NOTE

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Settlement and Strength of Soft Soil:
Design Software Including Effects of PVD's

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Introduction

Construction of embankments over soft soil is always challenging. First, the foundation soil relevant properties need to be identified. This is as much of an art (i.e., experience) as it is science. For example, was the soil profile including sand seams properly characterized, was the soil shear strength correctly interpreted, and are the field/lab coefficients to calculate settlement representative? Second, a design needs to be carried out in which the foundation's settlement and strength are estimated at any time. This allows for a construction rate or staged construction that implements such measures as PVD's (aka wick drains) to accelerate consolidation or for use of lightweight fill material (e.g., geofoam) to reduce the induced stress in the foundation. While determining the relevant data is the most critical element in the design process, the calculations of stresses and settlements are tedious often leading to short cuts (i.e., assess only one or two case scenarios) resulting in overly expensive construction. Design software is not a substitute to experience; however, it can be an excellent tool to reduce the tedium and increase productivity while producing an optimal construction based on a rational approach. Program FoSSA is such a tool.

FoSSA was developed by ADAMA Engineering (www.GeoPrograms.com). Version 1.0 was licensed to FHWA (http://www.fhwa.dot.gov/bridge/081803.htm). Version 2.0 is serves as the basis for future updates and upgrades.

Overview of Program FoSSA

Settlement in the foundation soil is in reaction to induced stresses by embankment loading. FoSSA calculates the stress distribution under embankment, possibly having complex geometry, followed by the elastic (immediate) settlement, the consolidation settlement (including excess porewater pressure and settlement during the consolidation process), accelerated consolidation settlement due to PVD's (triangular and square installation patterns), secondary settlement, and undrained shear strength distribution within consolidating layers. It can deal with foundation profile comprised of up to 50 layers having complex-geometry (consolidating or not) and up to 25 layers comprising the embankment (e.g., representing alternating layers of geofoam and soil or just simulating staged construction). The distribution of the induced stress is calculated based on numerical integration of the basic Boussinesq equation. Elastic settlement is based on numerical integration of Hooke's equations. Consolidation settlement (1-D) solves Terzaghi's differential equation using a finite difference scheme at any prescribed time and for any initial excess porewater distribution. PVD's design follows: "Prefabricated Vertical Drains, Vol. I: Engineering Guidelines," by Rixner, Kraemer, and Smith, Haley & Aldrich, FHWA report FHWA/RD-86/168, September 1986, Contract No. DTFH61-83-C-00101 (which is a practical modification of Barron's solution developed for vertical sand drains). The undrained shear strength calculations during consolidation follows: "Stability Evaluation during Staged Construction," by Ladd, Journal of Geotechnical Engineering, ASCE, 1991, Vol. 117, No. 4, pp. 540-615. The various theories are linked in a consistent manner to produce design that is compatible with existing practice. It can be used with field data to back-calculate the basic consolidation parameters (i.e., calibrate the parameters using field data obtained during field monitoring; useful in an observational approach).

Example

General: Stresses in soil increase due to, for example, external loading (e.g., embankment construction) or internal loading (e.g., lowering of ground water table). The soil response to stress increase is a decrease in its voids resulting in settlement. If the soil is saturated, any decrease in volume of voids can occur only if water, an 'incompressible' material, is simultaneously expelled thus allowing such reduction. The water in the void that initially carries the stress increase (hence, it is a pore water pressure in excess of hydrostatic or of equilibrium). This excess pore water pressure causes the flow of water; the flow rate depends on the opening size of the interconnected voids. If this size is large (e.g., gravel, sand), the water flow will be nearly instant. However, if the soil is made of fine particles such as clay, the water flow is a slow process. The term 'consolidation' refers to the settlement process associated with the reduction of volume of voids in saturated fine-grained soils. Consolidation occurs in response to stress increase; it represents a transitional phenomenon in which excess pore water pressure dissipates simultaneously with the development of settlement. Consolidation is considered complete when the excess pore water pressure returns to hydrostatic (static equilibrium). This complex process is described mathematically by a differential equation; typically it is Terzaghi's 1-D equation. Its solution is practically very meaningful since it enables us to predict the rate at which consolidation settlement will occur as well as the soil stresses and thus the soil shear strength at any time. Unfortunately, this equation cannot be solved in a closed-from solution. Some non-dimensional charts with the solution exist. However, such charts are limited to a few loading cases. Moreover, its application is cumbersome. Computers can solve this equation quickly thus taking the tedium out of the prediction (or design) process. The user needs to be a good engineer but not a mathematician.

Problem: To demonstrate the power of a computerized process, consider the problem shown in Figure 1. A soft clay layer, varying in thickness between 10 and 15, m is contained between two sand layers. Obviously, the sand is much more pervious than the clay thus it can easily drain the water that is 'squeezed' out of the clay layer as it consolidates (hence, the clay drains at its both boundaries). An embankment with the geometry shown in Figure 1 is to be constructed. It is 6 m high. Its left side slopes are 1(V):2(H) and 1(V):2.5(H) and it includes a setback of 6 m at mid-height. The right side slope is rather steep at 1(V):1(H) and is very likely reinforced with layers of geosynthetics (outside the scope of this article). The flatter slopes and the setback would produce smaller stresses increase compared with the steeper slope. However, the settlement of the deformable clay is also proportional to its thickness. Hence, it makes sense to use different geometry on either side of the embankment so as to obtain settlement that is closer to symmetry across the base. Note that there are 4 distinct layers of embankment, each 1.5 m high. We use this distinction to indicate the option of using staged construction. FoSSA allows for up to 25 embankment layers to simulate involved staged construction schemes. The geometry of the embankment and the foundation layers can be complex. In our example problem, however, we keep the problem simple yet instructive.

