SOIL AND WATER: THE ESSENCE OF SOIL MECHANICS

ZEMLJINA IN VODA: BISTVO MEHANIKE TAL

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Abstract

It is generally recognized that the beginning of modern soil mechanics as a rational engineering discipline dates back to the Terzaghi's 1923 paper in which he, for the first time, formulated the effective stress principle. It is not an accident that in the same paper he also formulated the theory of consolidation. Both of these developments address the important issue of the interaction between soil and water. Indeed, if it were not for the presence of water in soil we wouldn't have soil mechanics as a distinct engineering discipline. Two water related issues, consolidation and desiccation, are discussed in the paper. An in depth look at the historic developments and the current state of our understanding of these processes enable us to review fundamental principles that should guide most of the developments in soil mechanics.

Povzetek

Danes je splošno priznano, da se je sodobna mehanika tal kot racionalna inženirska disciplina začela leta 1923 s Terzaghijevim člankom, v katerem je prvič zapisal načelo efektivnih napetosti. Ni slučaj, da je v istem članku predstavil tudi teorijo konsolidacije. Oba prispevka se dotikata pomembnega vprašanja medsebojnega delovanja zemljine in vode. In če v zemljini ne bi bila prisotna voda, ne bi poznali mehanike tal kot posebne inženirske vede. Članek obravnava dva med seboj povezana pojava: konsolidacijo in izsuševanje. Poglobljen pogled v zgodovinski razvoj in trenutno stanje našega razumevanja teh procesov omogoča pregled temeljnih načel, na katerih bo temeljila večina nadaljnjega razvoja mehanike tal.

1. INTRODUCTION

As we are approaching the first centennial of Soil Mechanics it is fitting to pause and look back on how it started in the first place. In his 1923 paper, Terzaghi formulated the effective stress principle and used the solution to the heat conduction equation to explain and describe the consolidation process in clays. These two developments embody the essence of modern soil mechanics in more than one way. First, they both relate to the interaction between soil and water which is *condicio sine qua non* of modern soil mechanics. If it were not for the water in soil we wouldn't need soil mechanics as a separate engineering discipline. In such a case anybody with some decent training in engineering mechanics could solve problems of foundations, slopes and retaining structures without much effort. Terzaghi himself stated this nicely in his 1939 paper: "….in engineering practice, difficulties with soils are almost exclusively due not to the soils themselves but to the water contained in their voids. On a planet without any water there would be no need for soil mechanics." Second, they exemplify the use of both the empirical principles as well as rational theories in solving practical problems. The effective stress principle is an empirical statement that has served us well for the past nine decades, even though there is no point in soil where the stress with such value could be found. The consolidation theory on the other hand demonstrates the power of using rational models to describe important processes and of applying mathematical tools for solving the boundary value problems. Finally, the same 1923 paper inaugurates well the principle that the solutions to soil mechanics problems must include both the experimental and analytical work. The development of the consolidation theory would have been totally useless had it not been accompanied by the experimental procedure for the determination of the coefficient of consolidation.

Here we will examine the historical developments of two topics in which the interaction of soil and water is essential. We will highlight the advances that have been made in the past nine decades and we will emphasize the areas in which more work needs to be done in the near future. First, we review the history and the current state of consolidation processes and then we focus on desiccation. In addition to reviewing the current state of the development we will give examples of engineering problems in which the new developments have made the difference.

2. HISTORY

The original consolidation model was quite simple, consistent with development of the analytical and computational technology at that time. It assumed that the material consolidation characteristics do not change during the consolidation process and neglected any contribution of the self weight stresses to the compression of the consolidating layer. However, it is interesting to note that Terzaghi recognized that this is a moving boundary value problem since the consolidating layer changes its thickness in the process. Accordingly, he used the material coordinate system in the Lagrangian sense. In our 1982 paper we established that this was truly a finite strain theory that was only later, at an unknown time, restricted to the infinitesimal strain theory by simply assuming that the layer thickness does not change (Znidarčić and Schiffman, 1982). Even with this constraint the theory was quite suitable for solving practical problems. At that time most of soil mechanics problems were related to on-shore sites in temperate climate with relatively stiff clays. Thus, the assumptions of full saturation and infinitesimal strain were quite acceptable and did not compromise the accuracy of the solution.

Terzaghi in 1923 proposed a relaxation test to measure the coefficient of consolidation. The testing conditions were ill defined and the fundamental assumption of the theory, i.e. monotonic loading, was violated in the procedure (Znidarčić et al., 1984). For the following four decades a number of other consolidation tests and the associated analysis procedures were developed, but no major improvements in the theoretical developments can be noted. As our computational abilities rapidly improved at the beginning of the second half of the 20th century, the conditions were suitable for the development of a rational, nonlinear finite strain consolidation theory. McNabb (1960) and Gibson et al. (1967) developed such a theory that could be applied to solving engineering problems of soft soils as it relates to off-shore engineering as well as to various soft soil disposal problems in mining and dredging operations. Unlike the development of the original consolidation theory this time the theoretical framework was not complemented by the appropriate solution methodology or by the experimental development needed to determine the constitutive properties for the material. As such the theory remained unproductive for more than a decade until adequate computer codes were written to solve the appropriate boundary value problems (e.g. Gibson, Schiffman, and Cargill, 1981). The application of the new theory in the routine engineering practice was still hindered by the absence of an appropriate experimental procedure in which the soft soil constitutive properties, consistent with the nonlinear finite strain consolidation theory, could be determined. There was no point in using the sophisticated theory while the tests were analyzed using a theory in which the coefficient of consolidation is assumed to be constant. This situation highlighted the need that any development in soil mechanics must contain all three aspects: theoretical development, computational implementation and adequate experimental technique. Advancing only one facet of the problem will seldom produce any useful results.

During the 1980s we set out to not only develop an adequate laboratory testing technique for the determination of the soft soil constitutive properties consistent with the nonlinear finite strain consolidation theory, but also to verify the theory by performing well controlled centrifuge modeling experiments. These efforts resulted by the 1990s with a complete engineering technology that can be used in routine engineering applications related to soft soils (Croce et al.1984, Znidarčić et al.1986, Abu-Hejleh and Znidarčić 1996). Though we reference here mostly the work done at the University of Colorado at Boulder, at the same time there were parallel developments by others, mostly in the area of numerical implementation of the Gibson's finite strain consolidation theory. Simultaneously with these developments the research results have been applied to solve routine engineering problems of soft soil disposal in mining and dredging operations. There are many field examples in which the developed technology, from testing to numerical implementation, has been fully validated. It is fair to say that today we have a rational, comprehensive engineering tool needed for everyday applications.

Once we were satisfied that the developed methodology can answer the needs of the profession, we turned our attention to the next problem in the slurry waste management, the desiccation of soft soils. The desiccation can be triggered either by the evaporation from soil surface or by lowering the groundwater table. In either case a desiccated crust develops at the soil surface and eventually the desiccation cracks develop. We started modeling this process by first expanding the finite strain consolidation theory to include the desiccation process in which the pore water pressure drops below the atmospheric pressure and soil suction develops.

We then developed testing procedures in which we first experimentally verified that all the assumptions made in the theoretical development are justified and then developed the testing protocols to obtain the necessary constitutive properties for the desiccation process (Abu-Hejleh and Znidarčić 1995). We then developed a computer model in which the theory is implemented and a variety of field conditions can be properly simulated (Yao et al. 2002). Finally, we used the centrifuge modeling technique to verify that the developed theory and the testing procedures are appropriate and that they realistically predict the desiccating soil behavior (Oliveira-Filho 1998). Again, as soon as we were confident that the new theory is realistic we started its application to the engineering problems in the field.

