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SYNOPSIS Previously reported settlements of structures founded on loess soils in the United States have been limited to cases of rapid deformation: the result of wetting and structural collapse. While the possibility of subsidence is usually a consideration in design, when the potential for wetting does not exist, economics generally govern the use of a shallow foundation system; in which case an accurate prediction of settlement is required. Since most loess deposits occur as unsaturated sediments, the use of one-dimensional consolidation theory is not applicable to the problem of settlement prediction.

In 1977, a circular mat foundation was constructed on typical subsident loess to support a water tank for a small town in eastern Iowa. Between 1977 and 1983, settlement observations were made to monitor the magnitude of deformation. Laboratory one-dimensional compression tests and triaxial stress path tests were conducted to provide a means to predict settlements. Unlike many structures which are monitored for settlement, a water tank allows an accurate measure of load, thus eliminating an important unknown.

This paper compares the results of settlement measurements with a number of techniques to predict settlement. The results indicate a time-dependent behavior of deformation which must be considered creep in light of the current understanding of loess behavior.

INTRODUCTION

Accurate prediction of the deformation behavior of shallow foundation systems supported on unsaturated soil presents somewhat of a dilemma for foundation engineers who more often think of settlement as resulting from consolidation; i.e., decrease in moisture content with applied stress. Previously reported settlements of structures founded on loess soils in the U.S., e.g. Clevenger (1958), Peck and Ireland (1958), and Holtz and Hilf (1961), have been limited to cases of rapid deformation as a result of the subsident behavior of this material. The metastable characteristic of loess soils is usually indicated by oedometer testing, where a rapid decrease in void ratio occurs when a sample is artificially wetted while maintaining a constant load (Holtz and Gibbs, 1951; Kezdi, 1974). This behavior generally has left geotechnical engineers with the impression that similar deformation is likely to occur in the field so that the use of shallow foundations are for the most part considered inappropriate.

While the possibility of subsidence is usually a consideration in design, when the potential for wetting does not exist economics generally favor the use of a shallow foundation system, in which case an accurate prediction of settlement is required. This paper presents results of several techniques for estimating settlement and compares the results with field performance of a simple mat foundation on unsaturated loess.

PROJECT AND SITE CHARACTERISTICS

One of the largest variables influencing the comparison between prediction and observation in geotechnical engineering is the accurate estimation of applied field loads. For this reason, the structure chosen for study was a circular water standpipe located in east-central Iowa. A shallow foundation of reinforced concrete was used and consisted of a circular mat 8.4 m (27.5 ft) in diameter located 1.4 m (4.5 ft) below existing gound surface, thus necessitating a shallow excavation. The 18.3 m (60 ft) tall standpipe was made of steel plate and therefore the net dead load of the structure (dead load minus foundation excavation) is relatively small, 34.5 N (7.75 tons); the majority of additional load being exerted by the live load weight of water, 2060.6 N (463.1 tons). The geometry of the foundation is such that the system was analyzed as a rigid mat, thus the settlement was assumed to be uniform, in lieu of nonuniform contact stresses.

A schematic of the structure and subsurface soil conditions is shown in Figure 1. The soil profile at the site consists of 5.9 m (19.5 ft) of Peorian-age loess overlying a relatively thin, 0.9 m (3 ft), glacial till-derived buried clay soil, underlain by dense glacial till. Figure 2 shows this stratigraphy and basic geotechnical properties of site materials. Although slight variations in texture do occur with depth in the loess the composition is considered uniform as would generally be expected in this area. The contact between the loess and underlying materials is readily apparent. It is important to note that at the time of sampling, field moisture content was at or below the plastic limit in all cases, and that no static water table was encountered. The lack of free water is not surprising considering that the site is located on a narrow upland drainage divide providing excellent surface and subsurface drainage conditions. Oxidized soil colors present within the loess indicate that limited moisture occurs at the site.

The low density of the loess and corresponding low liquid limit values indicate that this material is considered prone to subsidence upon wetting (Gibbs and Bara, 1962). Calculated values of saturation moisture content, shown in Figure 2, are nearly all above the liquid limit; the criteria for collapsibility given by Handy (1973) for Iowa loess. This site falls into the 59-95% probability of collapse determined by Handy.

