Arid soil problems

Problèmes des sols arides

W.N. Houston, S.L. Houston & K.D.Walsh – *USA*

1 INTRODUCTION

Arid and semi-arid regions, comprising more than one-third of the world's land surface, are experiencing a rapid rate of development. Because this development is still in progress, it behooves us, as a geotechnical engineering profession, to enhance our understanding of the special characteristics of arid soils and to use our best engineering judgment and techniques in dealing with them.

Arid soils exhibit a set of common characteristics which set them apart from humid-region soils. The most important characteristic of arid soils is the naturally dry condition and associated deep desiccation (Fookes and Parry, 1994). The low natural water content corresponds to high soil water suction, which in turn contributes to high shear strength and stiffness. Cementation, which is typical, though variable, further contributes to high shear strength and stiffness.

The climatic conditions of arid regions and their typical materials give rise to the problem soils. The two most common problem soils are collapsing soils and swelling clays, followed by variably cemented soils and salts. Collapsible soils have been encountered in most parts of the world. The conditions in arid environments, however, tend to favor the formation of collapsible soils. The two mechanisms which account for almost all naturally-occurring collapsible soil deposits are debris flows and deposition of wind-blown material (loess). These deposits are at low density, but are relatively stiff and strong in their natural state. Cementation consists of dried clay binding together the granular particles and other chemical precipitates which may have been added after deposition. Wetting under load weakens the cementation, reduces the soil suction, and causes collapse.

Compacted soils can also be collapsible under certain conditions. Compaction to moderate to low density dry of optimum produces the greatest susceptibility to densification upon wetting, but almost any compacted soil can exhibit collapse if the confining pressure is sufficiently high. Clayey soils with significant plasticity may respond to wetting by swelling, if the confining pressure is low enough.

Swelling clays in arid and semi-arid regions arise from a variety of sources, including residual soils, alluvial deposits, and layers of weathered volcanic ash. These soils are particularly hazardous to infrastructure because they are initially very dry and possess a potential for large volume change when wetted, because montmorillinite is very common.

There is a prevalence of cementation in arid soils that can be largely attributed to the climatic conditions. In arid regions, annual evaporation exceeds annual rainfall and salts are precipitated near surface. The degree of cementation often varies dramatically over a scale of 1 or 2 m, both vertically and horizontally (Houston and El-Ehwany, 1991). This variability causes difficulty in sampling and testing, the need for more than the average number of samples and tests and, often, more than average differential movements of prototype structures. Although most cementing agents in arid soils can be thought of as salts, in engineering practice special attention is required for those salts, such as sulfates and chlorides, which are known to corrode concrete and steel structural components.

2 ASSESSMENT OF WETTING

The most challenging task of arid soil engineering is that of predicting the future extent and degree of wetting of the moisture-sensitive soils. The size, dimensions, and depth of the zone within which wetting occurs is a quantitative measure of the extent of wetting. "Degree of wetting" refers to a particular point within the profile and is best described in terms of the initial and final degree of saturation at the point.

Under normal circumstances naturally-occurring arid soils are not wetted to significant depth by precipitation. Rainfall either runs off or infiltrates a short distance and then evaporates to the surface. Most of the moisture-sensitive soils in arid climates (ML, SM, CL and CH's by the unified classification system) do not typically transmit water to the water table below (Rockhold et al., 1995). The net flux is negative, meaning that all precipitation is returned by evaporation or evapotranspiration. Some groundwater is brought up and evaporated as well, leaving salts behind. Even after some development results in added irrigation and reduced evaporation, many moisture-sensitive soils still return to net negative flux after an overall increase in equilibrium water content.

Problems with moisture-sensitive soils are almost always associated with man-induced changes in the surface water and groundwater regimes. Numerous potential sources of water that could cause soil wetting include (a) broken waterlines and landscape irrigation, (b) roof runoff and poor surface water drainage, (c) intentional and unintentional recharge, (d) rising groundwater table, (d) damming due to cut/fill construction, (e) moisture migration due to capillarity and protection from the sun.

