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Observational method of evaluating secondary compression settlements in artificial fills

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ABSTRACT

Secondary compression can be an important source of settlement in artificial fills, even when these fills are well-constructed. In some cases, especially when the fill thickness is greater than about 15 m, the resulting long-term settlements can adversely impact the performance of structures and infrastructure, and thus may necessitate special preventive design provisions. Yet, this source of settlement is often mistakenly overlooked. Secondary compression can be even more problematic when the fill is poorly constructed. Backfills of former open-pit mines are examples of practical projects where assessments of long-term secondary compression settlement are necessary, especially when these backfills are deep and/or not properly engineered.

Laboratory assessments of secondary compression in these materials are inherently problematic and become impossible when the fill contains large particles or has other complicating characteristics. However, this problem is an excellent opportunity to apply the observational method where the coefficient of secondary compression, $C_{\alpha\varepsilon}$, is assessed in-situ using settlement monument data. This $C_{\alpha\varepsilon}$ value is then used to forecast future settlements, which typically continue for decades, and thus provides essential information for the site-specific design of structures and infrastructure.

However, the experimental and analytical processes for conducting these evaluations are more difficult than might be expected, and missteps can lead to significant errors in the computed future settlements. Some of these difficulties are due to limitations in our knowledge of the underlying physical processes and in the analytical models used to describe them. Methods of collecting the required field data and conducting these settlement evaluations are discussed based on experience with deep fills in California as well as published data from elsewhere.

Keywords: ISC7; geotechnical instrumentation; site characterization; secondary compression

1. Background

An *artificial fill* is any anthropogenic earthfill. This term encompasses both *engineered fills*, which are the product of best design, construction and quality assurance/quality control practices, as well as *non-engineered fills* that do not satisfy these standards.

Poorly-constructed artificial fills are often problematic, exhibiting excessive settlement, horizontal displacement, inadequate slope stability, liquefaction, etc. In contrast, engineered fills typically have much better performance and usually satisfy the design requirements. Yet, even engineered fills sometimes exhibit long-term volumetric strains that produce settlements and differential settlements large enough to adversely impact the performance of structures and infrastructure. Such problems are increasingly likely when the fill thickness is greater than 15 m or when it varies significantly over short horizontal distances.

Problematic settlements within deep engineered fills have been recognized for decades. Lawton, et al (1992) reported that they personally had investigated multiple occurrences and the total repair costs were nearly $100,000,000. The role of hydrocompression settlement has been discussed extensively in the technical literature, and appropriately so. Seismically-induced settlements also have been discussed. However, the important role of secondary compression has not received enough attention.

Long-term settlement potential can be estimated before construction based on the proposed stratigraphy, geotechnical site characterization, and experience. However, these ex-ante methods have limitations, especially when evaluating the potential for secondary compression settlements, in part because pre-construction laboratory assessments of secondary compression are inherently challenging. While it is possible to form test samples of the proposed fill soil at the proper void ratio, the fabric is different than in the field. In addition, the rate of loading in the field is at least 100 times slower and the duration of secondary compression is 10,000 to 100,000 times greater than in the laboratory, both of which are problematic when evaluating a process that is time-dependent.

In order to obtain better predictions of long-term settlements and to verify the as-built conditions, good practice sometimes includes installing settlement instrumentation either during fill construction or immediately upon completion. These instruments are then monitored for a sufficient period to assess the as-built performance before proceeding with site development. Such instrumentation is especially useful in deep fills and, when well-implemented and properly analyzed, provides a much more reliable site-specific basis for the design of structures and site improvements. This is an excellent application of the observational method (Peck, 1969; ICE, 1996; Nicholson, et al, 1999).

