloughs	4	Less than ½	1½	1.5
Sloughs	7	1	2½	1.5

Figure 8
Predicted total settlements across the project site with development of housing units (Source: Project Geotechnical Report)[2].



The rate of settlement in the wick and non-wicked areas will be slightly different; therefore, although the total settlement between 2 and 50 years is about the same for areas with and without sloughs, there could be some differential settlement between the two areas over time. We estimate these differential settlements should be less than 2 inches in 40 feet. A profile through the slough, which shows our estimated settlements through the slough is presented on [redacted]. The above settlement estimates in Table 4 are based on 4 feet of fill over most of the site and 7 feet in slough areas. Our settlement analysis should be revised if these assumptions.

Figure 9
Identification of the expected differential settlement for the development (Source: Project Geotechnical Report)[2].

Figure 10 shows the general trend of settlement over time, with the majority of the settlement occurring in the first two to four years. The plot shown in **Figure 10** was prepared for the perimeter levee. No equivalent plots were developed for the interior residential development.

Findings (Actual Conditions)

The FE study found two major deviations from the design assumptions and over-simplification of analytic models: very heterogeneous fill materials used at the project site that were much larger than the assumed soil density; and highly variable fill thicknesses around the residential structures which exacerbated the magnitude of differential settlement experienced by the structures compared with the very linear and uniform site grading assumed as part of the design analyses.

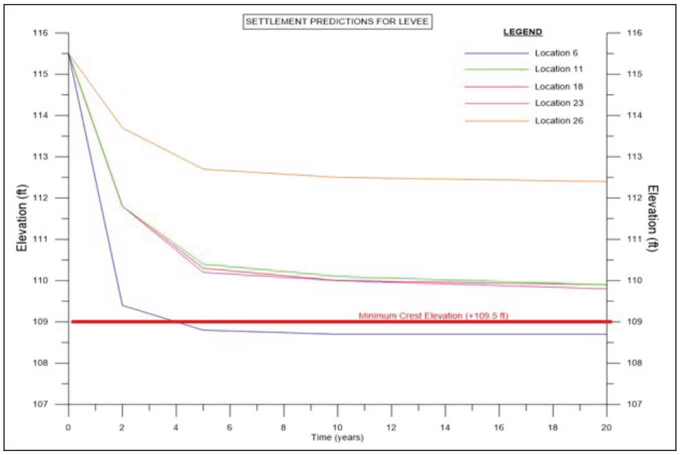


Figure 10
Plot of estimated site settlements at select locations for the first 20 years after levee grading. Settlement for the interior residential development would have a similar shape, but different ultimate magnitude 2 ft as predicted by the geotechnical engineer. Source: Author.

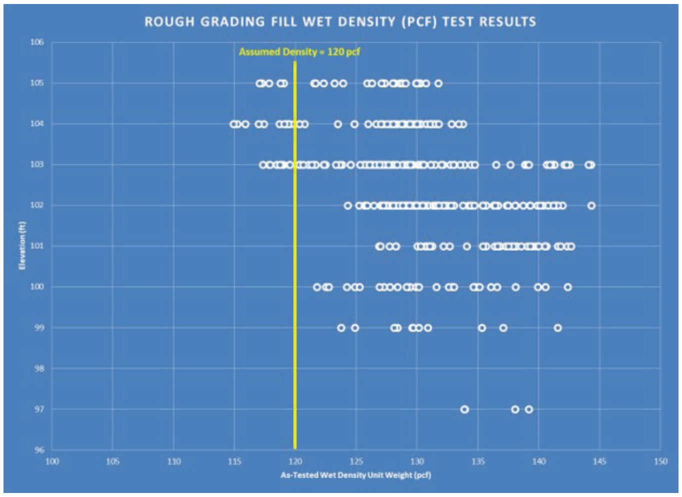


Figure 11
Distribution of actual in-place soil densities as a result of differing import sources and compaction effort. Source: Author.

Figure 11 shows a plot of measured soil densities during fill placement. The assumed density of 120 pcf is highlighted in yellow. The white circles are individual test results and span a density range of about 115 pcf to just under 145 pcf. Of the 359 soil density tests, 330 tests were in excess of 120 pcf, which is approximately 92% of all the tests. Additionally, the spatial distribution of the varying soil densities was not uniform, resulting in heterogeneous distributions of differing soil densities across the spatial footprint of the development. In addition to the large skew between assumed soil density and actual soil density, the complexity of the finish grading for the development further exacerbated the magnitude of realized differential settlements.

