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# Soil consolidation – From theory to practice

## Consolidation – De la théorie à la pratique

Carl B. Crawford – *Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada*

**ABSTRACT:** The theory of consolidation seldom, if ever, applies in full scale loading of the natural ground. Consequently, engineers use more judgement than theory in the prediction of consolidation settlements. Judgement is usually based on the observation of full scale performance of various kinds of structures resting on the ground. This paper reviews several case studies to illustrate the importance of secondary-type consolidation in the ultimate settlement of structures on some inorganic soils.

**RÉSUMÉ:** La théorie de la consolidation étant pratiquement inapplicable au cas de chargements à échelle réelle du terrain naturel; les ingénieurs ont recours au jugement plutôt qu'à la théorie dans la prédiction du tassement des sols. Le jugement est en général basé sur l'observation de la performance de différents types de structures reposant sur le sol. Cet article passe en revue plusieurs cas d'étude afin d'illustrer l'importance de la consolidation secondaire sur le tassement ultime des structures sur certains sols inorganiques.

### 1. INTRODUCTION

The basic understanding of soil consolidation began with Terzaghi's laboratory tests on soils and his development of the theory of consolidation more than seventy years ago. This fundamental work, first published in English by Terzaghi (1926) in a series of articles in *Engineering News-Record*, was more than an explanation of consolidation; it was the first statement of the principle of effective stresses which has dominated soil mechanics research and practice ever since.

Terzaghi never expected the theory of consolidation to provide the basis of engineering design because the assumptions in the theoretical analysis are seldom if ever satisfied in the field. In an interview just weeks before his death in 1963, Terzaghi was asked (*Engineering News Record*, 1963) to explain the unprecedented influence of his 1925 articles on engineering in America. He replied with two reasons: 1) "the papers contained a wealth of new and badly needed information concerning the engineering properties of the subsoil of our structures" and 2) "they aroused the unjustified hope that sooner or later all the problems of earthwork engineering could be solved by rigorous methods like those employed in the design of superstructures". He cautioned that rigorous solutions are not possible because "if a body of soil has an erratic pattern of stratification its significant engineering properties can be evaluated only in a very general way". He went on to state that "soil mechanics has explained the performance of soils under load, shear and seepage pressures. Therefore, it has become possible to locate in advance of construction, by boring and testing, the potential seats of trouble in the subsoil of our structures and to cope with them by adequate design". He added that "the instances in which my professional work called for advanced analytical procedures are very rare". With respect to research carried out to fill gaps in our knowledge of the engineering properties of soils in general he pointed out that "the value of these activities could be considerably increased if the study of the long-term performance of existing structures, such as earth dams, settling foundations, or moving slopes were more often included." In the decades since 1963 an enormous literature on consolidation has been published but there are relatively few documented case histories comparing predictions with performance and of these most are

records of performance with associated predictions made only after the actual settlements are known.

The observations of Terzaghi are as relevant today as they were thirty years ago. This paper summarizes several case studies that illustrate the difficulties of making predictions based simply on theoretical analyses and the great value of field observations to engineering practice.

Some of the projects show primary consolidation occurring very rapidly followed by an equal amount of secondary consolidation and others where almost all of the consolidation occurs at a constant effective stress (commonly considered to represent secondary consolidation). The paper is not an attack on theoretical analyses, which are usually essential for preliminary design, and always essential for understanding. On the contrary it is an attempt to show the value of good observations of performance and the need to analyse, publish and be guided by case studies that are relevant to all stages of design.

### 2. SECONDARY-TYPE CONSOLIDATION IN THE FRASER RIVER DELTA

The Fraser River encloses a triangle delta between north and south branches before emptying into the Pacific Ocean just south of the city of Vancouver, Canada. The cases reported in this paper are located within this triangular part of the delta where the soils consist of interlayered sands, silts and clays generally up to 300 m thick.