Sometimes the settlement acceptance criteria are based on demonstrating the rate of settlement does not exceed some maximum acceptable value without any specific physical process in mind. However, because the monitoring period is typically very short compared to the design life of the project, this criterion provides only minimal insight into the expected long-term behavior of the fill. In addition, imprecise surveying can mask small settlements and give a false impression of stability. When secondary compression is the dominant process, a much better method is to use precise settlement data to evaluate the in-situ coefficient of secondary compression, $C_{\alpha\varepsilon}$, and then use this value to assess future secondary compression settlement potential over the design life of the project, typically 50 years. However, the process of doing so is not as straightforward as might be expected.

The focus of this work is to draw attention to the important role of long-term secondary compression within artificial fills, especially engineered fills; to illustrate an application of the observational method for evaluating this process in situ using settlement instrumentation data; and to advocate for the use of this information in the design process. Settlements founded in underlying strata, which also can be important, are beyond the scope.

2. Published data

Unfortunately, case studies of settlement monitoring data in earthfills spanning multiple decades are rare, and it is often difficult to differentiate between settlements rooted in the fill itself and those occurring in the underlying strata, as well as distinguishing between secondary compression and other settlement processes. Nevertheless, case studies do provide insights and context for the analyses discussed in this work.

Sherard, et al (1963) observed that the post-construction settlement within well-constructed earth dams is typically 0.1–0.4% of the dam height 14 years after construction. Logarithmically extrapolating this data to 50 years produces settlements of about 0.15–0.6% of the dam height. Wilson (1973) presented 10 years of settlement data for Mammoth Pool Dam which, when extrapolated to 50 years, produce a settlement of 0.27% of the dam height. Given the excellent construction methods used in modern earth dams, these values probably represent the lower bound of expected long-term settlements in engineered fills intended for industrial, commercial, residential or transportation projects. Sowers, et al (1965) found 10-year observed settlements in rockfill dams were 0.25–1.0% of the height.

Watts and Charles (2015) and Charles (2008) provide eleven case studies of open-pit mine backfills in the UK, most of which did not satisfy current standards for engineered fill. The settlement monitoring period ranged from 4 to 26 years and included experimentation with preloading and intentional wetting. Both hydrocompression and secondary compression were significant contributors to the settlements, which were frequently greater than 1% of the fill thickness, sometimes as large as 2.5% and with localized strains occasionally exceeding 4%. The upper bound of expected long-term settlements in engineered fills should be much less than these values.

Waddell (2013) reported settlement monitoring results for a 13–26 m thick well-constructed engineered fill in Australia over a period of 455 days, then logarithmically projected the results forward to obtain 30-year predicted settlements assuming the coefficient of secondary compression significantly decreases with time. Their lower and upper bound solutions produced 30-year secondary compression settlements of 0.08% and 0.30% of the fill thickness, respectively. The role of hydrocompression was believed to be minimal. A reevaluation of their field data using a constant coefficient of secondary compression produces 30 and 50-year secondary compression settlements of 0.35% and 0.40% of the fill thickness, respectively.

Eliahu and Harrell (2013) provided data from four well-constructed engineered fills in the USA between 19.5 and 33.5 m thick and found post-construction settlements of 0.35% of the fill thickness in 5 years at Site 1, 0.14% in 13 years at Site 2, 0.23% in 15 years and 0.62% in 15 years at Sites 3 and 4. These settlements appeared to be almost exclusively due to secondary compression.

3. Settlement processes in artificial fills

Secondary compression is one of many physical processes that can produce settlement in artificial fills. These processes include the following:

3.1. Primary consolidation settlement

Primary consolidation is the reduction of void ratio due to increases in effective stress. Classical consolidation theory addresses primary consolidation in the context of saturated fine-grained soils where the rate of consolidation, and therefore the settlement rate, is governed by the dissipation of excess pore water pressures.

In comparison, artificial fills are unsaturated, the increase in effective stress within the fill is due to a gradual increase in total stress during the placement of overlying fill, and the primary consolidation settlement occurs almost very quickly. Or, stated another way, the rate of settlement is almost equal to the rate of loading. This behavior was observed in the field by Trow, et al (1993) and the author has found similar results from an analysis of deep settlement monument data. Thus, we can reasonably expect that almost all of the primary consolidation settlement within an artificial fill occurs during construction and this process is complete once the fill reaches finish grade or soon thereafter (i.e. months).