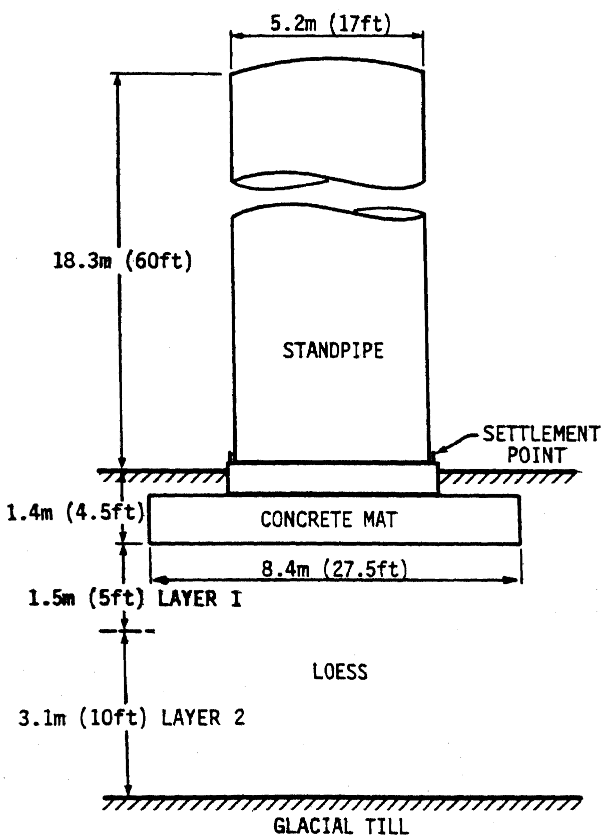

Figure 1. Foundation schematic of Oxford standpipe.

SETTLEMENT PREDICTIONS

Settlement predictions were made by several methods, however the assumptions used in each method were the same:

(1) All deformations were assumed to take place within the loess, i.e., the glacial till was assumed incompressible,

(2) The average contact stress was used in settlement calculations,

(3) $K_o = 1 - \sin\phi$, ϕ measured by Borehole Shear Test,

(4) Poisson's Ratio = 0.3.

Settlement Predictions Using Oedometer Tests

Undisturbed samples for oedometer testing were obtained at depths of 3.7 m (12') and 4.9 m (16') below ground surface. Kane (1973) has demonstrated that the shape of the e-log P curve for loess in eastern Iowa is highly dependent on initial moisture content. This is consistent with similar findings of Milovic (1969) for some European loess. Therefore, tests were conducted at natural moisture content in a fixed-ring consolidometer, using standard test procedures; i.e., 1 day load duration and load increment ratio = 1. Results of these two tests are shown in Figure 3. Each consolidation test was assumed to represent the behavior of arbitrarily selected layers shown in Figure 1.

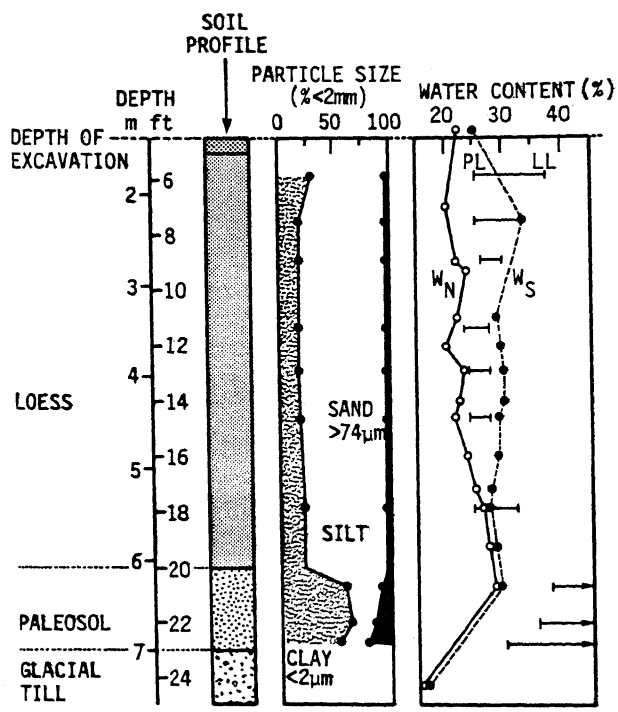

Figure 2. Subsurface material characteristics.