More than forty years ago when the construction of major facilities began to encroach on the soft, compressible alluvial soils in the delta engineers began to employ the technique of preloading the ground in order to consolidate the subsoil before constructing large buildings or other heavy structures. It was soon apparent that the complex interlayered subsoils were ideally suited to this technique; they allowed rapid lateral drainage of the porewater and sufficient consolidation could usually be achieved within acceptable time periods ranging from a few months to a year. This method of construction is now common practice in the delta area.

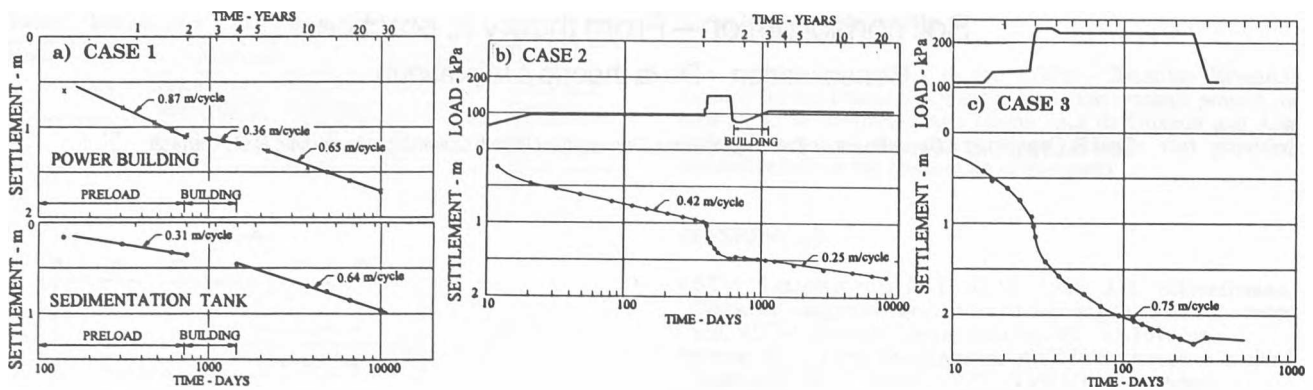


Fig. 1. Settlement observations in the Fraser River Delta

### 2.1 Case 1: Iona Island.

An early example of preloading of the deltaic soils was begun in 1959 for a sewage treatment plant on Iona Island, in the north arm of the Fraser River. This was an extremely difficult site, much more difficult than earlier projects, because of congestion, a wide variation in loads and a greater sensitivity of the structures to settlements. It required complex scheduling of preloads and surcharging based on careful interpretation of laboratory tests and earlier experiences. Fortunately the design, construction and 27 years of good settlement observations at the plant have been described by Ripley (1995). The settlement observations on the structures having the maximum and minimum long term settlement are reproduced in Fig. 1(a) (Crawford and Morrison, 1996).

### 2.2 Case 2: Lulu Island, Primary Treatment Plant

Another waste water treatment plant was built in the early 1970's on a preloaded site on Lulu Island along the south arm of the Fraser River. At this Primary Treatment Plant a preload of 100 kPa was applied in twenty days over an area about 150 metres square, causing a settlement of 0.5 m. At the end of the loading period a secondary-type consolidation (0.42 m per log cycle of time) began. After a total of 400 days the application of a surcharge to 150 kPa caused a further 0.5 m of primary consolidation settlement during the following 200 days. When an excavation in the fill was made for the plant there was a slight rebound and during and after construction the secondary-type consolidation continued at 0.25 m per log cycle for a further 20 years as shown in Fig. 1(b).

### 2.3 Case 3: Lulu Island, Secondary Treatment Plant

In 1993 a site adjacent to Case 2, approximately 220 metres square, was preloaded for the construction of a Secondary Treatment Plant. A preload of 225 kPa was applied in a month causing a settlement of about 1 m during loading. A further 1 m occurred during the following 50 days and then a secondary-type consolidation began at 0.75 m/log cycle as shown in Fig. 1(c).