3.2. Hydrocompression settlement

Hydrocompression settlement is the result of a reduction in void ratio due to post-construction wetting such as rising groundwater, infiltration of irrigation and storm water from the ground surface, leaky pipes or other sources (Brandon, et al, 1990; Lawton, et al, 1992; Noorany and Stanley, 1994). Hydrocompression is especially problematic in poorly-compacted fills (Kumar, et al, 2018) but also can occur in engineered fills (Vicente, et al, 1994). This potential must be evaluated on a site-specific basis and can be significantly reduced by using appropriate design and construction practices, especially proper moisture content control and compaction.

3.3. Expansive soil heave and shrinkage

Fills made of expansive clays often exhibit heave due to wetting from irrigation, storm water, rising groundwater, leaking pipes, and other causes. Shrinkage from drying due to evaporation, transpiration, and other processes also can occur, but these are generally near-surface processes.

3.4. Distortion settlement

Distortion settlement is that due to lateral shear distortion of the ground at a constant volume. This type of settlement can occur beneath applied loads acting on a finite area such as a spread footing foundation, or near sloping ground. In such cases the soil deforms laterally, producing distortion settlement at the ground surface.

3.5. Seismically-induced settlement

Poorly-constructed fills can be subject to significant seismically-induced settlements. Fortunately, engineered fills are much less vulnerable, but even they are not immune (Stewart, et al, 2001), particularly in deep fills. Seismically-induced distortion settlements, especially near slopes, can be especially problematic.

3.6. Secondary compression settlement

Secondary compression is the reduction in void ratio over time at a constant effective stress, or at least what appears to be a constant effective stress when viewed from a macro scale. Secondary compression is especially noteworthy in fat clays, but occurs in all soils. The underlying soil physics is only partially understood but in inorganic soils secondary compression appears to be the result of small-scale particle sliding and deformation, fracture and crushing at particle contacts, localized stress redistribution, localized drainage, time-dependent viscous deformation and other processes that cause interparticle movement and void reduction. These processes are triggered by mechanical disruption from an increase in effective stress. Additional processes occur in organic soils. Secondary compression can be an important contributor to post-construction settlements in artificial fills and in many cases it is the dominant process, especially when hydrocompression is kept under control.

Secondary compression is customarily formulated as a logarithmic function with time:

$$\delta_s = C_{\alpha\varepsilon} H \log\left(\frac{t - t_0}{t_1 - t_0}\right) \tag{1}$$

Where δ_s = secondary compression settlement at time t, $C_{\alpha\varepsilon}$ = coefficient of secondary compression, H = strata thickness, t_0 = time basis, and t_1= time at the beginning of the period of interest (perhaps the end of filling or the beginning of building construction). The t values (with any subscript) are expressed as calendar dates, so the numerator and denominator are elapsed times since t_0.

Equation 1 has most often been applied to clays and is generally believed to be an acceptable representation of their secondary compression. Its application to cohesionless soils is not as well established, and the physical processes are probably different, but is generally considered to be appropriate (Sowers, et al, 1965).

3.7. Interaction between settlement processes

Although these various processes and their associated settlements are often evaluated as if they act independently, in reality there are interactions between them and these interactions are not fully understood. The soil has a finite settlement capacity, so settlement that occurs due to one process leaves less remaining capacity for additional settlement from other processes. For example, as the void ratio of an engineered fill decreases with time due to secondary compression, the potential for future hydrocompression and seismically-induced settlements also decrease.

4. Settlement monitoring technologies

Settlement monitoring technologies are purposefully designed and constructed fixtures or instruments used to measure ground settlements in-situ, often in combination with precise surveying equipment, and provide a means of evaluating secondary compression in-situ. As with any geotechnical instrumentation, settlement measurments require proper planning, installation, and monitoring (Dunnicliff, 1988).