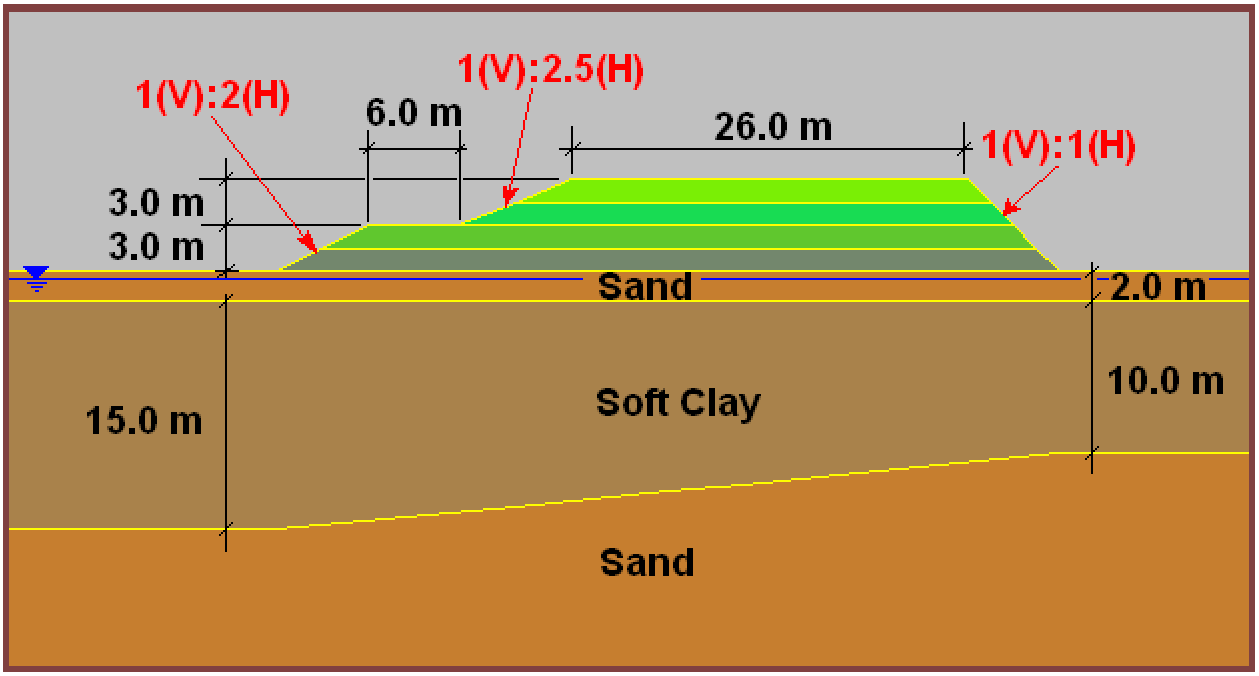

Figure 1. Example problem: Profile of foundation and geometry of embankment

Stress Increase: To find the consolidation reaction of the foundation to the embankment loading, the vertical stresses increase is sought. The basic equation of Boussinesq (linear elasticity) is integrated to yield the stress increase in any relevant zone of the problem. Boussinesq equation is frequently used in geotechnical engineering (especially stress distribution under footing) because, generally, it yields reasonable results without the need to carry out complex numerical analysis. Furthermore, the induced vertical stressed is independent of the material elastic properties, a very attractive feature when dealing with messy soil mass below. Figure 2, generated by FoSSA, shows the distribution of vertical stress increase due to load exerted by the complete embankment. Notice that the highest stress (Figure 2) is under the crest. Also, stresses under the first left side slope and the setback are relatively small (consequence of geometry – a designer choice when attempting to get approximately symmetrical settlement in response to loading).

