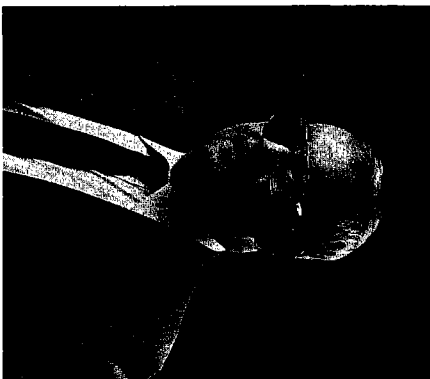


THE TWENTY-SEVENTH TERZAGHI LECTURE

Presented at the American Society of Civil Engineers

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October 22, 1991



J. MICHAEL DUNCAN

INTERNATIONAL SYSTEM OF UNITS (SI)

Each author must use SI units and units acceptable in SI. Other units are not required, but may be given in parentheses or in an appendix if the author desires. A complete guide to SI and its use may be found in the latest edition of *ASTM E380: Standard Practice for Use of the International System of Units (SI)*, which may be obtained from ASCE Headquarters by calling 1-800-548-ASCE. Other useful references include *ANMC Metric Editorial Guide*, 5th Ed., 1992, American National Metric Council, 1735 N. Lynn St., Ste. 950, Arlington, VA 22209-2022, and *Metric Manual*, by Lawrence D. Pedde et al., 1978, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colo.

As a preliminary assistance to authors, who must now prepare their papers and notes in SI units, the ASCE Committee on Metrication recommends the following conversion factors:

To convert	To	Multiply by
acre-foot (acre-ft)	m ³ (cubic meter)	1.23 × 10 ³
acre (acre)	ha (hectare)	0.405
atmosphere (atm)	Pa (pascal)	1.01 × 10 ⁵
cubic feet per second (cfs)	m ³ /s	0.028
°F	°C	[subtract 32 and divide by 1.8]
inch (in.)	mm (millimeter)	25.4
kilogram force (kgf)	N (newton)	9.81
kilogram-force-meter	N·m (newton-meter)	9.81
mile (mi)	km (kilometer)	1.61
millions of gallons per day (mgd)	m ³ /s	4.38 × 10 ⁻²
pound force (lbf)	N (newton)	4.45
pound-force/inch	N/m (newton/meter)	1.75
pound force per square inch (psi)	kPa (kilopascal)	6.89
pound mass (lbm)	kg (kilogram)	0.454
U.S. gallon (gal)	L (liter)	3.79

INTRODUCTION TO THE TWENTY-SEVENTH TERZAGHI LECTURE

By Clyde N. Baker Jr.

Dr. James Michael Duncan will feel right at home presenting the 27th Terzaghi lecture here today. He attended high school in Eustis, Florida, which is approximately 40 mi north of Orlando. One of the highlights of Mike's high school career was playing football, and he was team captain in his senior year. Unfortunately, that team had the worst record in the history of the school, and lost one game by a score of 67 to 6. Mike did a little better after high school. He attended Georgia Tech as a co-op student, graduating in 1959 with his B.S.C.E. His subsequent specialization in soil mechanics occurred accidentally. He resigned from his job as an engineer in Tampa when he was asked by a superior to falsify some time sheets. The next day, he received a phone call from a friend who said there was a research assistantship available in soil mechanics at Georgia Tech if he wanted to go back for his master's degree. Mike responded that he didn't really like soil mechanics, but since he had a wife and daughter to support, and it was better than starving to death, he'd take it. The rest is history.

Mike got his M.S.C.E. at Georgia Tech in 1962, and worked briefly in the Soils Division of the Waterways Experiment Station in Vicksburg on his way to the University of California at Berkeley, where he obtained his Ph.D. degree under Harry Seed in 1965. He taught at Berkeley until 1984 before moving to Virginia Polytechnic Institute and State University in Blacksburg, Virginia, where he now holds the title of University Distinguished Professor in the Department of Civil Engineering.