4.1. Surface monuments

Surface settlement monuments are installed near finish grade, ideally immediately after completion of the fill. It is essential that surface monuments are well-constructed, not subject to the near-surface effects of expansive soils or frost heave, and not prone to physical damage from equipment or vandalism. Figure 1 shows a typical design, but many variations also are used.

Surface monuments are monitored using conventional land surveying methods and equipment. Very accurate surveying is essential because the monitoring typically occurs over only a short period, perhaps months or years, while the resulting data will be extrapolated forward to the design life of the project (typically about 50 years). Many monitoring programs have been ruined by sloppy surveying.

With excellent workmanship, (i.e. much better than is typically exercised on construction sites) and top-quality equipment the manufacturer's stated accuracy is 0.3 mm. Examination of data sets suggests the real-world accuracy is not as good as advertised, but quite adequate for the purpose at hand.

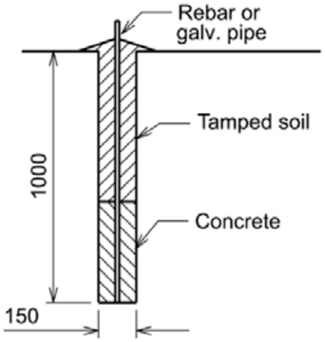

Figure 1. Typical surface monument constructed in a shallow boring. All dimensions in mm.

4.2. Settlement plates with risers

Deep settlement monuments installed during grading also can be useful in some situations. For example, data from deep monuments placed at the bottom of the fill combined with that from surface monuments provide clear differentiation between settlements occurring within the fill vs. those occurring in the underlying strata.

Steel plates or concrete pedestals, shown in Figure 2, can be constructed at key elevations as the filling progresses and continue to be monitored during filling using similar surveying methods through steel pipe risers that are sequentially extended (ASTM, 2019). However, even with careful workmanship, including conscientious backfilling around the riser and correcting for plumbness of each riser segment, accuracies during filling are about 5–10 mm. But, once filling is completed and no additional risers are being added these systems are capable of providing accuracies on the order of 1–3 mm.

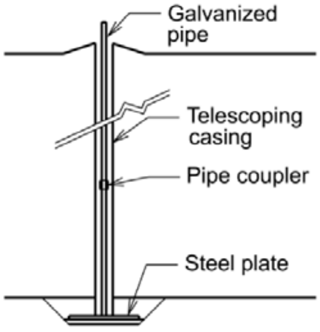

Figure 2. Typical deep settlement plate with pipe riser.

4.3. Induction coil and magnetic systems

Induction coil systems consist of a vertical compressible corrugated tube with steel rings attached at regular intervals, typically about 300 mm. This tube is installed in a borehole and the locations of the steel rings are then determined using an inductive probe. Magnetic systems are very similar but use embedded magnets (Stuedlein, et al, 2007). These instruments are normally installed after completion of the fill, so unlike settlement plates with risers they do not create obstacles for construction equipment during fill placement.

The manufacturers' stated precision approaches 1 mm, which appears to be realistic and is suitable for our purposes. These systems have the advantage of providing a strain vs. depth profile.

4.4. Borehole extensometers

Borehole extensometers measure the average strain over a specific interval inside a borehole (Watts and Charles, 2015). These devices can measure strains to an accuracy of about 0.1%, which is quite suitable.

4.5. Alternative technologies

Although less commonly used, other technologies also are available to monitor settlements in the field. These include:

- Remote-reading settlement plates that consist of a steel plate connected via plastic tubing to a stationary remote reservoir and a vibrating wire pressure transducer connected via wire to a remote readout unit
- Horizontal inclinometers

Unfortunately, both of these systems have significantly less precision, and thus may not be suitable.

5. Coefficient of secondary compression

Several definitions of the coefficient of secondary compression have been used, with corresponding adjustments to Equation 1 (Mesri, 1973). This work uses perhaps the most common definition:

$$C_{\alpha\varepsilon} = \frac{\mathrm{d}\varepsilon}{\mathrm{d}\log\,(t - t_0)} \qquad (2)$$

Where ε is the vertical strain. Mesri (1973) presented typical values of $C_{\alpha\varepsilon}$ as shown in Table 1.