3. CONSOLIDATION

The application of the developed methodology is illustrated here by analyzing a real problem of phosphatic clay consolidation. In addition to describing the necessary steps to obtain the constitutive properties, the analysis will allow us to demonstrate the physics of soft soil consolidation and desiccation. What is particularly valuable is that we will be able to “see” what is happening inside the consolidating and desiccating layer, the part that is hidden from us in the field and that is hard to document by field observations.

In the phosphate industry in Florida large quantities of soft waste phosphatic clays are produced in the process of extracting phosphates from the ore. This clay is highly active, having the liquid limit of over 200 and the plasticity index of over 150. In the process of phosphate extraction this clay is mixed with large quantity of water so that the slurry that is pumped into the disposal area has only about 5% to 10% solids, which corresponds to a void ratio between 25 and 50 and a water content that is ten to twenty times higher than the liquid limit of the material. Such slurry has a consistency of milk and the first question is if such a material is really a soil in the soil mechanics sense. This issue was first addressed by Monte and Krizek (1976) by defining a new “Flow Limit” at which slurry starts to behave as soil, i.e. the effective stress principle is applicable. Unfortunately, they did not propose a standard method on how to determine this value, but suggested that it would be four to five times the liquid limit for the material. Liu (1990) investigated the void ratio corresponding to the zero effective stress and found that this is not a constant value for a soil, but that it depends on the initial water content (or void ratio) of the slurry. Based on his work, today we determine the zero effective stress void ratio e_o in a simple experiment in which a small amount of the slurry is allowed to settle in a graduated cylinder. Knowing the initial water content and the ratio of the initial slurry volume to the final soil volume, the final water content is calculated. Since the soil is saturated at this time, the zero effective stress void ratio is obtained by simply multiplying the water content by the specific gravity of solids. Clearly in this experiment the actual magnitude of the “zero” effective stress depends on how tall is the final soil column. While this might seem like an arbitrary value, it actually provides us with the opportunity to define the needed accuracy of our analyses. In the engineering sense effective stresses in a slurry column of one to two centimeters in height could be considered negligible.

The zero effective stress void ratio represents the point at which the soil is formed and the sedimentation process ends and the consolidation process begins. The sedimentation theory was originally developed by Kinch (1952) and later discussed in detail by Pane (1985). In his work Pane (1985) developed the necessary testing procedures to obtain the sedimentation characteristics of soils and also combined the sedimentation and consolidation theories so that a continuous analysis can be implemented to describe both processes simultaneously. While this is an interesting exercise in itself, the sedimentation process often has relatively small influence on the geotechnical engineering problems and is seldom included in any real applications. Thus, we will leave a detailed discussion of the related issues to a later paper.

Determining the constitutive properties for such soft materials as phosphatic clays represents a major challenge. Both the compressibility and hydraulic conductivity characteristics must be known in order to utilize the Gibson's (1967) finite strain consolidation theory in engineering applications. Determining the hydraulic conductivity characteristics poses a special challenge. A flow through the slurry must be created in order to measure the flow processes. The flow in turn triggers the seepage forces that compress the soil and make the tested sample heterogeneous with the variable hydraulic characteristics. The only way that the problem can be solved rationally is to employ the inverse problem solution approach to the test analysis. The approach was originally used by Znidarčić et al. (1986) to analyze the constant rate of deformation consolidation test in order to obtain the consolidation characteristics for soft soils. It was soon realized that the hardware limitations for the constant rate of deformation test do not provide sufficient sensitivity for testing very soft soils. As the inverse problems are mathematically ill-posed, they require extremely accurate test data in order to obtain material characteristics of sufficient accuracy. An alternative testing method was proposed by Imai (1979) in which the seepage forces are used to consolidate soft soil samples and obtain both the compressibility and hydraulic conductivity characteristics. While Imai's test analysis required some inconvenient internal pore water pressure measurements, the basic idea of using the seepage forces as a trigger for the consolidation process is very appealing for testing soft soils. It is also an excellent candidate for using the inverse problems solution approach for the test analysis, as the test data can be obtained with a desired accuracy without major technical difficulties. We have adopted this approach to develop the Seepage Induced Consolidation Test and the associated Analysis procedure (SICTA). Liu (1990) established the basic testing procedure and the fundamental concepts of the analysis. In our subsequent work we improved on the analysis procedure and modified the testing protocol so that the test became suitable for routine use in engineering applications (Abu-Hejleh and Znidarčić 1994, 1996). Since that time the technique has been used in numerous research and engineering applications and has proven its usefulness and accuracy (e.g. Bartholomeeusen et al. 2002).

Te schematic drawing of the necessary equipment for performing the seepage induced consolidation test is shown in Fig. 1 and a photograph of the system is shown in Fig. 2. A slurry sample is placed into the testing cell and a light piston is placed on top of the sample to prevent the formation of flow channels during the seepage induced consolidation test (You and Znidarčić 1994). A selected flow rate is then imposed across the sample by using the flow pump and the head loss is monitored by the differential pressure transducer. When the steady state is reached, the sample height and the steady state pressure difference are recorded. The sample is then loaded gradually to the maximum desired stress level and allowed to consolidate under the applied load. The sample height is again recorded and the hydraulic conductivity is measured by using the flow pump again. The test lasts typically between 24 to 72 hours. The recorded test data is then input into the SICTA software and the inverse problem solution analysis is used to determine the five parameters A, B, Z, C and D for the constitutive model for soil consolidation. The constitutive model consists of the compressibility and hydraulic conductivity relationships. Liu and Znidarčić (1991) proposed a functional relationship for the compressibility characteristics in the form:

$$e = A(\sigma' + Z)^B \qquad (1)$$

and Somogyi (1979) proposed the hydraulic conductivity characteristics in the form:

$$k = Ce^D \qquad (2)$$

Both of these relationships have been proven to represent well the consolidation characteristics of soft soils. It is interesting to note that the compressibility characteristics described by eq. 1, not only properly model the behavior of soft soil but are applicable to the overconsolidated materials as well (Liu and Znidarčić 1991).

These constitutive relationships are then used to solve the Gibson et al. (1967) governing equation with the appropriate initial and boundary conditions that reflect the field conditions. Many numerical models are available today to solve the appropriate boundary value problems and most of them include a correct numerical algorithm to obtain a stable and accurate engineering solution (Bartholomeeusen et al. 2002). Thus, our success in solving adequately an engineering problem of soil consolidation hinges more on our ability to obtain the proper constitutive model parameters for the analysis than on the availability of any particular software package. One of such models is the CONDES model that we developed and that stands for CONsolidation and DESiccation (Yao et al. 2002). The model has been successfully used in numerous field and research applications and has proven its usefulness in the engineering practice. In order to demonstrate the basic features of the model as well as to gain some insight in the consolidation and the desiccation processes we analyze here a case of soft phosphatic clay disposal in Florida for which we have conducted field monitoring and collected data.