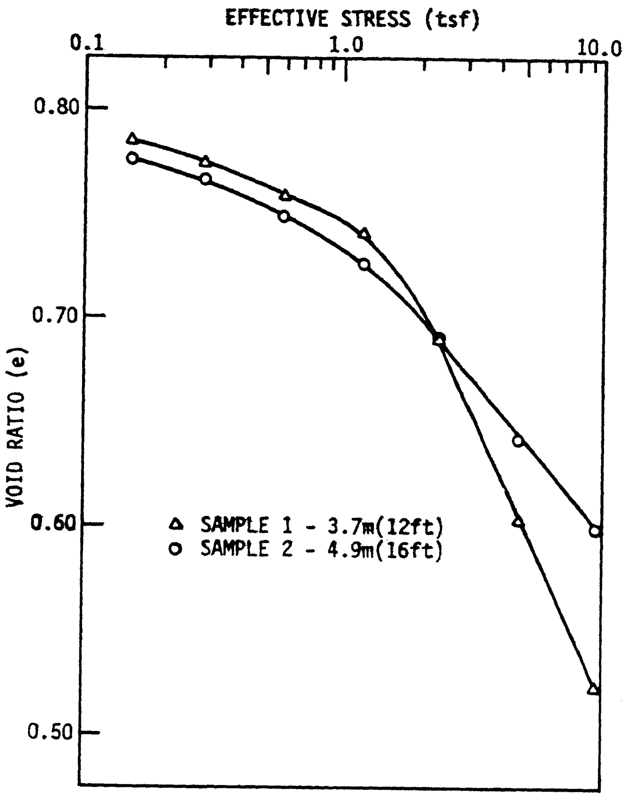

Figure 3. Oedometer results on loess at natural moisture content.

One-dimensional Consolidation

Settlement calculations based on conventional Terzaghi one-dimensional consolidation theory were not considered to be relevant in this case in view of the materials and site conditions. However, oedometer tests were performed for two reasons: (1) this test is still the most common test used by getoechnical consulting firms for calculating settlements and therefore the results are pertinent to practicing engineers; (2) even though it was considered unlikely that settlements would take place by consolidation, one-dimensional loading may be useful for applying either tangent or secant modulus for settlement analysis.

The total settlement from conventional consolidation theory can be calculated from the standard equation as:

$$\delta = \Sigma \frac{C_c}{1 + e_o} \log \frac{\sigma_o' + \Delta\sigma}{\sigma_o'} \qquad (1)$$

where $C_c/1+e_o$ is taken from consolidation test results between initial and final loading, σ_o' is the initial effective vertical stress and $\Delta\sigma$ is the additional vertical stress.

Tangent Modulus

Based on work by Janbu (1963, 1964, 1969) the vertical stress-strain results from oedometer testing can be used to define a value of soil compressibility, termed deformation modulus (M), and can be expressed as:

$$M = \frac{\text{stress change}}{\text{strain change}} = \frac{d\sigma'}{de} \qquad (2)$$

The tangent modulus is not a constant but varies with vertical effective stress (Janbu, 1969). Janbu developed the general expression for the value of M for all soils which can be stated as:

$$M = m\sigma_a \left(\frac{\sigma'}{\sigma_a}\right)^{1-a} \qquad (3)$$

where

M = deformation modulus

m = modulus number

σ_a = reference pressure (1 atmosphere, 101.32 kPa)

σ' = vertical effective stress

a = stress exponent.

Stress-strain data from the oedometer test on specimen 2 are shown in Figure 4. The tangent slope of the stress-strain curve M, was determined at increasing values of vertical effective stress and are shown plotted versus vertical effective stress in Figure 5. Since the loess typically has a high silt content and behaves more like a sand than a clay (Lutenegger, 1983) a power curve of the form of

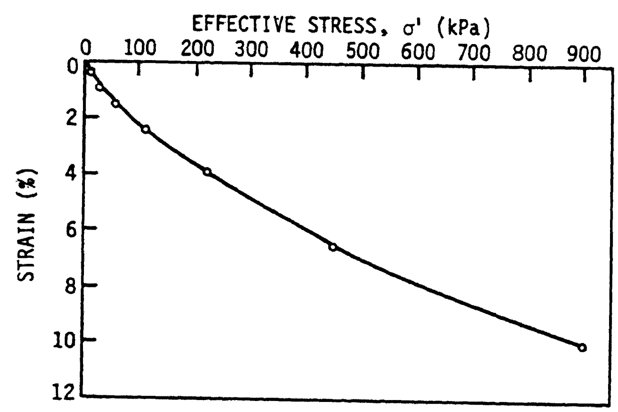

Figure 4. Stress-strain data from oedometer test.