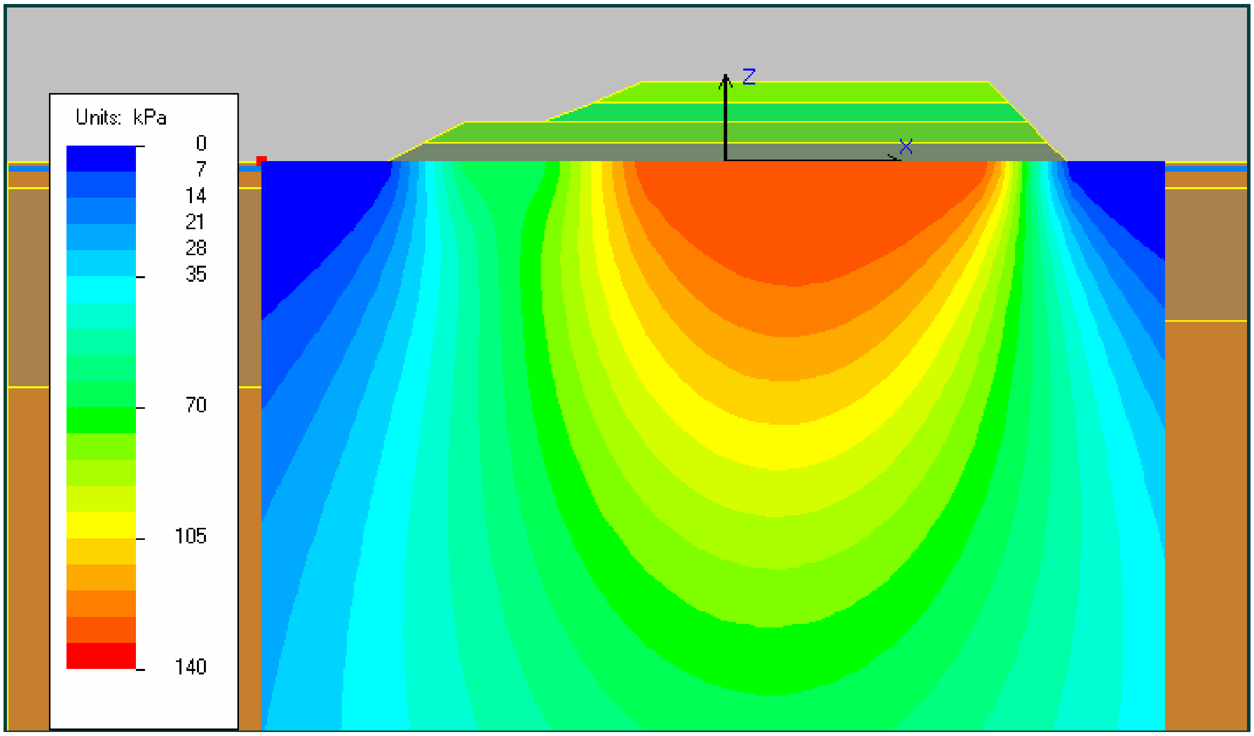

Figure 2. Vertical stress increase due to embankment loading

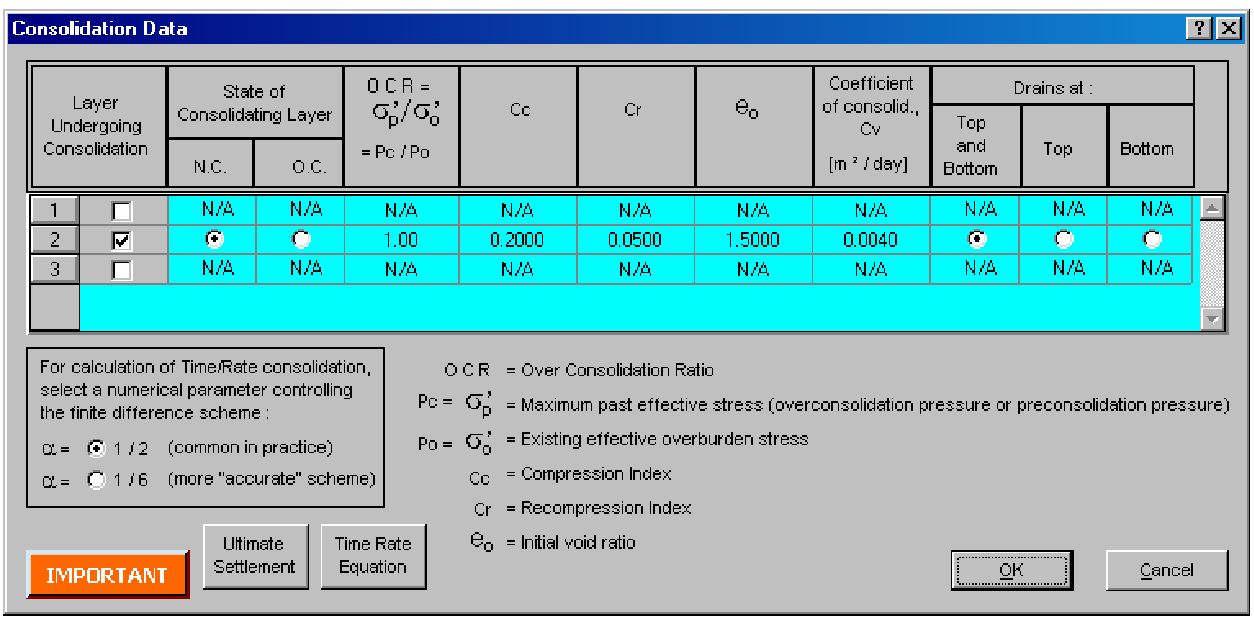

Figure 3. Input of parameters to compute consolidation

Ultimate Settlement: Once the increase in stress is known, consolidation settlement can be computed. Figure 3 shows the input data needed for such computations. It allows the user to invoke the consolidation computation for any desired layer. The user needs to specify whether the clay drains at the top, bottom or both ends; in our case it is both boundaries since sand augment the clays layer. The compression index and the initial void ratio dictate the ultimate consolidation settlement; the consolidation coefficient, Cv, dictates the rate of consolidation.

Figure 4 shows the ultimate consolidation settlement; i.e., the settlement at the end of the consolidation process when all excess pore water pressure dissipated. The distribution shown in the figure is plotted in an exaggerated scale. The deepest drawn bar represents an ultimate settlement of 0.52 m. Notice that on the left side of the lower embankment the settlement is about the same as on the right side while the thickness of the clay layers is 50% thicker.