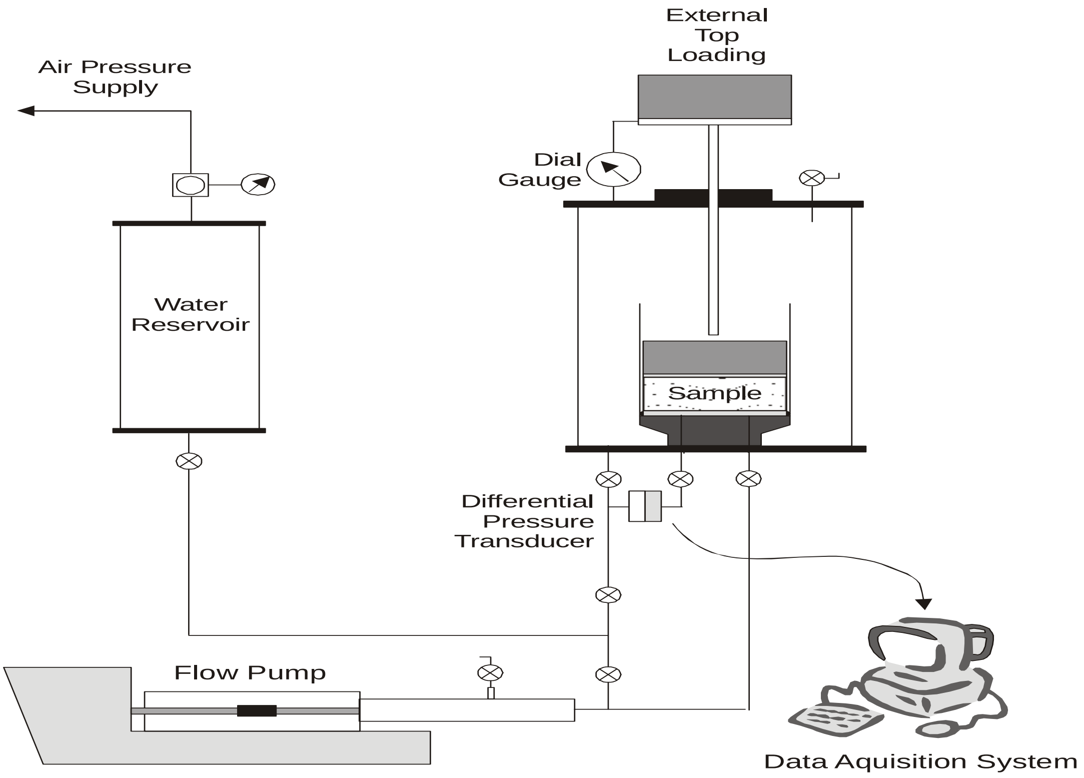


Figure 1 – Schematic drawing of the equipment for the Seepage Induced Consolidation Test

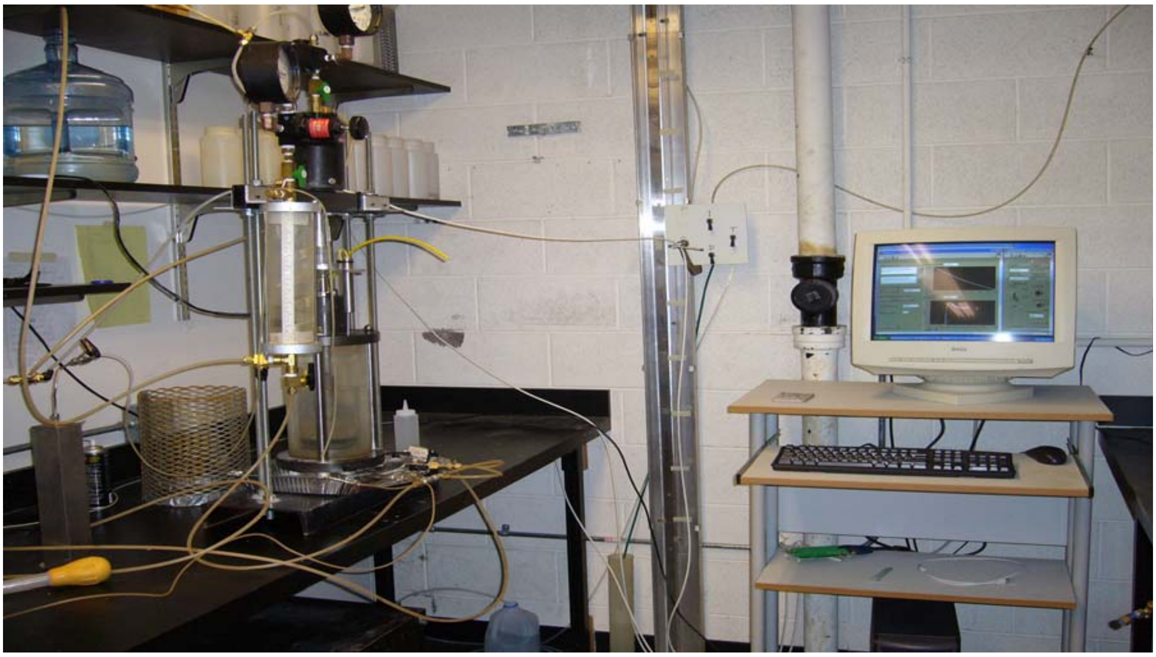
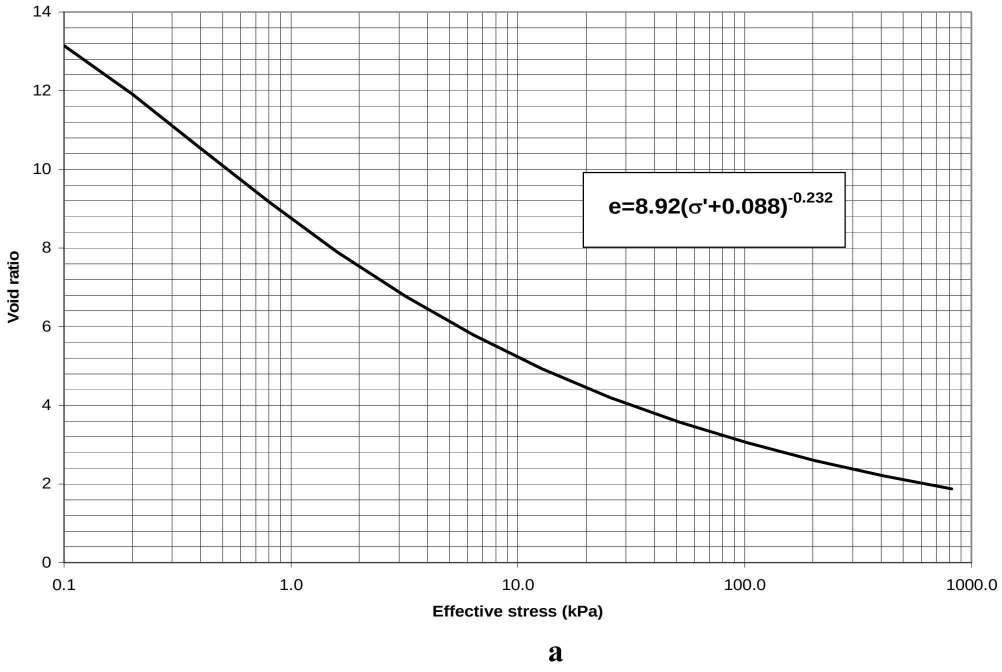


Figure 2 – Laboratory for Seepage Induced Consolidation Testing

The disposal site was filled over the period of 4 years and allowed to settle over the following 10 years. At that point the surface water was decanted and the slurry surface was allowed to desiccate under the natural climatic conditions. We monitored the desiccation process and modeled the slurry performance. The constitutive model used in the analyses is shown in Fig. 3. The parameters for the model were obtained from the seepage induced consolidation test. Fig. 4 shows the modeling results for three filling scenarios: instant filling of the pond with an impervious bottom boundary, gradual filling over the period of 4 years and the instant filling with a pervious bottom boundary. Several characteristics of the consolidation process of soft soils can be highlighted in the figure. The filling history does not affect the subsequent performance of the consolidating layer. As long as the amount of the material in the layer is the same, the consolidation process progresses the same way irrespectively of what is the filling history. The difference between the singly and doubly drained consolidation behaviors is relatively minor due to the highly nonlinear hydraulic conductivity characteristics. The material at the bottom boundary has much lower conductivity than at the shallower depth due to a significant reduction in the void ratio. Thus, the preferential water flow is still in the upward direction even when the bottom boundary is drained.