Figure 12 shows a simplified numerical model to examine the effects of small variations in fill thicknesses as a result of micro-topography. The micro-topography included levee fill on the left side of the houses and sloping landscape fill on the right-hand side of the houses. The analyses were not intended to directly replicate the realized differential settlements as the subsurface conditions and associated soil material properties were not sufficiently established. The model, however, was generally calibrated to the range of vertical settlements observed as part of the site response following fill placement and construction of the residential units.

The results of the numerical modeling of Building B-B are illustrated in **Figure 13**. The model evaluated the impact on differential settlement across the building. Point “A” is situated on the street side of the building with site grade at approximately El. +102 ft. Point “B” is located on the opposite side of the building, with site grade at approximately El. +106 ft. The numerical analyses of the simplified model show the impact of this fill thickness differential has the ability to increase the magnitude of differential settlement by a factor of two to three. Thus, the project geotechnical engineer’s predicted differential settlements of 2 in. in 40 ft, would increase, as a result

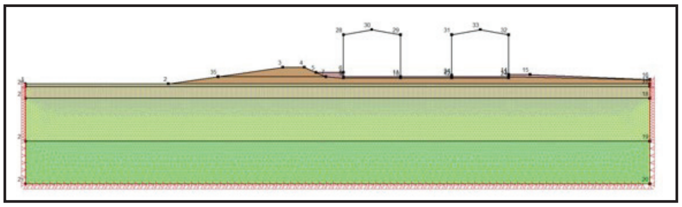


Figure 12
Simplified numerical model to explore implications of micro-topography. Source: Author.

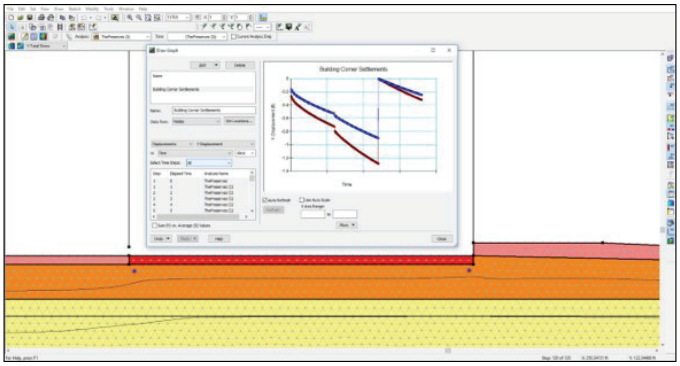


Figure 13
Calculated settlements at building edges
with micro-topography effects accounted for. Source: Author.

of the different fill thicknesses, to 4 in. in 40 ft or 6 in. in 40 ft. This simplified analysis illustrates the non-uniform fill results in differential settlements which are in excess of the maximum design differential settlement of 2 in. in 40 ft.

Conclusion

This FE study evaluated root cause errors associated with excessive differential settlements on a housing project constructed on top of a variable thickness layer of highly compressible clays. The soil deformation mode being address in this paper is consolidation and the heterogeneity of vertical settlements across a spatially diverse deposit of highly compressible clays.

This project comprised the construction of a residential development and perimeter levee on a highly compressible non-uniform clay deposit with variable thickness. The potential for large and variable settlements were identified early in the planning process.

The triggering of structure distress conversations between the homeowners and the builders initiated several years after completion of construction when the homeowners had problems opening/closing doors and windows.

The FE approach used to ascertain the root causes of the unintended differential settlements consisted of reviewing design calculations and associated assumptions; reviewing project plans and specifications (construction bid package); reviewing available construction documents; and comparing/contrasting the design details communicated via the construction bid package with the as-constructed conditions.

The FE study found two major deviations from the design assumptions and over-simplification of analytic models: very heterogeneous fill materials used at the project site that were much larger than the assumed soil density; and highly variable fill thicknesses around the residential structures that exacerbated the magnitude of differential settlement experienced by the structures compared with the very linear and uniform site grading assumed as part of the design analyses.

Reference

1. U.S. Army Corps of Engineers. “Engineering and Design, Settlement Analysis,” EM 1110-1-1904, dated September 30, 1990.

2. Geotechnical Design Report prepared for project and presented in disclosure documents.