Throughout his 30 year career, Mike has been an outstanding researcher, teacher, and worldwide lecturer. He has received eight awards for teaching excellence, seven awards for professional achievement, and six awards for research and publications, including the Wellington Prize, the Walter H. Huber Research Prize, the Collingwood Prize, and the Thomas A. Middlebrooks award twice from ASCE. Tomorrow, he will be receiving the ASCE State-of-the-Art Civil Engineering Award for 1991.

Two themes appear consistently in his more than 180 publications and research reports: practical applications of numerical analyses, and investigation of soil properties and behavior. These two themes will be evident in Mike's Terzaghi lecture on the "Limitations of Conventional Analysis of Consolidation Settlement." The basis for the talk comes from his analysis of extensive settlement records at Bay Farm Island in San Francisco Bay, and at the Kansai International Airport project in Japan.

Mike's wife, Ann, their children Mary, Susan, and John, and his sister Sally are here with us today to enjoy the 27th Terzaghi lecture. It is with honor and great pleasure, that I present to you Dr. James Michael Duncan.

LIMITATIONS OF CONVENTIONAL ANALYSIS OF CONSOLIDATION SETTLEMENT

By J. Michael Duncan,¹ Fellow, ASCE

(The Twenty-Seventh Karl Terzaghi Lecture)

ABSTRACT: Consolidation settlements are often large and potentially damaging to structures. Estimating their magnitudes, and the rates at which they will occur, plays an important part in many civil engineering projects. At Bay Farm Island in San Francisco Bay, and Kansai International Airport in Japan, settlement magnitudes and settlement rates were of great importance for design. In these and similar cases it is important to understand what factors control the accuracy with which settlement magnitudes and settlement rates can be estimated. Accurate predictions of settlement magnitudes require accurate evaluations of clay compressibility and preconsolidation pressure. Accurate predictions of settlement rates require improved methods of anticipating whether embedded sand strata will or will not provide internal drainage; use of computer analyses to take into account important factors such as variations in c_v within clay layers, nonlinear stress-strain behavior, and nonuniform strain profile effects; and research to develop an improved model of clay compressibility that includes the effects of strain rate.

INTRODUCTION

The writer appreciates very much the invitation to present this lecture named in honor of Karl Terzaghi. Consolidation of clay was one of the principal topics of Terzaghi's pioneering book, *Erdbaumechanik*, published in 1925. It was the subject of some of the first laboratory tests Terzaghi performed at Robert's College in the early 1920s, and consolidation settlements were the focus of his first consulting job. Consolidation settlements of clay thus seem an appropriate subject for a lecture presented in his honor.

Other Terzaghi Lecturers have addressed aspects of this subject, notably Rutledge (1970), and Lowe (1974). As illustrated by the cases described here, consolidation settlements are still very important in many civil engineering projects, and there is still important progress to be made to improve our ability to anticipate accurately the magnitudes and rates of consolidation settlements.

PROBLEMS CAUSED BY SETTLEMENTS

Consolidation settlements can result in many different types of problems, as indicated in Table 1 (Skempton and MacDonald 1956; Bjerrum 1963; Wahls 1990).

Where settlements are large, the ground surface may subside below water, and be flooded. Flooding can be prevented if the initial ground surface is made high enough so that it remains safely above water after all settlement has taken place. To remediate flooding, it is necessary to construct dikes, and to use ditches to lower the water level below ground level.

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Note. Discussion open until February 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on March 8, 1993. This paper is part of the *Journal of Geotechnical Engineering*, Vol. 119, No. 9, September, 1993. ©ASCE, ISSN 0733-9410/93/0009-1333/\$1.00 + \$.15 per page. Paper No. 5763.