Fig. 5 shows the void ratio distributions for the impervious bottom boundary and instant filling case. The graphs again show some interesting behavior of a consolidating soft soil layer. Though the bottom boundary is impervious the consolidation process starts from the bottom. This is somewhat counterintuitive, but a closer look at the physics of the process will show that the model correctly captures the real soil behavior. At the moment of the deposition the pore water pressure is equal to the self weight stresses of the slurry. The effective stresses are zero and the slurry is at the void ratio that corresponds to the zero effective stress. If the excess pore water pressure, above hydrostatic, is calculated and the upward gradient determined, it is found that the gradient is equal to its critical value which keeps the soil in suspension in the upper part of the consolidating layer. The gradient drops below the critical value first at the bottom, where the water supply is cut off by the impervious boundary. The upper portion of the consolidating layer is held in the suspension under the constant critical gradient until the consolidating front reaches the top surface. Until that time the settlement rate is also constant as shown in Fig. 4. This phenomenon can also be used in a simple settling column test to calculate the hydraulic conductivity corresponding to the zero effective stress void ratio. The measured settling rate represents the relative Darcy (discharge) velocity between the soil and water, the critical gradient is calculated from the void ratio through the submerged unit weight and the hydraulic conductivity obtained as the ratio of the two values.



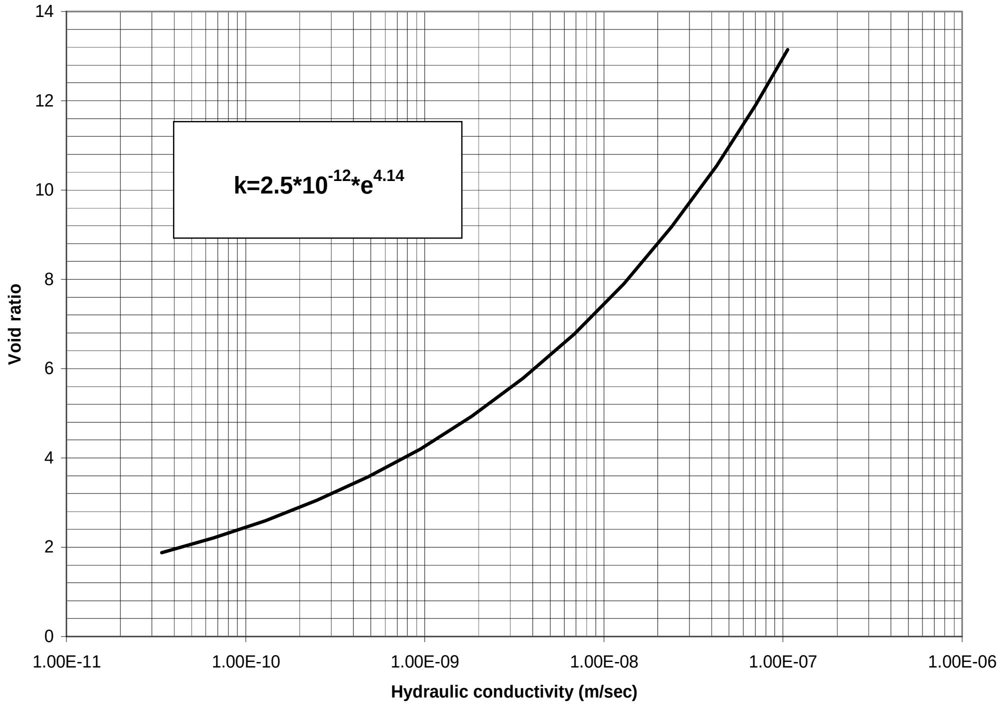


Figure 3 – Constitutive Relationships for Phosphatic Clay

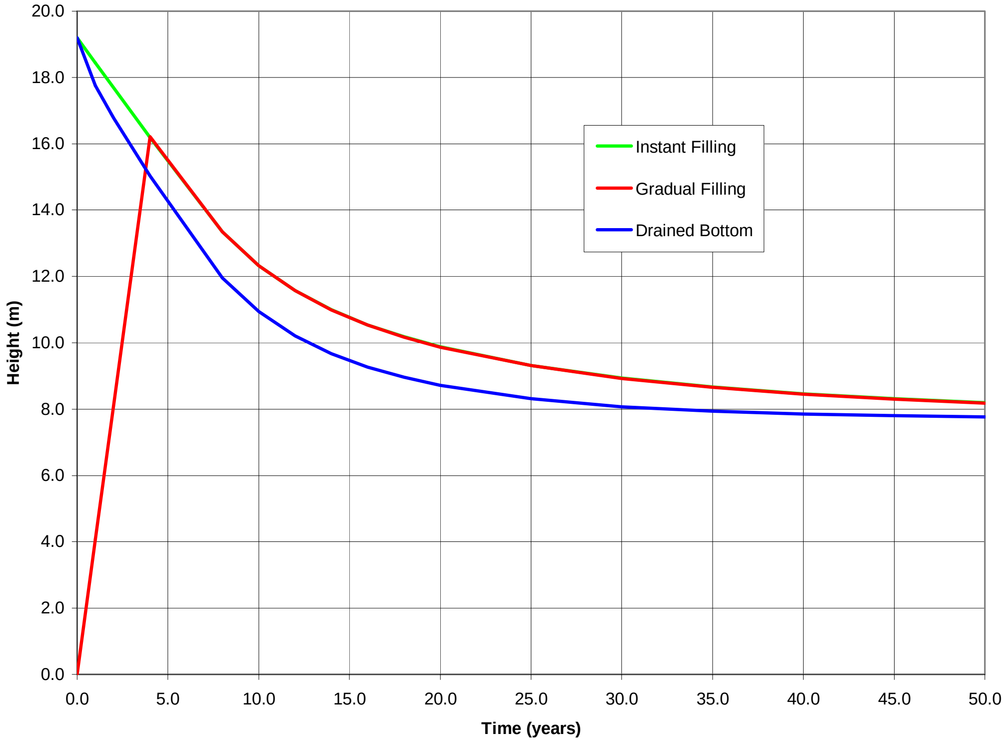


Figure 4 – Model Predictions for Three Filling Scenarios

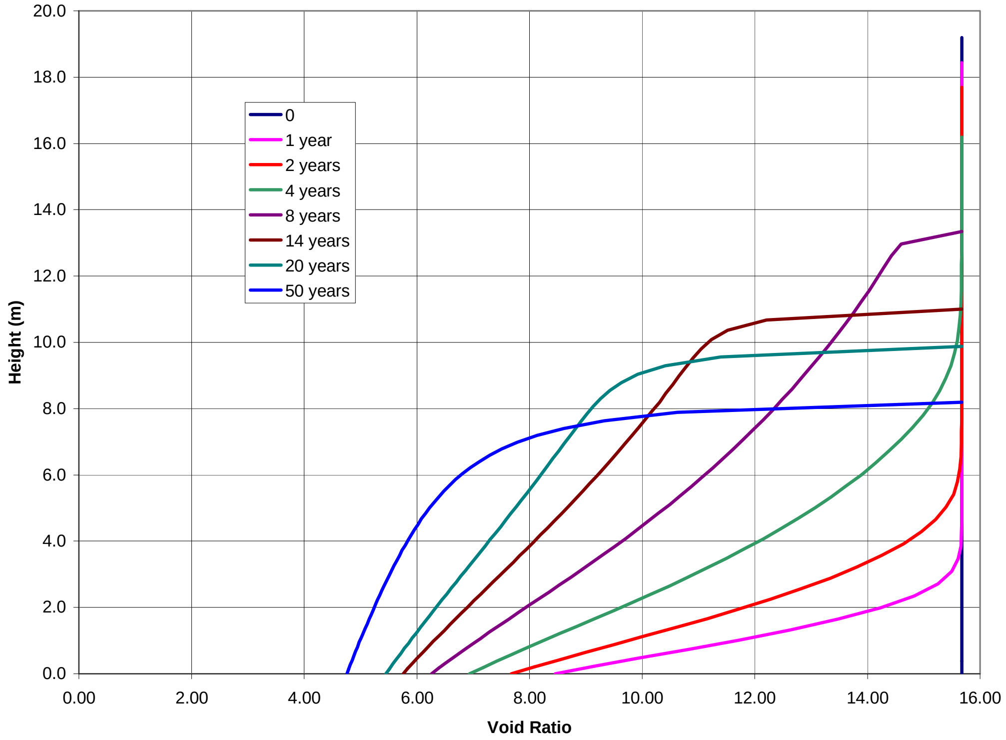


Figure 5 – Void Ratio Distributions for Instant Filling and an Impervious Bottom Boundary

4 . DESICCATION

At the beginning of the desiccation process we started the field monitoring of the clay behavior at a test plot. The monitoring program consisted of recording the climatic conditions at the site, observing the ground settlement and periodic sampling to obtain the void ratio distributions with depth. Fig. 6 shows the field site with the weather station. Half of the area was cleared of vegetation and half of the plot was left with the natural vegetation of cattails. The settlement records shown in Fig. 7 show that for the first nine months the settlement rate was lower at about 0.43 m/year and then it increased for three months to 1.2 m/year and then slowed again. Both of these settlement rates were substantially higher than the self weight consolidation rate at that time as shown in Fig. 8. The settlement rate during desiccation is equal to the effective evaporation rate from the soil surface as the material remains fully saturated as long as the air entry suction value is not exceeded. As a matter of fact for the phosphatic clay the air entry suction value is so high that the soil remains fully saturated until the shrinkage limit is reached. This is demonstrated by a lab experiment in which both the sample weight and volume are measured throughout the desiccation process. Fig. 9 shows the results of such a test. As long as the relationship between the water content and void ratio is on a straight line passing through the origin, the sample remains saturated. Thus, it is appropriate to use the recorded settlement rate as the evaporation rate at the soil surface as the top boundary condition for modeling the desiccation process.