Table 1. Classification of soils based on coefficient of secondary compression (Mesri, 1973)

Coefficient of Secondary Compression, $C_{\alpha\varepsilon}$	**Secondary Compressibility**
< 0.002	Very low
0.004	Low
0.008	Medium
0.016	High
0.032	Very high
> 0.064	Extremely high

Well-constructed engineered fills with a fines content less than about 30% would likely have $0.001 < C_{\alpha\varepsilon} < 0.005$, while those consisting of highly plastic clay might have $C_{\alpha\varepsilon}$ as high as 0.010. Based on an evaluation of 4 – 10 years of field data from several deep fill sites in the

UK, Hills (1994) and Hills and Denby (1996) found values ranging from 0.001–0.003 for engineered fills and as high as 0.019 for non-engineered fills. Gustafsson (2014) found values of 0.0016–0.0035 in rockfill. The author's analysis of 7 years of surface monument data from a cohesionless non-engineered inert debris fill produced $C_{\alpha\varepsilon} = 0.007$. None of these values are intended for design, and are presented only to provide a general order of magnitude. Design values must be determined on a site-specific basis. The highest ranges in Table 1 are associated with normally consolidated clays at very high moisture contents, organic soils and sensitive clays, none of which are likely to be used for engineered fill. For comparison, Sharma and De (2007) suggest values in municipal solid waste typically range from 0.01–0.07.

Primary consolidation and secondary compression both depend on similar physical properties, especially in inorganic soils, so there is a strong correlation in normally consolidated soils between C_α and the compression index C_c (Terzaghi, Peck and Mesri, 1996; Jesmani, Vaezi and Kamalzare, 2012), where:

$$C_{\alpha\varepsilon} = \frac{C_\alpha}{1+e} \tag{3}$$

This ratio ranges from 0.01 to 0.07, with material-specific values in Table 2. This correlation probably also holds true for overconsolidated materials such as engineered fills, by using the recompression index, C_r.

Table 2. Correlation between C_α and C_c for normally consolidated materials (Terzaghi, Peck and Mesri, 1996)

Material	C_α / C_c
Granular soils including rockfill	0.02 ± 0.01
Shale and mudstone	0.03 ± 0.01
Inorganic clays and silts	0.04 ± 0.01
Organic clays and silts	0.05 ± 0.01
Peat and muskeg	0.06 ± 0.01

6. Data interpretation

At first glance, the interpretation of in-situ settlement instrumentation data to evaluate $C_{\alpha\varepsilon}$ in situ and the use of this value to predict long-term secondary compression settlements may seem to be a simple exercise. However, in reality there are complications, and misapplication of the data can produce significant error in the computed 50-year design settlement values. In addition, our understanding of the physical processes is weak, so even the best analyses have limitations.

6.1. Time basis

The time basis for secondary compression analyses is the date at which the "clock" is set to zero, and marks the physical and analytical beginning of the secondary compression process. In other words, it is the calendar date at which $t = t_0$. Both the numerator and the denominator in the log term of Equation 1 are elapsed times since this date. When deriving $C_{\alpha\varepsilon}$ from settlement monument data, identifying the time basis is the most important variable to be defined (other than the settlement data itself), yet one of the most difficult.

If settlement instruments are installed soon after completion of the fill and the data is collected for a sufficiently long period and with sufficient accuracy, then appropriate dates for the time basis should be evident by fitting the best logarithmic curve through the data. However, settlement data spanning a period of perhaps several years is typically required to do so with acceptable precision, an aspiration that is rarely satisfied in practice. Financial constraints typically dictate moving forward with site development long before that point, so it becomes necessary to establish a means of defining the time basis using a shorter period of data collection.