TABLE 1. Settlement Problems

Problems (1)	Preventive measures (2)	Remedial measures (3)
Flooding	Raise ground elevation with extra fill	Keep ground-water levels below ground surface with dikes, ditches, and pumping
Loss of slope to drain	Allow all or part of settlement to occur before construction of drains Design original slopes with allowance for changes	Regrade surface drains Rebuild, replace, or supplement subsurface drains
Tilting of structures (tilt of 0.004 can be distinguished by unaided eye)	Allow all or part of settlement to occur before construction of structures Design foundations so they are concentrically loaded Use floating or deep foundations to reduce settlements	Relevel structures using jacks and shims, or mudjacking Possibly underpin foundations to minimize subsequent settlement
Architectural damage (cracks in walls or floors, jammed windows or doors, uneven floors)	Allow all or part of settlement to occur before construction of structures Use floating or deep foundations to reduce magnitudes of total and differential settlements Use stiff foundations so that differential settlement does not result in distortion of structure	Repair damage to restore value Possibly relevel structure Possibly underpin foundations to minimize subsequent settlement
Structural damage (cracks in column, floorbeams, or other structural elements)	Allow all or part of settlement to occur before construction of structures Use floating or deep foundations to reduce magnitudes of total and differential settlements	Repair damage to restore structural integrity Possibly underpin foundations to minimize subsequent settlement

Settlements are never uniform. Differential settlements can lead to many types of problems. One of these is the disruption of surface or subsurface drainage where differential settlements result in loss of slope to drain. This can be prevented, if the magnitude of differential settlement can be anticipated, by designing the initial slopes with allowances for the changes that will occur as settlement takes place. Impaired drainage can be restored by regrading existing drains or building new ones.

Uneven settlements cause a variety of problems for structures. When the structure or its foundation is stiff enough to prevent distortion of the structure, nonuniform settlements cause tilt. Tilt as small as 0.004 can be detected by the unaided eye, and gives the impression of instability, especially in tall structures. Designing foundations so they are centrally loaded eliminates one cause of tilting. Using floating or deep foundations can reduce the magnitude of settlement and tilt. Floating foundations reduce settlement by

reducing net load; excavation of 3 m (10 ft) of soil offsets the load of a building several stories high. Deep foundations (driven piles, drilled shafts, and caissons) reduce settlements by carrying loads to deeper, less compressible strata.

If structures and their foundations are distorted by differential settlements, they may be cracked and damaged. Architectural damage includes all those forms of distress that impair the looks or function of the structure, but do not reduce its structural load-carrying capacity. Architectural damage seldom occurs if the angular distortion resulting from the settlement is less than 1/500. Structural damage implies loss of structural capacity. Settlement damage rarely results in structural collapse, but a structure damaged by settlement is more likely to collapse under loads imposed by earthquake, wind, or live load.

Once a structure has been damaged by differential settlements, remediation can take two forms. One is repair of the architectural or structural damage to restore the structure to a useful state. Releveling the structure may be required to remove tilt or distortion. If settlement is continuing, it may be necessary to modify the foundations (underpin the structure) to reduce or eliminate future settlements.

It is not uncommon for settlements as large as several feet to occur as a result of consolidation of soft clays. It is therefore easy to understand the importance of being able to estimate the magnitudes and rates of consolidation settlements in advance, so that appropriate design features can be adopted to reduce settlements or to avoid settlement-induced damage. It is often desired to develop facilities, and to begin using them, while they are still settling, because time is money. To do this it is useful to be able to estimate accurately how much settlement will occur, and how fast it will occur.

The following sections of this paper discuss: (1) The effects of consolidation settlements on the design and construction of two modern projects constructed on fills over clays; (2) the difficulties involved in estimating the magnitudes and the rates of consolidation settlements; and (3) improvements that are needed in the current state of the art for estimating settlements and settlement rates.

The Bay Farm Island and Kansai Airport case histories that are described here have been treated in more detail by others (Duncan et al. 1991; Arai 1991; Arai et al. 1991; Endo et al. 1991; Maeda, et al. 1990; Okawa and Endo 1990; Takeuchi 1990; Tohma and Yamamoto, 1990). The following sections use these cases to illustrate the importance of estimating settlement rates accurately, and the difficulties in doing so.