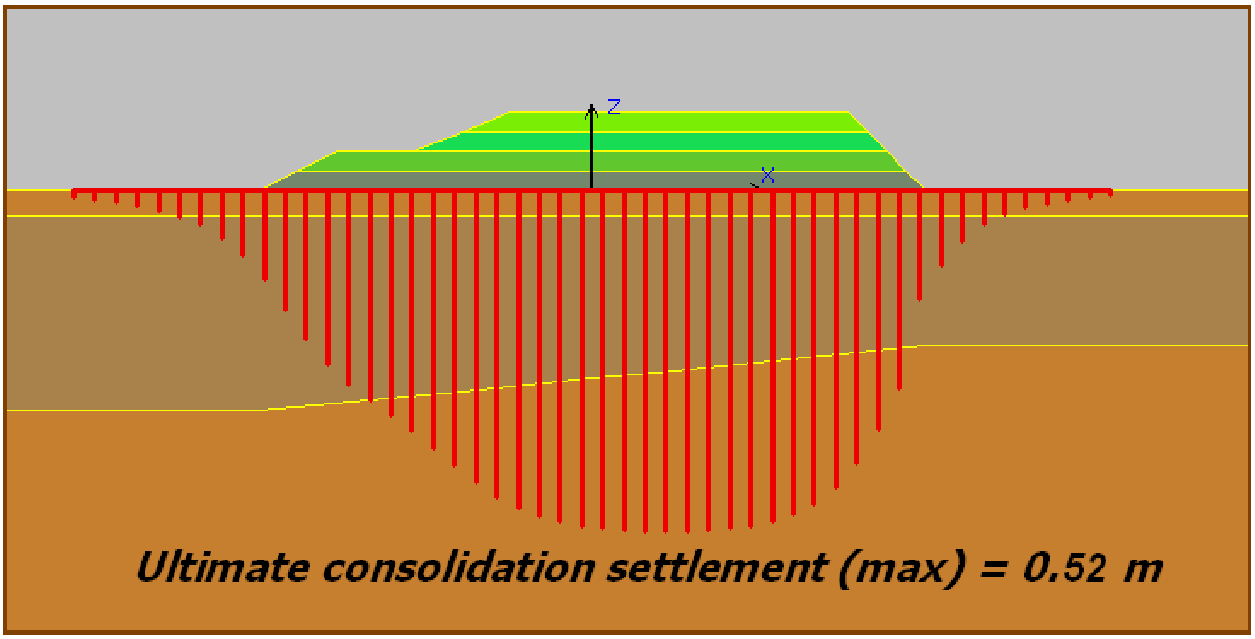

Figure 4. Distribution of ultimate consolidation settlement

Conventional Case: To calculate the time rate consolidation, a vertical section through the consolidating layer is selected. Figure 5 is for a section through which the maximum ultimate settlement of 0.52 m is predicted. The user of FoSSA can easily select several parallel sections to obtain a spatial perspective of the consolidation process. Figure 5 shows the distribution of excess pore water pressure, Ue, versus time, t; it is a solution of Terzaghi 1-D equation. The formal terminology for Ue curves, each at a different time, is *isochrones*. FoSSA generates isochrones based on user's specified average degree of consolidation, U, which is a function of the excess pore water distribution, Ue. Hence, for specified value of U, FoSSA solves Terzghi's equation by time increments to find the corresponding Ue and its associated U until such cumulative time that the computed U is same as the target value.

Figure 5 was generated for a specified target average degree of consolidation of U=90%. FoSSA found that it will take about 7,800 days to reach 90% average consolidation. The thick red line on the right represents the initial conditions (at time t=0, immediately after load application). It is equal to the Boussinesq vertical stress distribution initially carried entirely by the pore water as an excess pressure. Next shown are 10 curves (isochrones), each at a different time (first curve, turquoise color, is at about 780 days after load application, second is at about 1560 days, continuing in increments of 780 days until the last one at 7,800 days, which produces U=90%) . Notice that the excess pore water pressure drops quickly to zero at the draining boundaries. However, the maximum Ue (marked by a thick black bullet) quickly shifts to the center of the clay layer. That is, dissipation of excess pore water pressure will be the slowest near the center of the doubly drained clay layer since the water flow path needed to enable such dissipation is the longest.

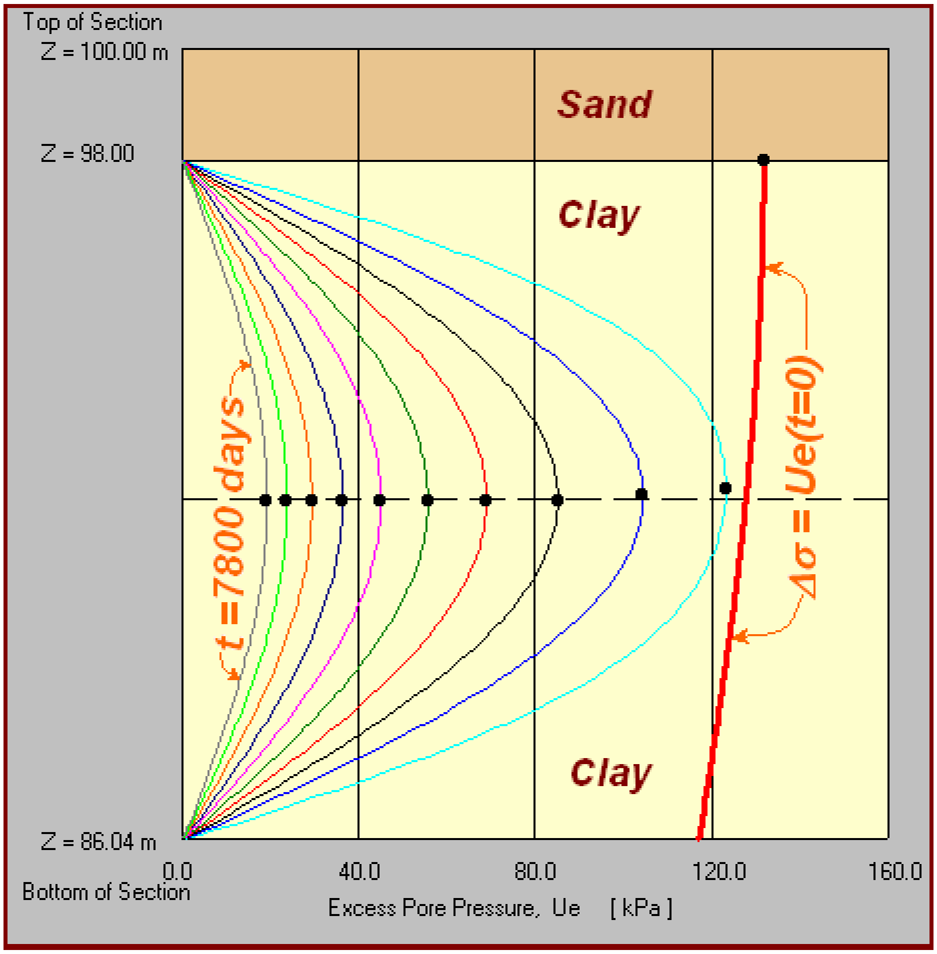

Figure 5. Dissipation of excess pore water pressure along vertical cross section through the consolidating clay layer