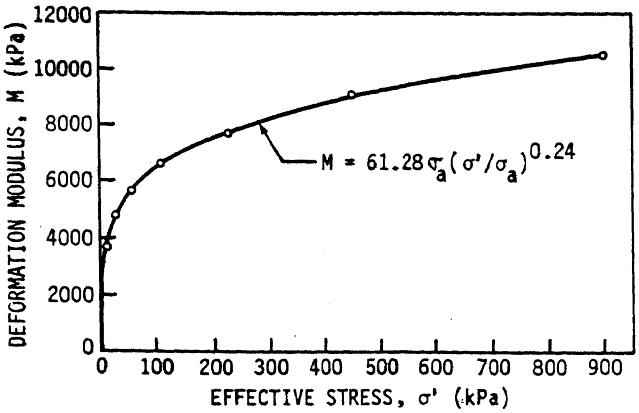

Figure 5. Deformation modulus vs. effective stress.

Equation (3) was determined by least squares method to describe the relationship in Figure 5 and is given as:

$$M = 61.28\ \sigma_a\ \left(\frac{\sigma'}{\sigma_a}\right)^{0.24} \tag{4}$$

with a correlation coefficient of 0.995.

The strain at any given depth can be calculated by rearranging Equation (4) and integrating with respect to σ, giving:

$$\varepsilon = \int_{\sigma'_o}^{\sigma'_o+\Delta\sigma'} \frac{d\sigma'}{M} \tag{5}$$

where σ'_o is the initial vertical effective stress. By combining Equations (3) and (5), the following expression for strain is derived:

$$\varepsilon = \frac{1}{ma}\left[\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma_a}\right)^a - \left(\frac{\sigma'_o}{\sigma_a}\right)^a\right] \tag{6}$$

This equation is valid except for the special case where a = 0.

Constrained Modulus

The secant modulus of the stress-strain curve in one-dimensional compression is defined as the constrained modulus (Lambe and Whitman, 1969). From the data of Figure 4, the value of constrained modulus, D, can be determined by:

$$D = \frac{\sigma'}{\varepsilon} \tag{7}$$

and is taken between σ'_o and $\sigma'_o + \Delta\sigma'$ from the oedometer data. It follows then from elastic theory that:

$$E = \frac{D(1 + \nu)(1 - 2\nu)}{(1 - \nu)} \tag{8}$$

Since compression is assumed to be one-dimensional, $\varepsilon_2 = \varepsilon_3 = 0$. Thus the unit vertica strain can be claculated from:

$$\Delta\varepsilon = \frac{1}{E}\ (\Delta\sigma' - 2\nu\Delta\sigma_3) \tag{}$$

and settlement from a layer of thickness z is calculated from:

$$\delta = z\varepsilon \tag{1}$$

Stress Path

The stress path method of estimating deformations was developed and presented by Lambe (1964, 1967) and more recently has been reviewed by Lambe and Marr (1979). This technique involves following the stress path loading sequence computed by elastic theory as a result of the applied loads. Tests are performed in a triaxial cell so that both vertical and horizontal effective stresses car be controlled. Measured net vertical strains can then be used to estimate total settlement.

Two samples were tested by this method, one obtained at a depth of 2.2 meters (7 ft) and another at a depth of 4.5 meters (14.5 ft). Samples were consolidated to their respective at-rest pressures using the calculated overburden for vertical stress and the calculated value of K_o to obtain lateral stress. The vertical stress was then decreased to account for foundation excavation, during which time the lateral stress was held constant. Imposec stresses due to construction and subsequent loading to full static head of water were ther applied to each sample, based on elastic theor Stress paths for each sample are shown in Figure 6.

COMPARISON OF RESULTS

The observed settlement versus time data are shown in Figure 7. Long-term measurements dis play a decidedly time-dependent settlement behavior which must be attributed to unsaturated creep. The importance of such creep in

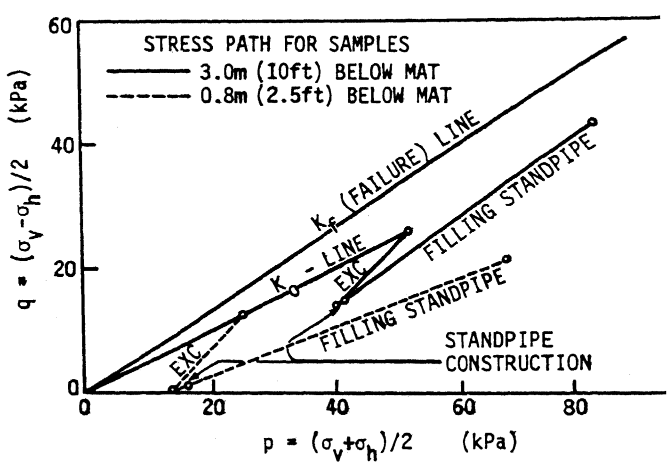

Figure 6. Stress paths used for settlement analysis.