BAY FARM ISLAND

Bay Farm Island is located south of Alameda, on the east side of San Francisco Bay. The area where large settlements occurred [about 260 ha (one square mile)] was originally a tidal flat underlain by 6–15 m (20–50 ft) of San Francisco Bay mud. The area was farmed beginning in about 1880, and was diked off and drained for more efficient farming in 1930. In 1945 the dikes failed. Episodes of draining and reflooding led to development of a rather complex crust on the top of the Bay mud. It was thick in some places, thin in others, and nonexistent where water-filled sloughs or ditches crossed the area. Detailed information regarding the conditions at the site and the consolidation properties of the San Francisco Bay mud can be found in Duncan et al. (1991).

Development of the site for commercial and residential use began in 1967 with placement of 2.5–6 m (8–20 ft) of hydraulic sand fill over the Bay mud. A cross section through the area is shown in Fig. 1. Thicker fill was placed where the underlying Bay mud was thicker. The fill was left in place for 12 years, so that most of the settlement due to consolidation of the Bay mud would occur before construction of streets and buildings. In 1979 final grading was done, and development of the infrastructure in the area began. Photographs of the area before and after development are shown in Fig. 2. Bay Farm Island today is an attractive area densely populated with residential and light commercial uses.

A total of 45 settlement plates were used to monitor the settlement at Bay Farm Island from 1967 to 1979 (Javete 1983). The settlements measured at the 10 locations where the Bay mud was thickest are shown in Fig. 3. Two things can be seen clearly in this figure: First, the settlements are large. As much as 2 m (7 ft) of settlement occurred by 1979. Second, the settlement is not uniform. In 1979 the measured settlements varied from a little more than 1 m (4 ft) to a little more than 2 m (7 ft).

The differences in the magnitudes of the settlements from point to point are not due to different thicknesses of Bay mud. For the 10 locations where the settlements shown in Fig. 3 were measured, the thickness of the Bay mud varied only from 14 m (45 ft) to 15 m (50 ft). The smallest settlements shown in Fig. 3 were measured at a location where the Bay mud was 14 m (46 ft) thick, the largest where it was 14.6 m (48 ft) thick.

The magnitudes of the settlements bear some relationship to effective fill depth. Javete (1983) defined effective fill depth as the thickness of fill weighing 17.3 kN/m^3 (110 lb/cu ft) that would produce the same load on the underlying Bay mud, considering moist unit weight above the observed average water level and buoyant unit weight below. Although there is some relationship between settlement and effective fill depth, it is not consistent. The point with an effective fill depth of 5.1 m (16.6 ft) settled less than the point with an effective fill depth of 3.3 m (10.9 ft). The point with an effective fill depth of 6.8 m (22.4 ft) settled less than a point with an effective fill depth of 6.2 m (20.3 ft). The scatter in the measured values is significant. Studies done since 1980 (Javete 1983; Duncan et al. 1991) indicate that much of the erratic variation in settlement from place to place at Bay Farm