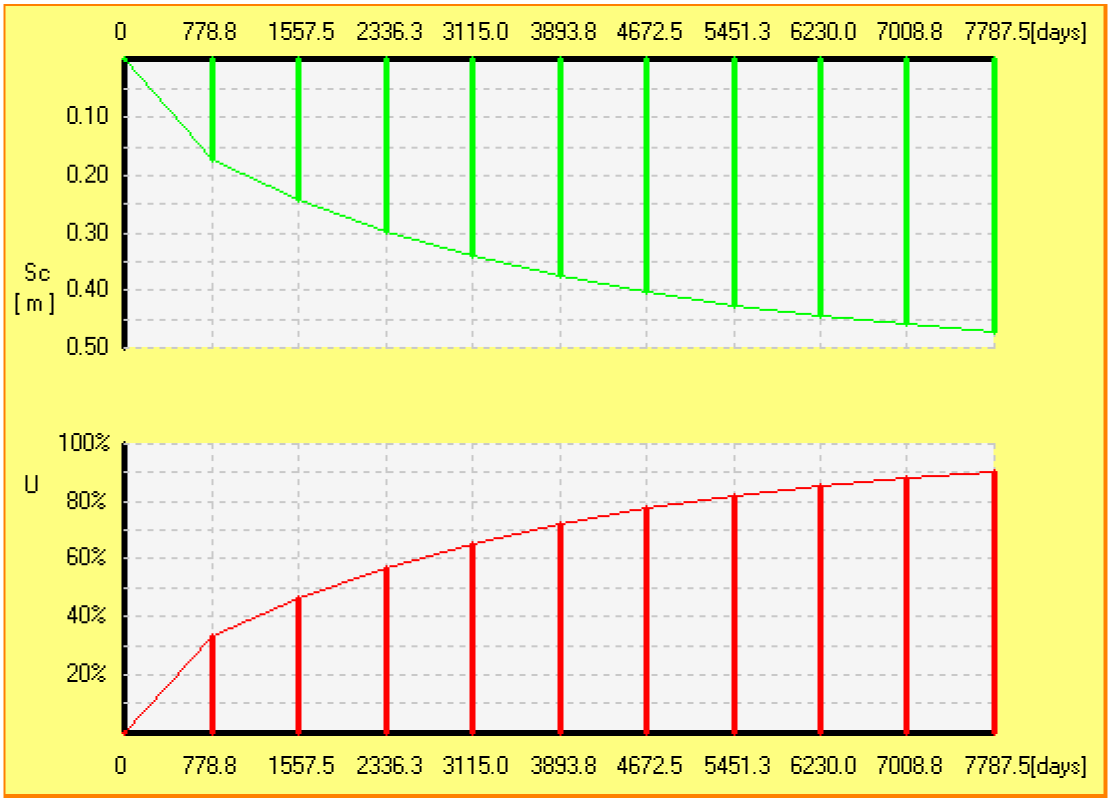

Figure 6. Settlement, Sc, and average degree of consolidation, U, versus time

The distribution of excess pore water pressure, Ue, serves to calculate the average degree of consolidation, U, and subsequently, the settlement, Sc, at any time during the process. It should be noted that in a strict mathematical sense, it will take infinite time for U to reach 100% (i.e., as Ue dissipates, the flow rate of water through the interconnected voids decreases). It is quite common in geotechnical engineering to consider U=90% as practical limit that is "close enough" to complete (100%) consolidation. Figure 6 was generated by FoSSA following the results in Figure 5. One sees that U rapidly increases; at 90% it reaches an asymptote (i.e., increase in U versus increase in time increments that becomes smaller). The respective settlement, Sc, is directly proportional to U. It should be pointed out that field measurement of settlement is quite simple. Hence, the validity of results can be ascertained. Quite often the rate of consolidation is faster than predicted. This is mainly due to the existence of thin sand seams within the consolidating clay layer which facilitate drainage. Using field data, a designer can re-assess the computations by 'calibrating' the input data in FoSSA to hopefully produce more reliable prediction for the next time increment (i.e., observational methods) and thus adjust construction activities.

The distribution of Ue, Figure 5, makes it possible to assess the average actual soil stress (i.e., effective stress). That is, Ue dissipates the intergranular stress increase proportionally (the induced stresses by the embankment carried initially by the water are gradually transferred to the soil solid particles to carry). This is accompanied by a decrease in the volume of the voids (hence, settlement) and an increase in the shear strength of the foundation soil. Figure 7 shows such an increase. Initially (t=0), the shear strength distribution in linearly distributed (see thick red line). As consolidation proceeds, the strength increases rapidly reaching it full consolidated value at the boundaries. The heavy black dot shows that the lowest strength is slightly above the center of the clay; however, with time it shifts upward signifying the same trend as at t=0. The location of the lowest strength would depend on Ue and the specified initial distribution of strength. Knowledge of the shear strength is extremely important in design of embankments over soft soil. It enables the designer to assess the stability against deep-seated failure versus time (and not only settlement as implied by basic consolidation calculations). In fact, the main motivation for staged construction is to allow the foundation soil to gain sufficient strength before adding another layer of soil. FoSSA enables the designer to estimate the shear strength gained after each loading stage and thus estimate the needed time lag of ceased construction until the next soil layer can be placed so as to maintain a sufficient margin of safety against collapse. Stability analysis was not conducted in this example problem. It is possible that such analysis will lead towards staged construction to ensure constructability.