### 2.4 Fraser River Delta Cases Compared

Details of Cases 2 and 3 are given by Crawford and Morrison (1996) and the results compared with Case 1 on Iona Island and three additional widely separated cases in the delta area. In all six cases most of the consolidation settlement occurred during or shortly after the loading period followed by a continuing period

of secondary-type consolidation (i.e. a straight line on a semi-log plot of settlement with time).

In all of these cases the rate of secondary-type consolidation settlement depended on the magnitude of the loads and on the magnitude and duration of previous loads. The term "secondary-type consolidation" is used because there are insufficient observations of pore pressures and settlements at depth to know whether or not some primary consolidation is occurring in deep soil strata while the surface observations indicate secondary consolidation. There is enough variation from site to site to conclude that results are site specific but the nature of the curves appears to be sufficiently consistent and long term to aid in settlement predictions for foundations on the delta.

### 3. CASE 4: BAY FARM ISLAND, CALIFORNIA

In his Karl Terzaghi Lecture Duncan (1993) pointed out that conventional consolidation theory has found wide application in geotechnical engineering practice and is commonly used by most practicing geotechnical engineers. He explained that conventional theory is likely to continue to provide the most effective tool for teaching and learning the fundamental physics of consolidation; he examined the reasons why the conventional theory has serious limitations in practice and he supported his views with two case histories.

His first case is the Bay Farm Island landfill project on the east side of San Francisco Bay where an area of 2.6 square km was loaded hydraulically with sand to a depth of 2.5 m to 6 m. Surface settlement plates were monitored at the site from 1967 to 1979, and the maximum and minimum observed settlements at 10 locations are shown in Fig. 2.

In 1979, after the fill had been in place for 12 years, the developer retained two independent consulting firms (both having experience at the site), to estimate the maximum amount of differential settlement that might occur in a 23 m square building supported on shallow foundations. One firm estimated a maximum differential settlement of 300 mm for such a building, while the second firm, using the same information, estimated a maximum differential settlement of only 30 mm.

There is no doubt that this was a difficult assignment as illustrated by the 10-fold spread in the estimates of differential settlements. As it turned out, in 1992 the maximum differential settlement measured in any of the buildings was 60 mm. The probable reason for the variation between the estimates of minimum and maximum settlements are discussed in detail by Duncan (1993). The last half of the total settlement during the 12-year period follows approximately a straight line on a semi-

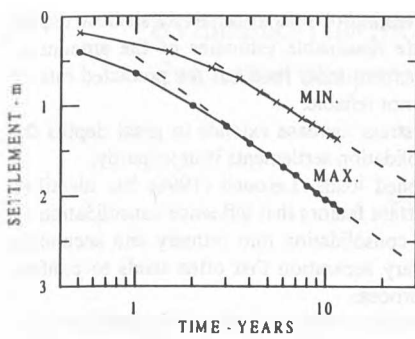


Fig. 2 Case 4: Settlement at Bay Farm Island

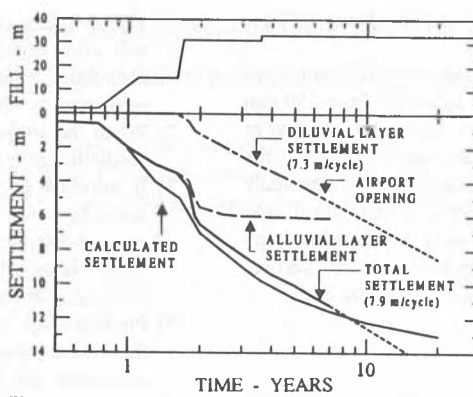


Fig. 3 Case 5: Settlement at Kansai Airport

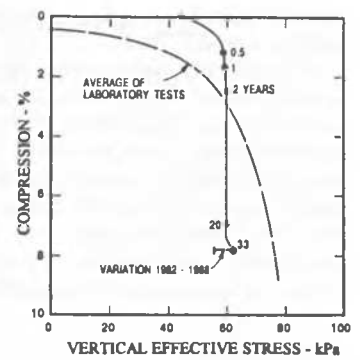


Fig. 4 Case 6: Settlement at Gloucester

log plot with time, but unlike Cases 1, 2 and 3 the rate of settlement is very high, ranging from 1.3 to 1.5 m per log cycle, and the records are too limited to draw conclusions with respect to primary and secondary consolidation phases. Clearly the rate will have to decrease and future observations at the site would be extremely valuable to the understanding of the actual consolidation characteristics in this case.