A natural soil profile influenced only by precipitation, evaporation, and evapotranspiration, is shown in Figure 1. This profile is similar to the Steady State Suction Profiles presented by Lytton (1992). For most engineering applications aimed at quantifying the effects of wetting moisture-sensitive soils, the maximum degree of saturation, corresponding to the upper bound curve in Figure 1, is of particular interest. In the case of swelling clays, however, shrinkage to the minimum water content could occur. Thus, the lower bound curve is also of interest for this case. When water is added or evaporation is impeded by one of the mechanisms listed above, for example, the equilibrium and upper and lower bound curves shift to the right to a depth corresponding to the extent of wetting. Estimating the initial positions of the curves and the magnitude of this shift is the difficult job of the geotechnical engineer. Obtaining accurate simulations of unsaturated flow because of the complexity of the surface flux boundary conditions is one of the often-cited difficulties.

Rather than estimate the extent and degree of wetting, many practitioners choose to make conservative assumptions for most of their projects. For example, when the moisture-sensitive soil layers are near surface and not thick, it is common practice to assume that the entire layer of moisture-sensitive soil will become wetted. Likewise, it is common practice to assume that the wetted soil will be thoroughly wetted to a degree of saturation of 100%. Field studies have shown that the degree of saturation behind the wetting front for downward infiltration is significantly below 100% and sometimes as low as 50 to 70% (Houston and

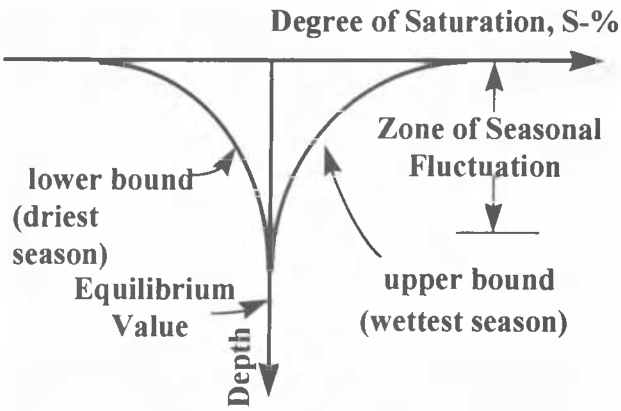

Figure 1. Schematic of Degree of Saturation Variation with Depth

Houston, 1995). The additional project construction costs of employing these conservative assumptions must be compared to the cost savings derived from simplifying the testing and analyses. The relatively recent emergence of the unsaturated soil mechanics theory and associated constitutive models makes the use of the knowledge of degree and extent of wetting more practical (Fredlund and Rahardjo, 1993).

3 PROCEDURES FOR DEALING WITH PROBLEM SOILS

3.1 *Collapsing Soils*

The general techniques for dealing with problem soils in arid regions have many tasks in common, regardless of the soil type. The techniques for collapsing soils will be addressed first, followed by brief discussions of swelling clays, cemented soils, and soils with corrosive salts.

Identification of Collapsible Soil Deposits and Site Characterization. Geomorphological considerations form an important part of the identification of collapsible soils. Although geological reconnaissance and experience with similar depositional environments are valuable tools in establishing regional expectations, site-specific testing is recommended for characterizing a construction site. Testing can be done in the laboratory on undisturbed samples or in the field, in-situ. Because the unit cost of laboratory or field response to wetting tests are only slightly more than that of most index tests which have been correlated to collapse potential, the authors have a strong preference for the direct measurement of collapse potential, rather than for the use of correlations.

Assessment of the Probable Extent and Degree of Wetting. As discussed previously, this is the most challenging task in dealing with collapsible soils. Field ponding tests can be quite useful in developing estimates of downward infiltration from surface or near-surface sources. The probable extent of wetting is dependent on the precautions taken to prevent wetting. If anticipated wetting is downward, infiltration precautions include (a) restricted irrigation watering, (b) restricted landscape vegetation, (c) paved surfaces around the structure, (d) use of tight water and sewer lines in double pipes, and (e) replacement or removal and compaction of near-surface layers to form a low permeability, moisture-insensitive barrier. When wetting from a rising groundwater table is anticipated, precautions include (a) avoidance of the creation of dams when filling valleys and canyons, (b) provision of horizontal and vertical drains, and (c) monitoring of the groundwater table levels and use of pumping.

For near-surface water sources the probability of wetting to great depth during the life of the structure is obviously less than the probability of wetting to a shallow depth. Also, the probability of wetting to any depth is dependent on the degree of precautions employed. These relationships are depicted schematically in Figure 2.