Figure 6 – Field Site at a Phosphate Mine in Florida

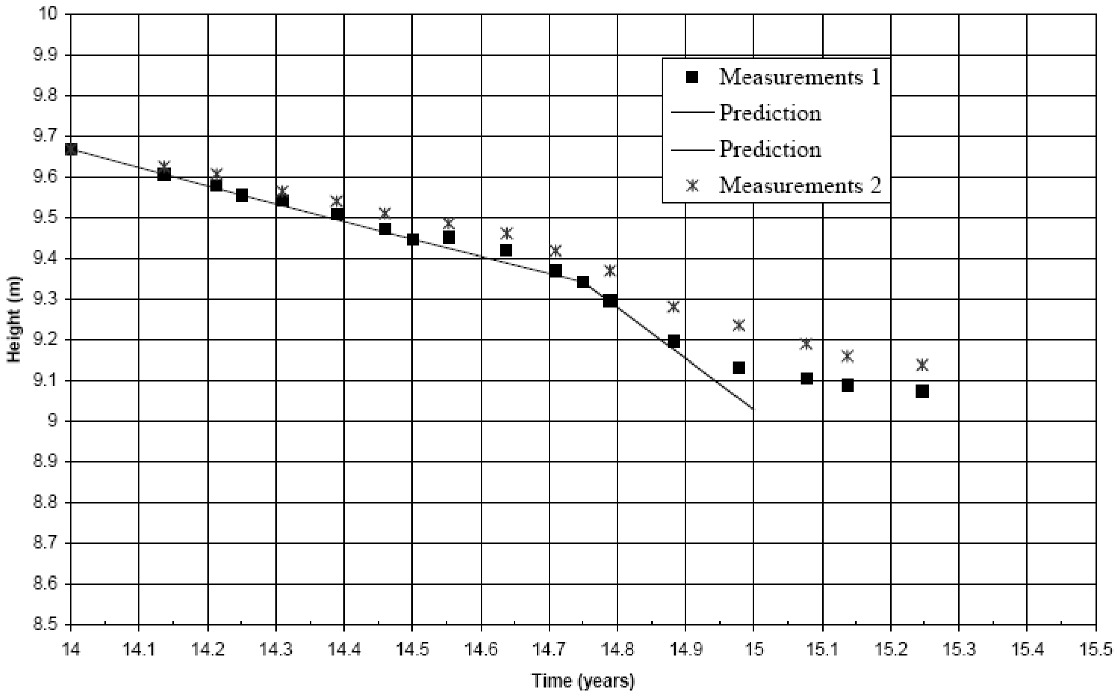


Figure 7 – Settlement Records During the Monitoring Period

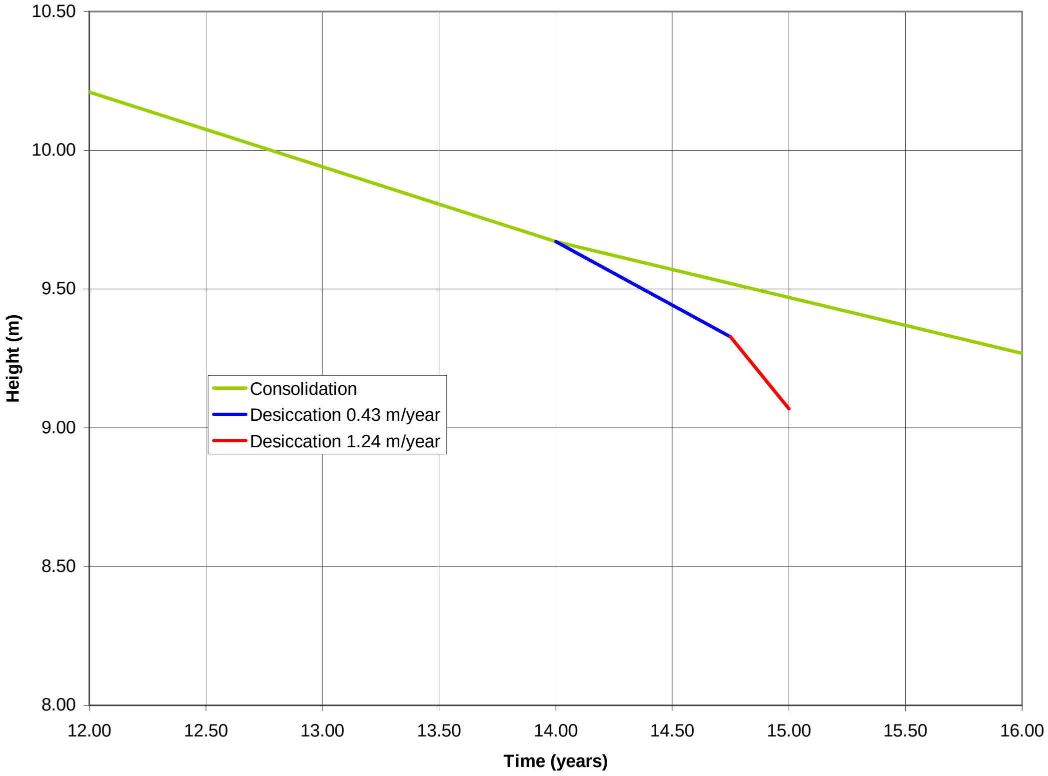


Figure 8 – Comparison of Consolidation and Desiccation Settlement Rates in the Monitoring Period

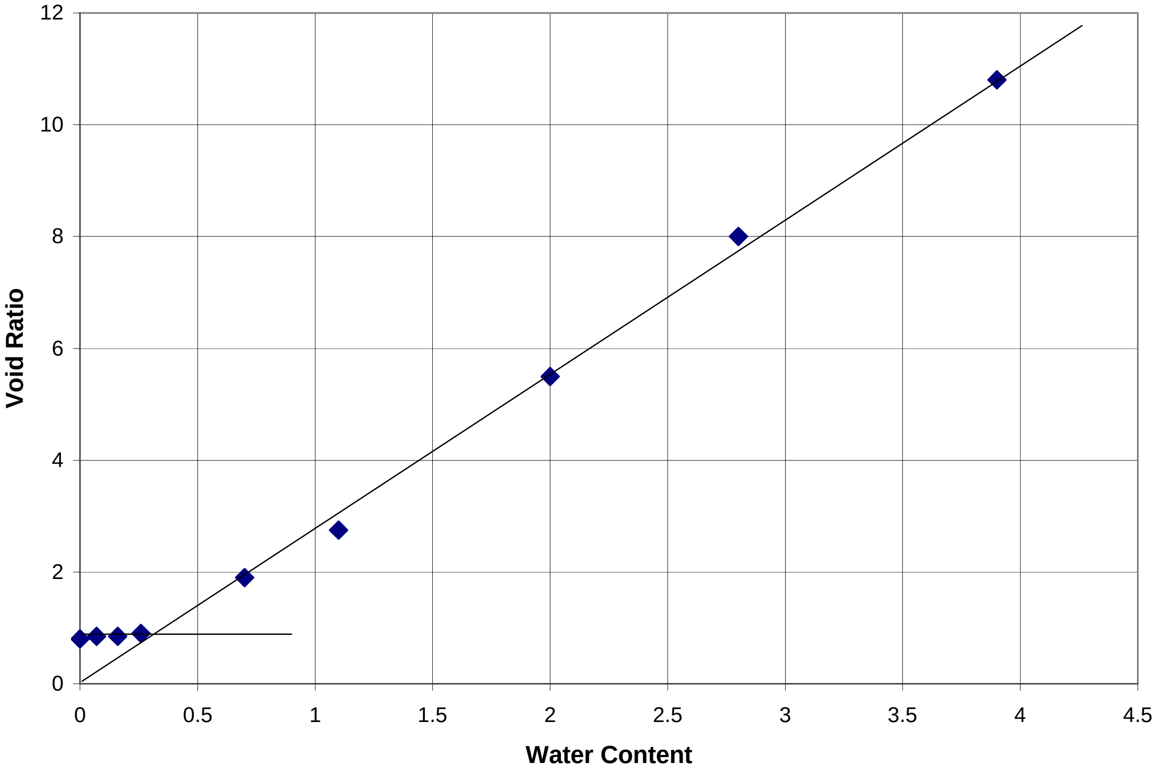


Figure 9 – Shrinkage Test on a Phosphatic Clay Sample

It is interesting to analyze what is happening to a soil element inside a slurry layer that undergoes consolidation and then desiccation. Fig.10 shows the effective and total stress paths for a soil element at an arbitrary depth. It is assumed, for the ease of the discussion, that the total vertical stress remains constant throughout the consolidation and desiccation processes, but this is not an essential condition for the analysis. At the beginning of the consolidation process, when the effective stresses acting on the slurry soil element are zero, the element is at the effective stress state 0 and the total stress state W. The initial positive pore-water pressure acting on the soil element, equal to the total vertical stress, is the distance on the graph between the total stress state W and the effective stress state 0. Due to consolidation and desiccation, this initial positive pore-water pressure decreases. Before the initiation of cracks, the lateral strain for any soil element remains zero, and so the effective stress path during consolidation and desiccation must follow K_o line where K_o is the coefficient of lateral earth pressure at rest. For a constant total vertical stress the total stress path at this phase has a slope of -3/2 in the coordinate system shown in Fig. 10. Along the total stress path WK and effective stress path OK, the pore-water pressure remains positive, and thus consolidation under one-dimensional compression takes place. Along the total stress path KM and the effective stress path KB, the pore-water pressure is negative while the soil undergoes one-dimensional shrinkage. Soils start cracking during one-dimensional shrinkage when total lateral tensile stress at the crack tip reaches the soil tensile strength. In a soil having no tensile strength, vertical desiccation cracks can open only when the total lateral stress vanishes, that is, only atmospheric pressure acts on the face of an open crack. Thus, the total stress state for this case is at N, which is on the $\sigma'_h = 0$ line (Fig. 10). However, the effective stress state is at Z, where the lateral effective stress is compressive and equal to the suction (negative pore-water pressure) at the moment the cracks open. If the soil possesses some tensile strength, a larger suction is needed to create cracks. In this case, the cracking criterion is reached at the total stress state M and the effective stress state B, as shown in Fig. 10. At that point, the soil element is at the cracking void ratio for the given total vertical stress. In other words the crack in a desiccating soil can develop only to the depth where the total shear strength of soil (a function of the void ratio) is high enough to sustain a vertical crack.