If the time frame $t - t_0$ being considered is much larger than the likely range of time bases then an approximate date for t_0 should be sufficient, typically the date at which the fill was halfway completed (Sowers, et al, 1965). This methodology might be suitable for computing long-term secondary compression settlements if $C_{\alpha\varepsilon}$ is already known, but unfortunately is inadequate when attempting to compute $C_{\alpha\varepsilon}$ from settlement monument data because $t - t_0$ is much smaller and even a small error in assigning the time basis can produce a large error in the computed value of $C_{\alpha\varepsilon}$.

Deep engineered fill construction requires weeks, months or even years to complete, so if we assume the secondary clock begins ticking when the fill is placed, then the lower portion of the fill is compressing according to an earlier clock and the upper portion on a later clock. So, rather than assigning a single time basis it is much better to divide the fill profile into a series of n finite horizontal layers and assign an individual time basis, t_0, to each layer (Hills, 1994) as shown in Figure 3. The settlement observed at the surface is the sum of those in the various layers.

6.2. Time basis resets

Although we consider the secondary compression clock for each layer to begin ticking when that layer of fill is placed, it could be argued that an additional load of sufficient intensity alters the soil fabric which then resets the time basis clock back to zero and starts the secondary compression process over again. For example, Shafiee (2015, 2016) found such clock resets when subjecting peat to cyclic loads in the laboratory. Partial clock resets also have been proposed.

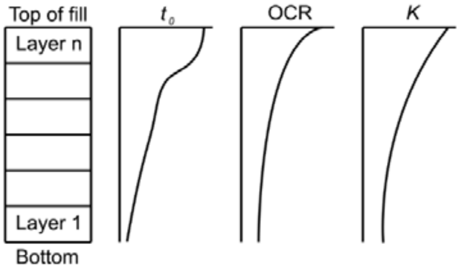

Figure 3. Analysis of secondary compression in an artificial fill using a series of finite horizontal layers.

A similar resetting of the clock is customarily used in the laboratory when conducting conventional incrementally-loaded consolidation tests where a new time basis is established each time a new load increment is applied and $C_{\alpha\varepsilon}$ for each load increment is computed using t_0 equal to the time that load was applied. These tests are typically conducted using a load increment ratio (LIR) of 1 which, at least for normally consolidated soils, may be enough to sufficiently alter the soil fabric and reset the clock. Consistent with theory, this data analysis method typically produces semilogarithmic plots of secondary compression vs. time. However, at stresses greater than the preconsolidation stress, equally compelling plots are produced by fixing the time basis at the time the preconsolidation stress was achieved, indicating the actual soil behavior is more complex than suggested by the customary data analysis method.

Extension of the clock reset concept to the field introduces more complexities and uncertainties. Unlike in the laboratory, field loading is continuous, not incremental, and often includes random fits and starts, so the concept of load increment ratio loses meaning. Hills (1994) proposed a broad framework for resetting the clock in the field, but with few specifics.

Because t - t_0 for the settlement monument data is small, resetting the time basis in the field from the date of fill placement to a later date can significantly decrease the computed value of $C_{\alpha\varepsilon}$, sometimes by a factor of 2 or more. This reset value reduces the computed 50-year design settlements and thus, if correct, could be a basis for more economical design. However, if the clock resets are not accurate representations of the secondary compression process or are too aggressively applied, then unconservative error is introduced that could result in an inadequate design. In addition, the clock reset hypothesis is less compelling for overconsolidated soils, such as engineered fills, because the soil fabric is already acclimated to an even higher load.

Time basis clock resets, or possibly partial clock resets, may have merit. However, the mechanics are largely unknown even in the laboratory, much less in the field. Perhaps further research will produce additional insights. Until then, they should be used cautiously, if at all. For example, a modest clock reset might be appropriate for an initial fill placement followed by a long hiatus and subsequent placement of an equal or greater fill thickness. However, given our limited understanding of the underlying physical processes, in most cases setting the time basis for each layer in the analysis equal to the date of fill placement at that layer appears to be a judicious and, if anything, conservative procedure for the task at hand. In addition, doing so appears to produce secondary compression estimates that are consistent with those observed in published data.