Interpretation of Lab or Field Test Results and Estimation of Volume Change and Differential Movements. Figure 3 is a schematic representation of a typical response to wetting test results for a collapsible soil. The following test result is from a lab test on an undisturbed sample of naturally occurring collapsible soil. After seating at point A the specimen is loaded at its natural water content to point D, obtaining the "dry-loading" curve AD. At point D, corresponding to the overburden pressure (and any expected structural load), the specimen is submerged, and collapse to point F occurs. While still submerged, the stress is increased to point G, obtaining the wetted curve FG.

Moderate to large-scale model footing tests in the field on cemented collapsible soils have shown that the settlement upon dry loading is almost too small to measure (El-Ehwany and Houston, 1990). Thus, one would expect that the dry loading curve for a "perfect" truly undisturbed specimen would be a flat curve like AB in Figure 3. Dry loading curves, AC, AD, and AE represent successively increasing degrees of disturbance (Houston and El-Ehwany, 1991). However, experience has shown that the position of the wetted curve is relatively insensitive to the degree of disturbance. Therefore, the more the disturbance, the less the strain upon wetting; that is, EF is less than CF. In the field we would expect that the strain upon wetting would be from curve AB to the wetted curve. A technique for estimating the position of AB is proposed by Houston (1995), but this refinement is rarely justified. A very reasonable approximation for engineering practice is to assume that collapse strain in the field is from the origin to the wetted curve.

The position of the wetted curve can be determined by testing a single specimen or multiple specimens, each of which yield one point on the wetted curve. A single specimen can be loaded dry to D, then wetted to F, and then further loaded to G. Alternatively, to trace out a larger segment of the wetted curve, the specimen can be loaded dry to D', then wetted to H', then further loaded to F and G. The disadvantage of tracing out a large segment of the wetted curve is that its position is somewhat path dependent; that is, point F achieved by AD'H'F is somewhat different than point F achieved by ADF. However, this path dependence is believed to be less than normal site heterogeneity (Houston, 1995). The band obtained from several test results at a site can be handled in practice by choosing a design curve that is slightly conservative but within the band. The authors recommend a design curve about halfway between the average curve and the lower limit of the band.

If the undisturbed test samples come from an existing fill, the recommended procedure is exactly the same. However, a specimen compacted in the laboratory to represent the soil for a particular point within a fill has no stress history other than that induced by the compaction itself. The corresponding element of soil in the actual fill may experience compression as the overlying layers are placed. This compression can be represented by the

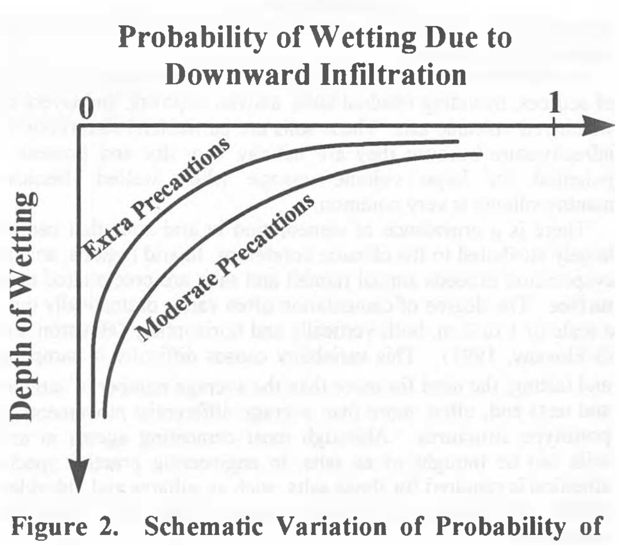

Figure 2. Schematic Variation of Probability of Wetting vs. Depth of Wetting

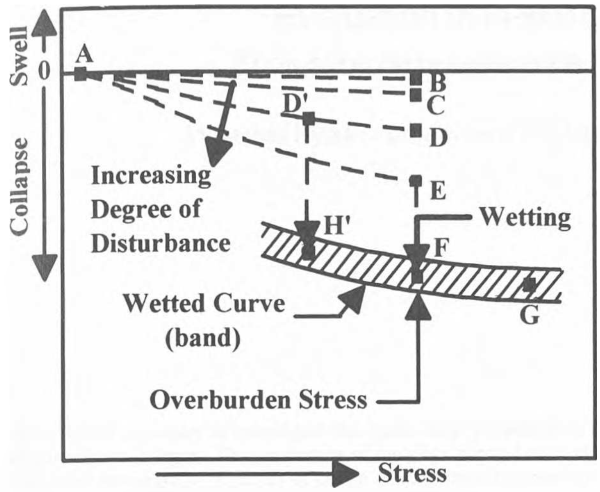

Figure 3. Schematic of Response to Wetting for a Collapsible Soil

curve AD in Figure 3. If wetting occurs after the infrastructure is in place, the wetting strain from D to F in Figure 3 could distress the infrastructure. These test interpretations are further discussed by Houston (1995).