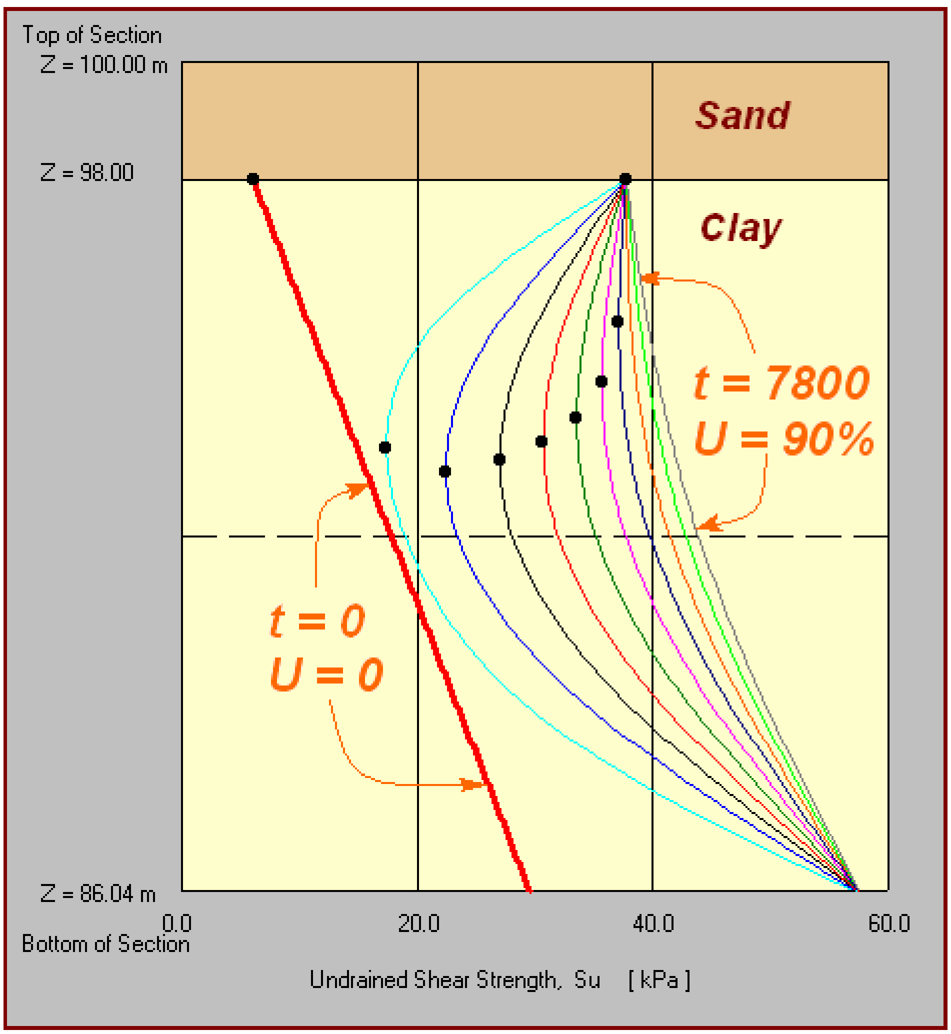

Figure 7. Shear strength distribution versus time

Prefabricated Vertical Drains (PVD's): The computed results show that it will take about 21 years for the foundation soil to consolidate. If the embankment carries a structure (e.g., highway), it means continues maintenance (and resources) as consolidation settlement develops. The use of PVD's (*aka* as wick drains) can be very effective in accelerating the consolidation process. Such drains can shorten the drainage path of water squeezed out; in addition to vertical flow, water now can drain horizontally to the PVD and move quickly outside the clay layer. The design challenge is to determine the spacing (and pattern) of the PVD's installation so as to dissipate the excess pore water pressure quickly. Figure 8 shows the input data required in FoSSA. It includes Ch, the coefficient of consolidation in the horizontal direction, signifying the horizontal permeability of the clay. Depending on the clay formation, Ch can be larger by an order of magnitude as compared with its vertical counterpart, Cv. The user can select between triangular and square pattern as well as spacing. Specific parameters related to the effectiveness of a particular PVD can be input (typically provided by fabricators).