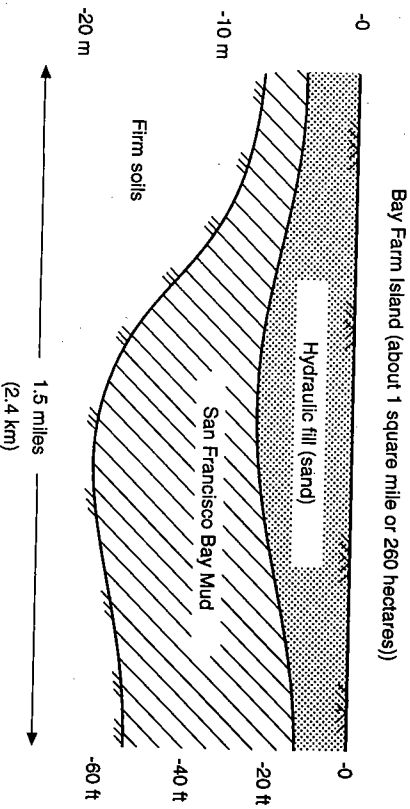


FIG. 1. Cross Section through Bay Farm Island

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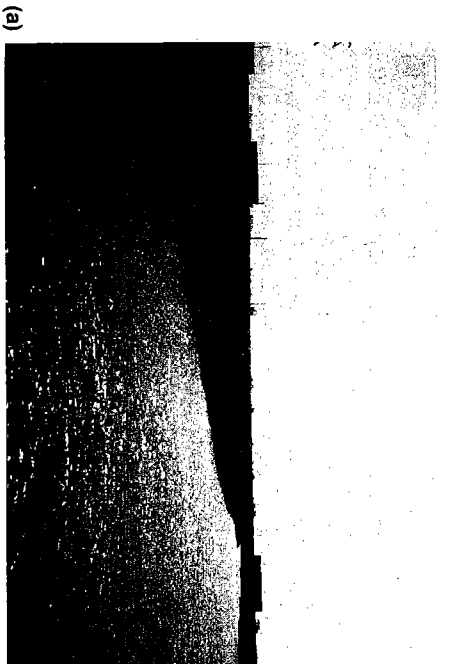


FIG. 2. Bay Farm Island: (a) after Filling, before Development of Infrastructure; and (b) after Development

Island was due to random variations in crust thickness from one location to another, as discussed later in this paper.

In 1979 the settlements were still continuing, at rates varying from 50 mm (2 in.) to 75 mm (3 in.) per year. Just before final grading and construction of streets and buildings was to begin in 1979, the developer asked a geotechnical engineering firm to make an estimate of the maximum amount of differential settlement that might be experienced by a building supported on shallow foundations at the site. This information was needed to obtain a permit for development of the site. For purposes of the estimate, a building was considered to cover an area of 23 m square (75 ft square).

The geotechnical firm (firm A) had done work at the site for many years. They had made borings, performed laboratory tests, estimated settlements

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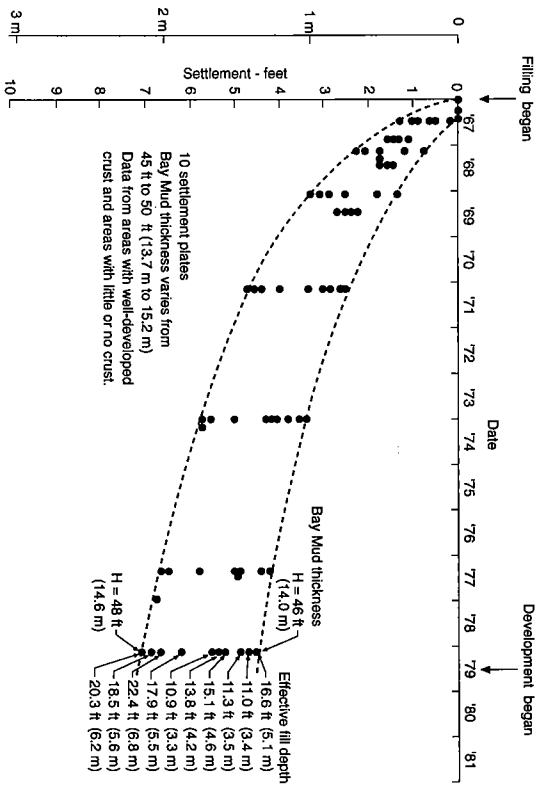


FIG. 3. Measured Settlements at Bay Farm Island

and settlement rates, and participated in evaluating the data obtained from the 45 settlement plates at the site. They thus had considerable information and experience on which to base their estimate of the maximum possible differential settlement in a building. They were also well aware of the possible legal consequences of underestimating the differential settlements. If differential settlements occurred that were larger than they estimated, they might be deemed liable for a share of the resulting damages.