When the collapse test data are derived from in-situ testing as recommended by the authors (Mahmoud, et al, 1995), the end product is a band of wetted curves, similar to Figure 3, from which a design curve can be constructed. The in-situ collapse test is particularly useful for difficult-to-sample materials such as gravels and nearly cohesionless sands.

Once the design curve is established, the estimate of settlement proceeds as follows. Several representative points under the structure or a footing are first selected as computation points. At each of these points the stress due to overburden plus structural loads is estimated and used to enter the design curve to get the potential collapse strain. The strain obtained, when the design curve was derived from laboratory tests on submerged samples, will correspond to full collapse induced by wetting to near saturation. However, both lab and field test results have shown that partial wetting results in partial collapse (Houston, et al, 1993). Thus, it is necessary, to obtain an unbiased estimate of the collapse strain at each point, to use the results of the "Assessment of Wetting" task described earlier. The maximum probable degree of saturation at each computation point is then used to adjust the potential collapse strain obtained above (Houston, et al, 1993). Many practitioners choose to make the conservative assumption that the soil will be thoroughly wetted to near saturation rather than make a correction for partial wetting. It should be noted here that if the in-situ testing procedure is used, a correction for partial wetting is not necessary. It has been found that the degree of wetting obtained by the in-situ test procedure is comparable to the degree of wetting achieved by the downward infiltration of water from ponds in the field.

After the collapse strains have been reduced for partial wetting, or conservatively taken at full value, they are assigned to each computation point. To obtain the estimated settlement at a point, a vertical strain profile is constructed from the foundation level or ground surface down to the depth of the extent of wetting. The area under the strain diagram is the estimated settlement for the profile.

Development of Mitigation and Foundation Design Alternatives. When the estimated differential or total settlement is excessive, some type of mitigation or alternative must be found. Infrastructure alternatives could range from deeper or stiffer foundations to more aggressive precautions against water infiltration. Possible mitigation measures for the subsoil could include removal and recompaction, in-place compaction, and grouting. Case histories illustrating these techniques are presented by numerous investigators, and many of these reports have been collected by Houston and Houston (1989).

3.2 Swelling Clays

The identification and site characterization tasks for swelling clays are very similar to those for collapsible soils. Geological reconnaissance and knowledge of the history of swelling clay problems in the given region are both very valuable. Correlations between index test results and volume change potential are probably more abundant for swelling clays, but for site characterization the authors still prefer the direct measurement and presentation shown in Figure 3.

The assessment of the probable extent and degree of wetting for swelling clays involves the same considerations and objectives as for collapsing soils, but ponding tests, for example, are not used because of the very low permeability of swelling clays. Heavy reliance must be placed on past experience with accumulation of water under covered areas. Testing and test result interpretation are similar to that depicted in figure 3, except that the ordinate will reflect swell. The computation of heave and differential heave is analogous to the settlement computations described for collapsing soils. Most of the mitigation techniques are similar. The most common technique is removal of the moisture-sensitive soil, as is the case for collapsing soils. The second most common technique is the deepening of foundations to apply the structural loads below the zone where volume changes are likely to occur. Additional details can be found in an excellent treatment of the many challenging aspects of swelling soil engineering by Jimenez-Salas (1995).

3.3 Cemented Soils

Cemented soils are typical of arid and semi-arid regions and encompass more than just collapsible and swelling soils. Obviously, if a soil were both collapsible and cemented, which is common, the procedures recommended for collapsible soils would apply; likewise for swelling clay. If an arid soil were cemented, but neither collapsible nor swelling, it would still very likely be subject to weakening upon wetting. This loss in strength would arise both from a loss in soil suction and a softening of cementing agents. Thus, this soil would be described as moisture-sensitive, and good engineering practice would require that its important properties be evaluated in the wettest state it is likely to achieve. The two most often-cited problems in dealing with cemented soils are difficulty in excavation and variability (heterogeneity). The best approach to handling these problems is to anticipate them via a thorough site investigation involving a combination of sampling, testing, and seismic wave velocity measurements.