#### 4. CASE 5: KANSAI INTERNATIONAL AIRPORT, JAPAN

The second case discussed by Duncan (1993) is the airport built on a man-made island in Osaka Bay, Japan. This project began in 1987 with the dumping of 33 m of fill into water 18 m deep over a huge area 4.3 km by 1.3 km. The underlying natural soils consist of 20 m of soft, alluvial clay lying over more than 400 m of somewhat over-consolidated diluvial clay of Pleistocene age with layers and lenses of sand. In 1986, the 50-year settlement estimates were 6.5 m in the alluvial clay and 1.5 m in the diluvial clay, for a total of 8 m.

Sand drains were used through the 20 m alluvial layer and as expected consolidation of this layer occurred very quickly, almost coincidentally with the applied load, but a little less than the predicted value. The diluvial layer, on the other hand, consolidated much more and at significantly faster rates than predicted. At the end of 1990 the measured settlement of the alluvial layer was about 6 m and of the diluvial layer more than 2 m for a total settlement of about 8 m after 3 years, an amount equal to the 50-year prediction. Consolidation of the diluvial deposit was continuing at a rate of about one-half metre a year, so the prediction was re-assessed on the basis of the actual settlement records.

In a recent publication Shiraishi and Suzuki (1995) explained that with the re-analysis, based on modified drainage conditions, the settlement of the Pleistocene layers was calculated to be 4 m at the time of airport opening in 1994 and a further 1.5 m during the next 50 years. The observed and re-calculated settlements are reproduced in Fig. 3. Since 1989, the consolidation of the Pleistocene soils has followed a secondary-type curve although the re-calculated curve indicates that the rate should soon decrease. Only future observations can confirm this prediction.

The profession is indebted to Japanese colleagues for publishing information on the performance of the Kansai airport site from the beginning of the project. This case has illustrated the great difficulty of predicting consolidation settlements in very deep soil strata. Estimates for the upper alluvial soils were quite adequate but for the lower diluvial layers both the predicted magnitude and rate of consolidation were much too low. In their own view this was caused primarily by uncertainties in determining the pre-consolidation stresses from standard consolidation tests, and in assessing the influence of thin diluvial

sand layers on pore water drainage (Endo et al., 1991). Consequently, predictions are continually under review based on settlement observations at the site; observations that may be expected to guide engineers in that region for many decades to come.

#### 5. CASES OF CLAY DESTRUCTURATION

##### 5.1 Case 6: New Liskeard, Ontario, Canada

The planned stage construction of a highway embankment over varved clay at New Liskeard had to be abandoned because pore pressures under the embankment did not decrease and shear strengths did not increase after more than two years (Stermac et al., 1967). In a discussion of the paper by Crawford and Eden (1967) it was noted that the imposed total stress increase in the consolidating layer was approximately equal to the measured preconsolidation stress of the natural soil. On the basis of this observation and simultaneous work on the Leda clay at Ottawa it was concluded that "owing to structural breakdown in the natural soil, the pore pressures were increasing as quickly as they could be relieved by drainage"

##### 5.2 Case 7: Vasby, Sweden

A further dramatic example of pore pressure generation by structural collapse was given by Chang et al. (1973) for a test fill in Sweden. It was shown that 22 years after loading, the pore pressures at the middle of the consolidating layer were still approximately equal to the total stress increase at that level and it was concluded that "the dissipation of pore pressures due to consolidation was compensated by pore pressure regeneration. This portion, called secondary consolidation, has generally been considered to begin after the completion of the primary phase, and very low excess pore pressures have been thought to exist during the secondary phase".