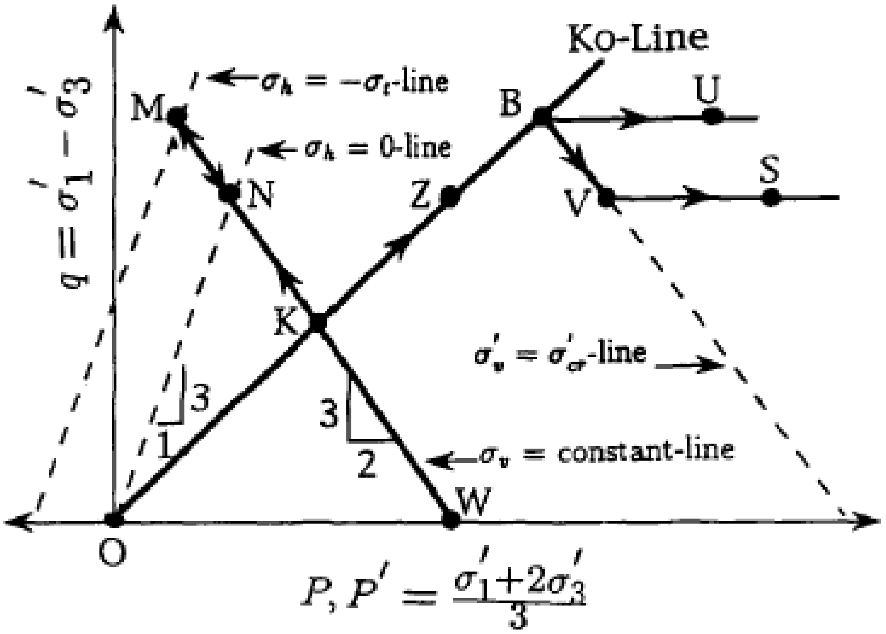


Figure 10 – Total and Effective Stress Paths for a Soil Element

Modeling the desiccation process requires that the compressibility and hydraulic conductivity constitutive relationships be know for the soil and a “cracking function” be defined in order to predict the desiccation cracking. Laboratory test results have suggested that the void ratio vertical effective stress relationship is the same irrespectively of what causes the increase in the effective stress, either the applied load or the developed suction. The hydraulic conductivity is a function of the void ratio and it is assumed to be the same during both the consolidation and desiccation processes. The cracking function is obtained from the analysis of a centrifuge model test in which a soil sample is allowed to desiccate under an increased gravity level to properly simulate the stress range encountered in the field. Oliveira-Filho (1998) demonstrated that the cracking function obtained from the centrifuge experiments in the form of void ratio – total vertical stress is consistent with the fracture mechanics principles.

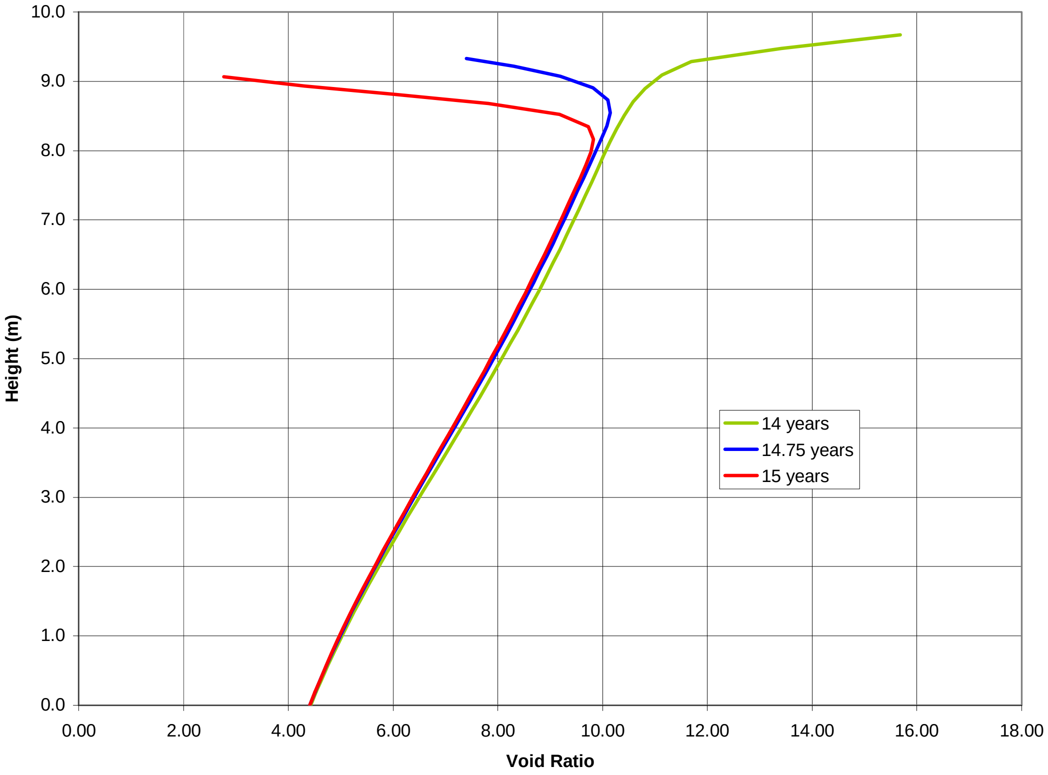


Figure 11 – Void Ratio Distribution During the Desiccation Process

The computer model CONDES is used to simulate the desiccation process monitored in the field. Fig. 11 shows the void ratio distributions at the beginning of the monitoring period (14 years after the initial soil deposition), at the point when the desiccation rate increases (14.75 years) and at the end of the high evaporation rate period (15 years). The formation of a thin desiccated crust is readily noted, as well as relatively small changes in the void ratio at larger depths. These void ratio changes are due to the self-weight consolidation that is progressing in parallel to the desiccation process as can be seen on Figs. 4, 5 and 8. The appearance of the desiccation cracks was also monitored in the field and their development (depth of penetration) with time was recorded. Fig. 12 shows a comparison between the observed crack depth in the field and the prediction of the numerical model with the parameters obtained in the laboratory and the geotechnical centrifuge tests. It is noted that the model correctly shows the absence of the cracks in the early part of the desiccation process when the evaporation rate was low and the shrinking of the top soil was gradual and more uniform. The sudden development of the cracks as the evaporation rate increased by a factor of three is also correctly simulated by the CONDES model. The simulation was stopped at the moment when the evaporation rate decreased as at that point the soil would experience suction reduction and the effective stress decrease which violates the fundamental assumption in the desiccation theory that the soil undergoes only the monotonic loading. It is also noted that at the same time the field observations indicated that the cracks stopped growing in depth.

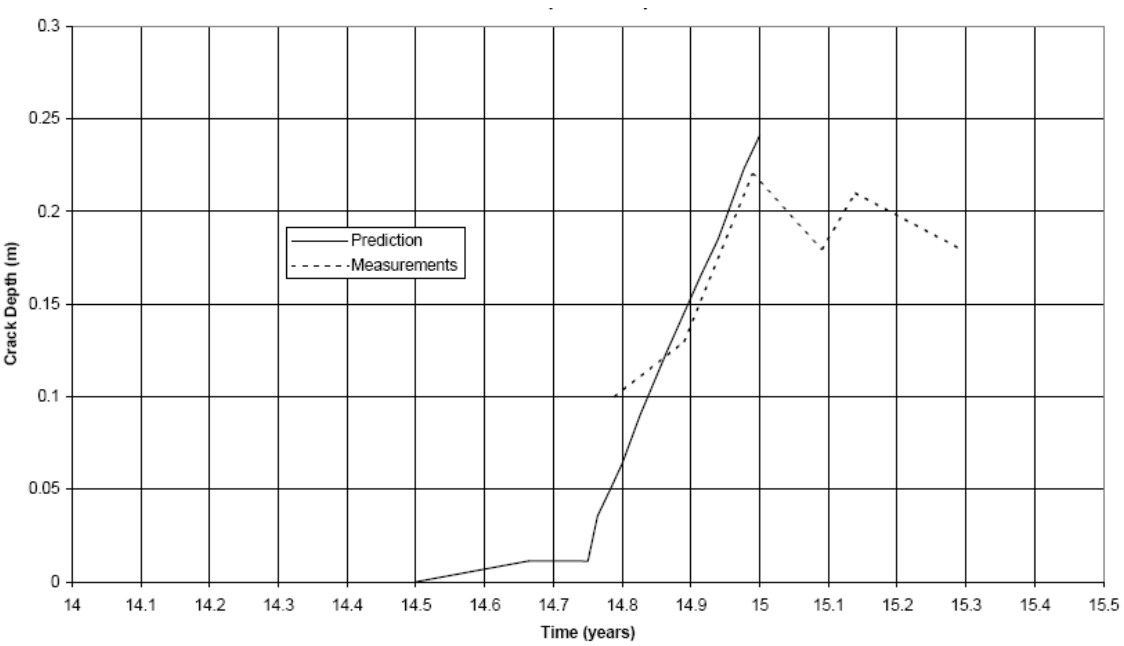


Figure 12 – Observed and Modeled Crack Development with Time

5. DISCUSSION

The presented analyses demonstrate that today we do have an adequate technology to rationally solve any problem of soft soil consolidation. The development of this technology has been facilitated by the development of our computational abilities as well as the testing techniques and field and laboratory instrumentation. However, above all an in depth understanding of the physics of the consolidation and desiccation processes was crucial as a guide in the theoretical development.