3.4 Soil With Corrosive Salts

Sulfates and chlorides are the most common corrosive salts found in arid soils. Chemical weathering (corrosion) includes reactions involving various salts and the calcium aluminum hydrates in cement and the corrosion of reinforcing rods in the presence of chlorides. Physical weathering processes include breakdown by salt crystal growth, hydration of salt crystals, or thermal expansion of salt crystals. Dissolution of soluble salts from arid lands soils can also be problematic. Testing for excessive sulfates and chlorides is a routine part of site investigation in most arid regions. As with collapsible soils and expansive clays, the most commonly employed remediation for excess salt is removal and replacement of the soil.

4 SUMMARY

Arid and semi-arid regions are widespread throughout the world and experiencing a rapid rate of development. The climatic conditions of arid regions and their typical materials give rise to the problem soils: Collapsing soils, swelling clays, cemented soils, and soils with corrosive salts. Deep desiccation and extremely dry initial conditions amplify the moisture-sensitivity of these soils, which often possess large potentials for volume change when the inevitable wetting associated with development occurs. The most challenging task of arid soil engineering is that of obtaining realistic estimates of the extent and degree of wetting. Given a reliable assessment of wetting, techniques are available for satisfactorily estimating volume changes and foundation movements. When mitigation is indicated, numerous techniques are available, although the full repertoire is not being fully utilized in engineering practice. The most pressing needs for future research in arid soil engineering are development of better techniques for the minimization of water content changes and assessment of wetting.

5 REFERENCES

El-Ehwany, M. and Houston, S. (1990). Settlement and Moisture Movement in Collapsible Soils, J. Geot. Engr. Div., ASCE, Vol. 116, No. 10, 1521 - 1535.

Fredlund, D., and Rahardjo, H. (1993). Soil Mechanics for Unsaturated Soils, Son Wiley & Sons, Inc., New York.

Fookes, P. and R. Parry, eds. (1994). Engineering Characteristics of Arid Soils, Proc. 1st Int'l Symp. on Engr. Characteristics of Arid Soils, London, July, 1993, Balkema.

Houston, S. (1995) State of the Art Report on Foundations on Unsaturated Soils (Part I: Collapsible Soils), Unsaturated Soils, Alonso & Delage, eds., Balkema, , Vol 3.

Houston, W. and Houston, S. (1989). State of the Practice Mitigation Measures for Collapsible Soils, Proc. Found. Engr. Cong., ASCE, Evanston, June, 161 - 175.

Houston, S., and El-Ehwany, M. (1991). Sample Disturbance of Cemented Collapsible Soils," Journ. of the Geot. Division, ASCE, Vol. 177, No. 5, 731-752.

Houston, W. and Houston, S. (1995). "Infiltration Studies for Unsaturated Soils," Unsaturated Soils, Proc. of the 1st International Conf. on Unsaturated Soils, Paris, Sept. 6-8, Vol. 1, 869-875.

Jimenez-Salas, J. A. (1995). State of the art report. second part: expansive clays. Unsaturated Soils, Proc. of the First Int'l Conf. on Unsaturated Soils, Sept. 6-8, Paris, E. E. Also and P. Delage, eds., Vol. 3.

Lytton, R. L. (1992). "Use of Mechanics in Expansive Soils Engineering," Keynote address in Proc. of the 7th International Conf. on Expansive Soils, Dallas, TX., Vol. 2, 13-23.

Mahmoud, H., Houston, W., and Houston, S. (1995). "Apparatus and Procedure for an In-Situ Collapse Test, " Geot. Testing J., GTJODJ, V. 18, No. 4, 431 - 440.

Rockhold, M. L., Fayer, M. J., Kincaid, C. T., and Gee, G. W. (1995). "Estimation of Natural Groundwater Recharge for the Performance Assessment of a Low-Level Waste Disposal Facility at the Hanford Site." Report on U.S. Dept. of Energy Contract DE-AC06-76RLO 1830, PNL-10508, UC-702, March, Battelle Pacific Northwest Laboratory, Richland, WA.

Walsh, K., Houston, W., and Houston, S. (1993). Evaluation of in-place wetting using soil suction measurements. J. Geot. Engr., ASCE, Vol. 199, No. 5, 862-873.