##### 5.3 Case 8: Gloucester, Ontario, Canada

Long term settlement observations, beginning in 1955, were made on a building founded on a gravel fill over the sensitive Leda clay near Ottawa, (total applied stress = 35 kPa). Most of the consolidation of the clay occurred in a 3.6 m layer below a 2 m thick crust. During the first year the increase in pore pressures limited the increase in effective stress at mid-layer to the laboratory measured preconsolidation stress, but the vertical compression was about 60 mm. After 20 years, there was still little change in the effective stress at mid-layer but the compression of the layer had increased to 250 mm, indicative of secondary consolidation. Similar observations were made under

an earth embankment in the same vicinity at Kars, Ontario (Eden and Poorooshash, 1968).

From the 20th year until the 33rd year the maximum compression of the 3.6 m consolidating layer increased from 250 mm to 280 mm (i.e., from 6.9% to 7.8%), and was then occurring at a rate of about 1 mm per year. The discrepancy between the stress-compression measured in situ and from incrementally loaded laboratory tests is shown in Fig. 4 (Crawford and Bozozuk, 1990). For more than 30 years a secondary-type consolidation had occurred at an almost constant vertical effective stress equal to the measured preconsolidation stress.

## 6. DISCUSSION

In a summary of the highlights of the 4th International Conference on Soil Mechanics and Foundation Engineering, D.J. Maclean (1957) expressed disappointment that there was an "absence of any significant advance in obtaining a better understanding of secondary consolidation". Thirty-six years later Duncan (1993) stated that "there is still important progress to be made to improve our ability to anticipate accurately the magnitudes and rates of consolidation settlements". The cases described above indicate the discrepancies from theory to practice that can occur and that probably do occur often.

It is often useful to separate consolidation into primary and secondary consolidation phases but these studies emphasize the value of the definition of Terzaghi (1943) that "Every process involving a decrease of the water content of a saturated soil without replacement of the water by air is called a process of consolidation". It follows that consolidation is a continuous process, interrupted temporarily by pore pressures caused by low permeability of the soil and in some cases by a collapsing soil structure.

The literature on soil consolidation is heavily weighted toward laboratory tests and theoretical analyses without corresponding full-scale performance studies. The probable reason is that laboratory and desk studies fit nicely into student research projects that are valuable training exercises. Case histories, on the other hand, are time consuming and very expensive if field work is required. This creates a dilemma for research managers but the solution could be in the development of improved liaison between researchers, consulting firms and government agencies. Practicing engineers always have many records of foundation designs and performance in their files but seldom have time to prepare them for publication. The opportunity for graduate students to work with consulting engineers on case histories would be excellent experience for them, would help seasoned engineers to improve their expertise, and would produce valuable publications.

Leroueil (1996) has brought much of the consolidation research into focus in a recent paper which explores the influence on compressibility of natural clays by "strain rate, temperature, sampling disturbance, stress path and structuring phenomena". His conclusions are based on a blending of laboratory and field research that show influence trends of the above factors and finally he noted that "using judgment and local experience, the engineer will decide how to calculate the settlements of the considered structure"

## CONCLUSIONS

These case studies describe some extreme departures from calculated consolidation settlements and lead to the general conclusion that the approach to consolidation calculations needs revision, taking account of Terzaghi's original concepts. Some specific conclusions are:

- 1) The sampling and testing of soils at relatively shallow depths will usually provide reasonable estimates of the amount of consolidation settlement under load but the predicted rate of settlement is often not reliable.
- 2) When the applied stress increase extends to great depths the prediction of consolidation settlements is in jeopardy.
- 3) In addition to applied loads, Leroueil (1996) has identified several other important factors that influence consolidation.
- 4) The separation of consolidation into primary and secondary phases is an arbitrary separation that often tends to confuse the consolidation process.
- 5) Predictability would be greatly enhanced if publications of theoretical analyses were accompanied by observations of settlement and pore pressure at depth.
- 6) The search for near perfect, widely applicable analytical solutions to consolidation problems has been and will probably continue to be in vain because of sampling difficulties and the inability to assess the rate of pore pressure dissipation in situ.

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