Considering carefully all of the available information, and not wishing to incur exposure to undue liability, firm A estimated that differential settlements as large as 300 mm (1.0 ft) might be possible within a structure 23 m square (75 ft square) supported on shallow foundations at the site.

The developer was not pleased with this answer. Designing structures and foundations for such conditions would be exceptionally difficult and expensive. Obtaining the required development permit was probably out of the question if the developer had to base the development plan on such large values of estimated differential settlement.

Understandably, the developer (who already had made a very large investment in the site) wanted a second opinion. For this he turned to another geotechnical firm (firm B) that had also done considerable work at the site. Firm B considered the same information as firm A, but was more influenced by how their prospects of receiving further work from the developer might be influenced by their estimate.

Considering carefully all of the available information, and not wishing to jeopardize their chances for further work with the developer, firm B estimated that differential settlements larger than 30 mm (0.1 ft) were not likely to occur within a structure 23 m square (75 ft square) supported on shallow foundations at the site.

This answer was received more warmly by the developer. If differential settlements did not exceed 30 mm (0.1 ft) within any building, there should be little or no damage due to settlement. However, it was not possible

simply to accept the more favorable answer and to ignore the less favorable. Both had to be accommodated in the permit application.

At this stage the developer asked the writer if he could work with the two firms, to get them to agree on a common estimate. The writer, being optimistic and perhaps a little naive, replied that that certainly would be possible. He explained to the developer, as he had explained to students many times, that once the conditions to be analyzed had been decided, the answer was determined. Therefore all that would be necessary would be to get the two firms to agree on what conditions should be considered, and they would then arrive at the same answer.

It proved to be not so easy to get firm A and firm B to agree on the conditions for analysis. After a number of meetings, agreement was reached on many (but not all) of the points concerning what parameter values represented the conditions likely to result in the largest differential settlements within a 23 m square (75 ft square) area. However, there were still differences between the soil properties and analysis procedures that firms A and B chose to use. When it became evident that neither firm was willing to make any more adjustments in properties or analysis procedures, and that a complete agreement was not possible, firms A and B then each prepared a new report to the developer, revising their earlier estimates of differential settlement. The revised estimates were: firm A = $\Delta_{diff} \leq 250$ mm (0.85 ft) and firm B = $\Delta_{diff} \leq 50$ mm (0.15 ft).

The developer was disappointed that the new estimates did not differ much from the earlier estimates. The writer was disappointed in his lack of success in resolving what he believed at the outset was a technical problem, amenable to fairly precise quantitative evaluation. It was clear from the outcome that: (1) Evaluating the parameters that defined the problem required the exercise of judgment, even though a considerable amount of detailed data was available; and (2) the intentions of the people performing the analyses had a very considerable bearing on their choices of properties and conditions for analysis, and therefore on the results of their analyses.

It was clear that further meetings and calculations would not close the gap between the estimates made by firms A and B. The developer therefore took a different tack, and asked the writer if he would prepare a report, discussing firm A and B's estimates, and making an independent estimate of the possible differential settlement. The writer agreed. By this stage of the proceedings so many trips had been made through the numbers that the range of possible answers was well known, and no further calculations were needed for the writer to arrive at his estimate of the maximum differential settlement in a 23 m square (75 ft square) area. Quite understandably, given the writer's involvement as a mediator, his estimate of differential settlement was less than firm A's and more than firm B's. The writer's estimate was 100 mm (0.35 ft), a little less than half firm A's revised estimate, and a little more than twice firm B's revised estimate. It seemed like a reasonable compromise.

The plan for development of Bay Farm Island was approved with a requirement that the design should allow for differential settlements. Allowances were made for grade changes in the streets and sewers, posttensioned foundation slabs were used beneath the structures, and an amount of money was accumulated in escrow for each structure built at the site, to be sure that repairs could be made, even if the developing company did not stay in business. As of 1992 the maximum differential settlement in any of the