6.3. Overconsolidation

Laboratory tests have clearly demonstrated that overconsolidated soils exhibit slower rates of secondary compression than the same soil in a normally consolidated condition. This difference is probably due to the reduction in void ratio that occurs during the process of overconsolidation as well as the increase in the coefficient of lateral earth pressure, *K* (Terzaghi, Peck and Mesri, 1996). This effect is customarily modeled using a coefficient of secondary compression in overconsolidated soil that is lower than that for the same soil in a normally consolidated condition.

An alternative hypothesis states that overconsolidation moves the time basis backward and that $C_{\alpha\varepsilon}$ is the same as for the normally consolidated condition (Shafiee, personal communication). From this perspective the slower rate of secondary compression in overconsolidated soils is due to more time having elapsed since the time basis, not to a change in $C_{\alpha\varepsilon}$. This is an intriguing perspective that deserves further research.

Mechanical compaction during construction of engineered fills produces an overconsolidated soil by imparting a compaction prestress (Nwabuokei and Lovell, 1988) with a corresponding reduction in the coefficient of secondary compression (or backward reset of the time basis). However, due to the small contact area of standard compaction equipment and the short duration of loading, this initial overconsolidation ratio (OCR) may be less than expected. In addition, it probably varies widely in the field, likely much more than might be implied by small differences in the relative compaction.

Continued placement of fill then progressively increases the vertical effective stress in the previously-placed fill which decreases its OCR and *K*. The final result in the completed fill is a profile similar to that shown in Figure 3. Depending on the intensity of the initial overconsolidation, the OCR in the lower portions of deep fills could drop to a value of 1.0 (i.e. normally consolidated). In such cases, time basis resets in the lower, now normally consolidated, portion of the fill might be more clearly justified.

6.4. Stress dependency

Other than the effect of being either above or below the preconsolidation stress, it is unclear whether $C_{\alpha\varepsilon}$ is stress-dependent or an invariable with respect to effective stress. Mesri (1973) noted inconsistent results in the technical literature, with some research finding $C_{\alpha\varepsilon}$ increasing with effective stress, others finding it decreasing and yet others finding no relationship. The intervening half century has generated additional conflicting results as summarized by Garoushi (2017). Inconsistencies in defining the time basis is probably one of the reasons for these discrepancies.

The author's evaluation of multiple deep settlement monuments in a 67 m thick engineered fill did not reveal any clear pattern of stress dependency. Hills and Denby (1996) reached the same conclusion from an analysis of their field data. However, Waddell and Wong (2005) found $C_{\alpha\varepsilon}$ increased with effective stress. So, there is no consensus on how or if $C_{\alpha\varepsilon}$ is stress dependent. Regardless, other factors, most notably the selection of the time basis, appear to be more dominant.

6.5. Formulation

Combining these various considerations with Equation 1 produces a formula that evaluates secondary compression settlement for a finite series of n soil layers using the characteristics of each layer:

$$\delta_s = C_{\alpha\varepsilon} \sum_{i=1}^{n} H_i \log\left(\frac{t - t_{0i}}{t_1 - t_{0i}}\right) \tag{3}$$

Once the stratigraphy and time basis profiles have been established and the potential role of overconsolidation has been considered, the only unknown is $C_{\alpha\varepsilon}$ which can be determined by finding a best-fit through the settlement monument data.

This computed value of $C_{\alpha\varepsilon}$ and Equation 3 may then be used to compute forward-looking estimates of future secondary compression settlements.

7. Differential settlements and lateral movements

Differential settlements are usually more important than total settlements, and thus also must be evaluated. Angular distortion, θ, can be a useful way to express differential settlements (Coduto, et al, 2016):

$$\theta = \frac{\delta_D}{S} \tag{4}$$

Where δ_D is the differential settlement that occurs over a horizontal distance S.