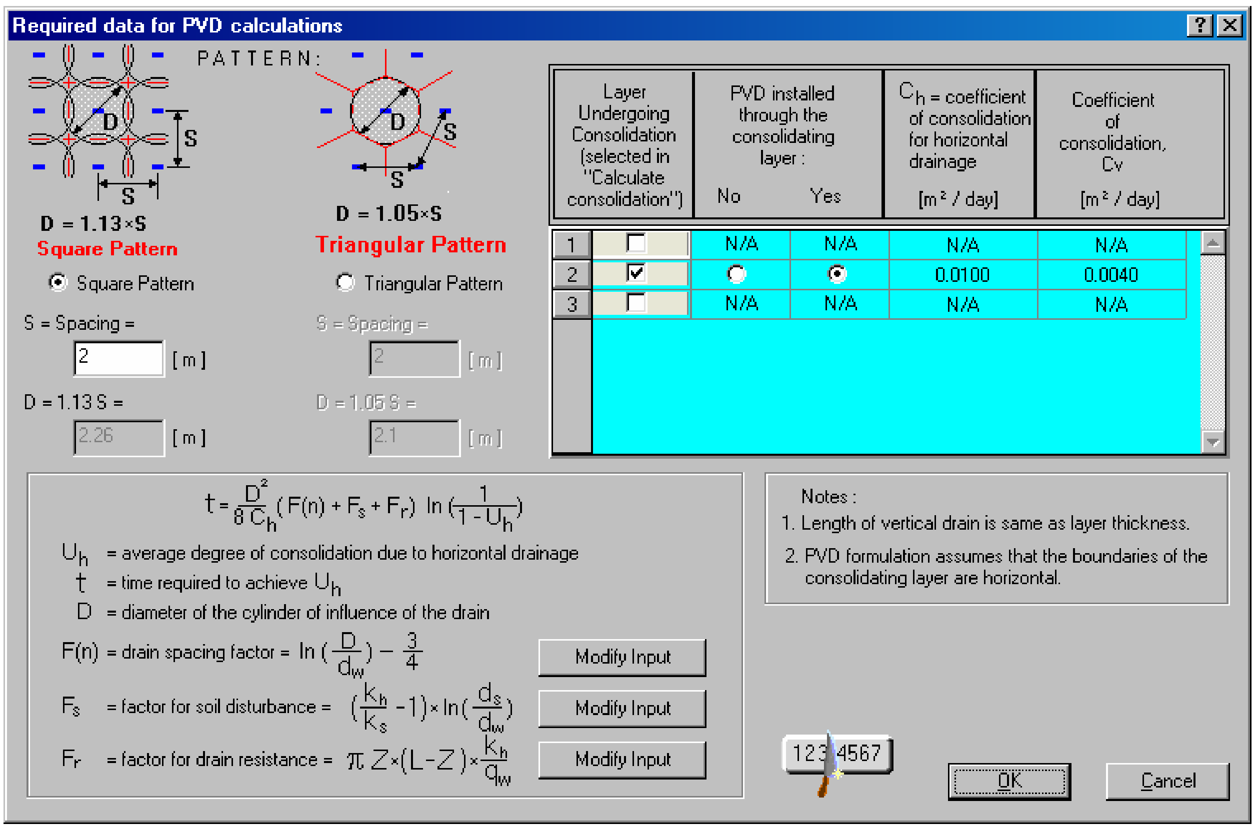

Figure 8. Input of PVD data in FoSSA

For the data in Figure 8, FoSSA calculated the required time to attain 90% consolidation. Figure 9 shows that this can be attained within 560 days, about 14 times faster than without PVD's. Clearly, the economics of using PVD's can be rationally assessed. Furthermore, FoSSA allows for quick optimization of the PVD's layout. The effectiveness of PVD's can also be assessed in a staged construction scenario.

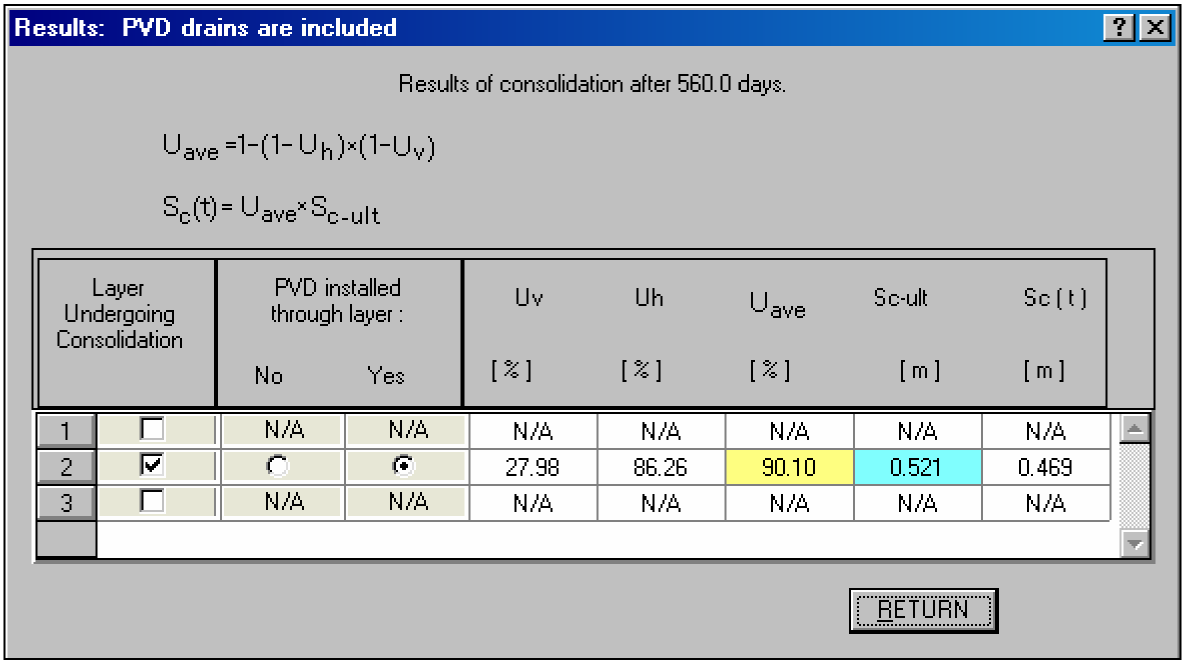

Figure 9. Effects of PVD's

Lightweight Fill: The effect of PVD's was evaluated last demonstrating a significant decrease in consolidation time. However, the case with soft soil is often related to insufficient stability to low shear strength. One way to increase stability is to use high-strength geotextile reinforcement at the foundation interface. Another one is to conduct staged construction, placing predetermined layers of soil until sufficient strength gain is generated to allow the placement of the next layer. Often, base reinforcement combined with staged construction and PVD's is used. Alternatively, the load that produces settlement and possible instability can be reduced by using lightweight fill (e.g., geofoam, foamed concrete). Geofoam has negligible weight (relative to soil) and is easy to work with. It has to be protected, however, by a layer of soil. Hence, let us examine the case shown in Figure 10. We wish the final installation to be as shown in Figure 10a – geofoam core protected by a soil cover. The soil cover will generate some settlement. Figure 10b shows a simulation of this cover as used in FoSSA to assess settlement (actually, the exact section shown in Figure 10a can be replicated in FoSSA; however, the simplification in Figure 10b is easier to follow and is practically valid). PVD's as specified in Figure 8 are used in combination with the geofoam.