This example again highlights the essential principles, stated in the introduction, that any development in modern soil mechanics requires parallel advancement in theory, experimentation and numerical implementation. Any new theoretical development is completely useless unless at the same time the experimental (read: empirical) procedures do not provide an adequate method to obtain critical soil parameters. At the same time any empirical experimentation will fall short of describing the physical processes unless it is accompanied by a theory and analysis procedure that allow us to gain an insight into the physical process. The theory and experiments should function in a mutually supportive role. Thus, there must be no partition of geotechnical engineers into experimentalists, theoreticians or numerical analysts. In soil mechanics we deal with a material with an extremely complex behavior and we need to feel comfortable in using any tool that is needed to solve challenging problems. Only when we advance all aspects of a true solution we serve our profession. Anything else is only a futile exercise that attempts to reduce a real engineering problem into something, most often unrealistic, that we feel comfortable in solving.

In our discussion here we have described a problem limited to one-dimensional flow and deformation. The reader could question the importance of solving such a problem and ask if we are also doing something that we are comfortable doing. In order to answer these questions we need to use two quotes. The first one is from Baran and Sweezy (1966) who state that: “Scientific understanding proceeds by way of constructing and analyzing models of the segments or aspects of reality under study. The purpose of these models is not to give a mirror image of reality, not to include all its elements in their exact sizes and proportions, but rather to single out and make available for intensive investigation those elements which are decisive. We abstract from non-essentials, we blot out the unimportant to get an unobstructed view of the important, we magnify in order to improve the range and accuracy of our observation. A model is, and must be, unrealistic in the sense in which the word is most commonly used. Nevertheless, and in a sense, paradoxically, if it is a good model it provides the key to understanding reality." The second one is from Wood (1990) who expands on this idea and emphasizes: "Hierarchies of models of increasing complexity might be produced to illustrate the various roles that different models can play. The Cam clay model is a student's model, and its purpose is to describe and explain patterns of soil behavior, enabling the student to proceed further in understanding soil than is possible with the simple, traditional, ideally elastic and perfectly plastic models. Developments beyond the student's models provide engineer's models applicable perhaps to particular classes of problems and introducing such extra features as are thought necessary for each problem. In the distance are the scientist's or philosopher's models which match comprehensively and precisely all aspects of soil response. Perhaps such models will, like the philosopher's stone, always remain elusive."

In that sense the CONDES model blots out the unimportant to get an unobstructed view of the important and introduces only the features that are thought necessary for the problem under consideration. Most importantly the model brings the solution to a real geotechnical engineering problem. Though the problem is limited, consolidation and desiccation of soft soil is not trivial. Its complexity stems not from the complex geometry but from the highly nonlinear material properties where the hydraulic conductivity changes over several orders of magnitude during the consolidation and desiccation processes and varies by the same amount from top to the bottom of the layer. Unless this nonlinearity is correctly accounted for in the testing and analysis, the obtained results would be entirely unrealistic. Disposal of mining and dredging operations waste is often a process in which soft soil is pumped into a large containment facility and allowed to consolidate and eventually desiccate. As the disposed material thickness is much smaller than the horizontal extent due to its low viscosity, the vertical one dimensional flow and compression are the dominant processes in the impoundment. These are the essential aspects of the field behavior that should be properly captured in the model and the additional multidimensional complexity is unnecessary.

It is appropriate here to compare the developments described in this paper to some other efforts in soil mechanics over the last several decades. The comparison might give us some insight in how we should proceed in searching for solutions to geotechnical engineering problems. It is fair to say, that even after several decades of intensive research in the general area of constitutive modeling of soils, we still do not have a robust model that can be used in engineering practice by an average geotechnical engineer. Most models beyond Cam-Clay or Mohr-Coulomb are too complex for routine applications. Besides their complexity and the large number of parameters, they also lack proper testing procedures that could be used to obtain these parameters. We attribute this lack of progress to the desire of many model developers to create a comprehensive model that will "properly" describe the soil behavior for any application. Unfortunately it appears that such efforts are impractical as the soil behavior is too complex and too much stress path dependent for a single model to have multiple applications and produce realistic results. Perhaps, the time has come for us to focus our attention to the development of problem specific models which "blot out the unimportant to get an unobstructed view of the important and introduce only the features that are thought necessary for the problem under consideration.”

Looking back at the development of the nonlinear finite strain consolidation technology described in this paper we attribute its successful implementation into the engineering practice to the fact that in this case we were able to test the material under the identical stress path (i.e. one dimensional or K_o compression) that will be experienced in the field by the soil in the consolidating layer. Thus, the constitutive parameters are obtained under simulated field conditions and no extrapolation to other stress paths was necessary. Is it possible that the time has come when we need to create specialized models that will be appropriate for a particular set of problems? What would be wrong with a specialized finite element computer program that would be applicable only to slope stability problems and that would incorporate constitutive models that have been calibrated over a narrow stress path that duplicates stress conditions in a slope? Different programs could equally well apply to the problems of shallow or deep foundations or of retaining structures. We are convinced that this is the direction that we need to take at the end of the first centennial of soil mechanics, looking into the future.

6. CONCLUSIONS

We hope that our discussion has laid a solid foundation so that the following conclusions can be drawn:

The essence of soil mechanics is in the interaction between soil and pore water and the solution to the engineering problems should always start with an in depth understanding of the physics of this interaction. While the nature of this interaction is at the soil particle level, it is its macroscopic manifestation that is of main concern to the engineer.

Optimal solutions to soil mechanics problem require both rational and empirical approaches that always include experimental work, theoretical and mathematical development and numerical implementation. A geotechnical engineer must be at ease in using all of these tools in mutually supportive roles. There must be no partitioning of geotechnical engineers into experimentalists, theoreticians or numerical modelers. A development in only one or two of these areas is no advancement at all. No matter how sophisticated a numerical model is, it is completely useless without proper experimental support. Likewise, any experimental procedure that is not supported by a rational analysis can produce only questionable data.

Geotechnical models must include only necessary features and disregard the unimportant so that they can remain simple and manageable in the engineering sense. It is an illusion that we could develop an ideal model that will solve all our problems once and for all. Even if we could reach this quixotic goal the amount of site investigation that would be required to feed the necessary parameters would be prohibitive and never justified from an engineering perspective. The soil behavior is just too complex for the soil to submit to our theoretical rules and niceties.

The modern computational and experimental tools provide us with ample of opportunities to effectively attack the most complex soil mechanics problems. It is up to us to use these tools effectively and not to have a narcissistic attitude towards our expertise in using any one of these tools. We hope that this will be our path in the near future.

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