Stratigraphic changes, such as steep subsurface contacts between the fill and the underlying natural soils and the associated rapid change in fill depth can be a source of excessive angular distortion as well as lateral movements of the fill (Hills, 1994; Skinner and Charles, 1999).

Even when the depth of fill is consistent, differential settlements can occur due to variations in the compressibility of the fill which may result from differences in soil type and construction processes. These variations are often larger than might be expected, even in a fill that appears to be very consistent by other measures such as relative compaction. Spatial variations in K might be an important factor. Variations in the fill placement date and thus the time basis also are a source of differential settlements, especially during the early years following completion of construction.

8. Impact on the design process

Application of the methodology described in this paper can have an important impact on the design process. For example, evaluations of the expected post-construction secondary compression settlements in backfills of deep open-pit mine have sometimes resulted in larger-than-usual design values of angular distortion, even when the fill is well constructed. Such values must be considered in the design of structures and infrastructure.

9. Validation

The author is not aware of any published settlement data for engineered fills spanning 50-years, especially not for fills constructed to current standards, so the methodology outlined here has not been validated over the period of interest. In addition, published data usually does not include sufficient information on fill age to properly assess t_0. However, the author's application of this method using 2 – 7 years of settlement data combined with well-defined fill placement records appears to generally produce reasonable values of $C_{\alpha\varepsilon}$ and long-term predicted settlements that are consistent with the published data described earlier.

10. Case study

A former open-pit sand-and-gravel mine with a maximum depth of about 60 m has been backfilled to natural grade. This backfill consists primarily of nonplastic gravelly sand, with a maximum particle size of about 250 mm and about 10% passing the #200 sieve. This fill was designed and constructed in accordance with current best practices and has been certified by a geotechnical engineer.

Surface and deep settlement monuments were installed and monitored for 4 years after completion of the fill. An analysis of this data using the techniques described herein produced a design $C_{\alpha\varepsilon} = 0.0032$ and the settlement contours shown in Figure 4. A 40,100 m^2 single-story reinforced concrete tilt-up warehouse building is to be constructed on this site. See Coduto (2024) for further details.

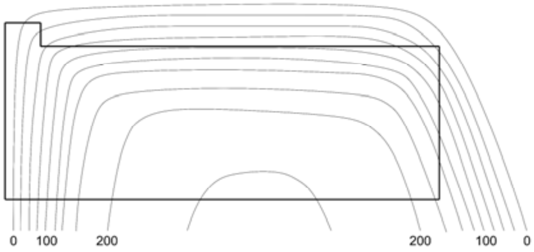

Figure 4. Proposed building at a backfilled open-pit mine site and 50-year secondary compression post-construction settlement contours in mm. Author's interpretation of data provided by LGC Geotechnical, Inc.

11. Conclusions

Secondary compression is an often overlooked but important component of long-term settlement in engineered fills, especially deep fills, but is difficult to evaluate using laboratory tests. However, when properly collected and interpreted, field settlement data provide more accurate assessments of $C_{\alpha\varepsilon}$ which then can be used to predict long-term settlement. This methodology is an excellent application of the observational method, and the associated settlement predictions should improve the design process, especially at sites where the fill thickness exceeds about 15 m or when the fill thickness varies considerably over short horizontal distances. For example, long-term settlement estimates may influence the siting of structures, selection of the foundation type, and design grades for gravity flow utilities.

However, as with any geotechnical evaluation, this analytical model is an idealization of the true behavior, and the field data may not be fully representative of the overall site conditions. Our limited understanding of the time basis for secondary compression is especially noteworthy and there are few long-term case studies to confirm the efficacy of the analysis. Finally, the analysis involves significant extrapolation of short-term settlement data. Leroueil and Tavenas (1981) rightly highlight the dangers of over-confidence in back-analyzed parameters, and their warnings are certainly applicable to this case. Other factors and processes also are surely at play and are not explicitly being considered. Therefore, an appropriate level of conservatism must be incorporated into the analysis and design process.

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