Figure 11a shows that after 560 days, the settlement due to the soil cover only will reach 90% consolidation. Note that the consolidation rate is the same as in Figure 9 where the full embankment height was used. However, for the entire embankment the ultimate settlement was 0.52 m whereas for only the cover soil it is 0.19 m (Figure 11a).

In case settlement of 0.17 m over a period of 560 days is unacceptable, the following construction scheme shown in Figure 10c is possible. In addition to the cover material, place another layer of soil to preload the clay (i.e., by design, over-consolidate the clay prior to actual construction). Once the consolidation settlement reaches the ultimate value which would have been generated by the cover soil alone, the preloading layer can be removed (and, perhaps, used to construct the embankment at less other locations where preloading is not needed). The cover soil is then also removed, the geofoam placed, and the cover soil replaced on top. Looking at the results in Figure 11b, one sees that a settlement of 0.19 m is generated within 200 days by preloading. Hence, at this stage scheme shown in Figure 10a can be built with near zero settlement and with high level of stability.

The construction scheme using the geofoam in this example is not more involved than the conventional case with PVD's (considering the placement of preloads and replacement of cover). In fact, it shortens the construction time to one 'season' and, contrary to the case without the preloading, it produces nearly zero settlement right at the end of construction. This has clear economical implications and can be compared against the cost associated with the use of geofoam.

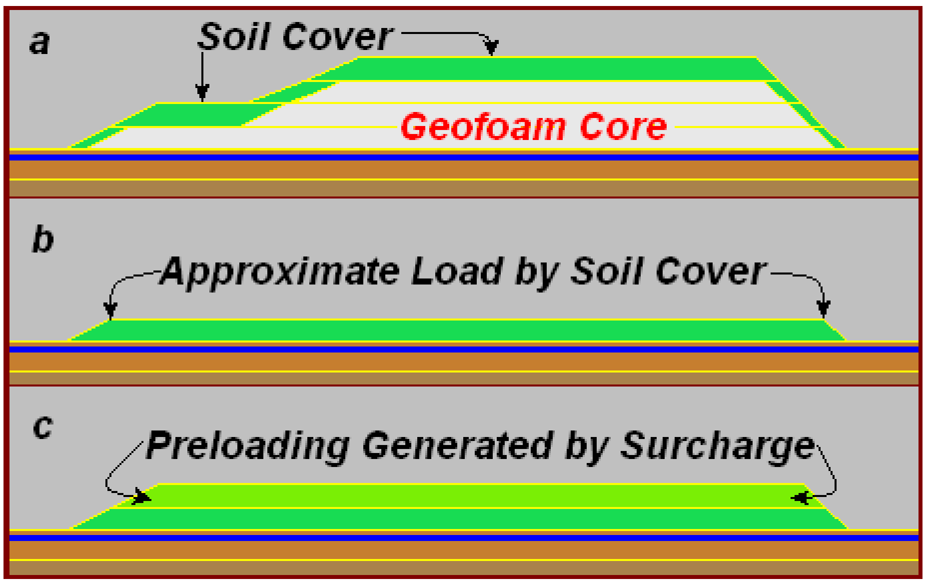

Figure 10. Use of lightweight fill: a. Geofoam core, b. Settlement is due to cover material, and c. Preloading to facilitate consolidation settlement

Layer Undergoing Consolidation		PVD installed through layer : No	Yes	Uv [%]	Uh [%]	U_{ave} [%]	Sc-ult [m]	Sc (t) [m]
1	☐	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	☑	○	◉	28.06	86.26	90.11	0.193	0.174
3	☐	N/A	N/A	N/A	N/A	N/A	N/A	N/A

a. Response to loading by soil cover: t = 560 days

Layer Undergoing Consolidation		PVD installed through layer : No	Yes	Uv [%]	Uh [%]	U_{ave} [%]	Sc-ult [m]	Sc (t) [m]
1	☐	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	☑	○	◉	16.68	50.78	58.99	0.330	0.194
3	☐	N/A	N/A	N/A	N/A	N/A	N/A	N/A

b. Response to preloading by surcahrge: t = 200 days

Figure 11. Settlement the geofoam case: a. No preloading, and b. With preloading

Concluding Remarks

Construction over soft soil is concerned with two major aspects of performance: stability and settlement. Both increase with time after the end of construction. There are several potential designs. Checking the alternative options is cumbersome. Program FoSSA is a tool that facilitates the selection of the most suitable solution. It complies with sound geotechnical practice. However, it is not a substitute to knowledge and experience.

The example problem shows that consolidation settlement and foundation strength gain is a lengthy process if left to develop naturally. The use of PVD's can accelerate the process by one or two order of time magnitude. Reducing the load by using geofoam can further reduce the time yielding near zero settlement. FoSSA enables the user to rationally assess various design options or 'what if' cases thus making the selection of the most economical solution less involved.