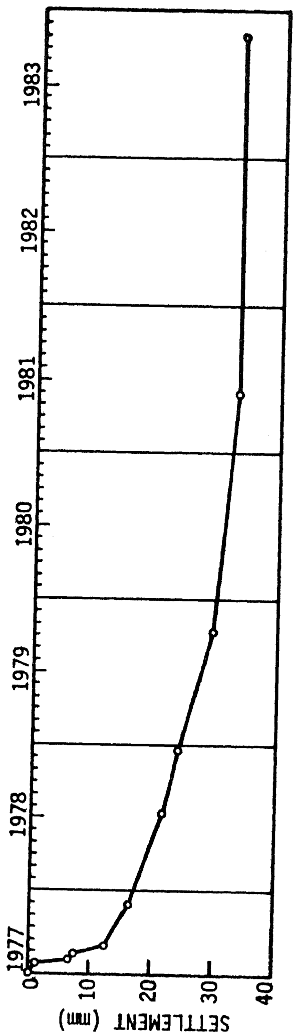

Figure 7. Settlement versus time.

sands has been previously noted and is accounted for as a log-linear decay by Schmertmann (1970). The authors are not aware that this behavior has been described for unsaturated loess, however, owing to the low density of this material a tendency for creep might be anticipated. Settlement measurements obtained in 1981 and 1983 would indicate that settlement is essentially complete.

Settlement calculations based on the methods previously described gave varying results as summarized in Table I. The ratios of predicted to observed settlement from oedometer tests are generally within the acceptable limits of most routine investigations, particularly considering the magnitude of total settlement. However, it is of interest to note that the stress path technique considerably underestimated the actual settlement. We may speculate that the reason for this error may partially be accounted for by considering the amount of time that loads are held constant during loading in the triaxial cell.

Table I. Comparison of observed and predicted settlement.

Method	Settlement mm (in.)	Predicted / Observed
Observed	33 (1.3)	1.0
Predicted:		
Terzaghi	46 (1.8)	1.4
Tangent Modulus	38.5 (1.5)	1.2
Constrained Modulus	58.5 (2.3)	1.8
Stress Path	10.7 (0.4)	0.3

During oedometer testing, the end of "primary" compression took place within the first half hour under all load increments. Following this, additional strain occurred prior to placement of the next load increment at 24 hours. Thus, settlement predictions from oedometer data reflect laboratory creep. By contrast, load increments during stress path testing were placed nearly continuously, in a step-wise fashion and so were held constant only a few seconds to obtain strain measurements. Thus, these data represent only immediate deformations which would occur in the field.

As a check on this explanation we may note that settlement predictions made from the stress path method very closely match the observed "immediate" settlement as indicated by the first few data points of Figure 7.

SUMMARY AND CONCLUSIONS

Settlement observations made of a shallow rigid mat foundation on unsaturated loess were compared with four methods of predicting settlement. These methods were; (1) conventional one-dimensional consolidation theory; (2) tangent modulus method using oedometer test data; (3) constrained modulus using oedometer test data; and (4) stress path loading. The magnitude of total settlement observed, 33 mm (1.3 in.), is well within the tolerance of the structure and was predicted most closely by the tangent modulus technique. Of those techniques applied, all but the stress path method overpredicted the observed settlement.

Observations of actual settlement of the structure indicate a creep behavior for unsaturated loess. Oedometer tests conducted at natural moisture content and with a 1 day load duration appear to be appropriate for predicting such behavior, while stress path tests performed in the triaxial cell should be run for a longer period of time at design load to more accurately determine long-term settlements.

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REFERENCES

Clevenger, W.A., (1958). Experience with Loess as Foundation Material. Trans. ASCE, vol. 123, 151-170.

Gibbs, H.J. and Bara, J.P., (1962). Predicting surface subsidence from basic soil tests. ASTM STP No. 322, 231-246.

Handy, R.L., (1973). Collapsible Loess in Iowa. Proc. Soil Sci. Am., vol. 37, 281-284.

Holtz, W.G., and Gibbs, H.J., (1951). Consolidation and Related Properties of Loessial Soils. ASTM STP No. 126, 9-33.

Holtz, W.G. and Hilf, J.W., (1961). Settlement of Soil Foundations Due to Saturation. Proc. 5th Int. Conf. on Soil Mech. and Found. Engr., vol. 1, 673-679.

Janbu, N., (1963). Soil Compressibility as Determined by Oedometer and Triaxial Tests. Proc. Europ. Conf. on Soil Mech. Found. Engr., Wiesbaden, vol. 1, 19-25.

Janbu, N., (1964). Settlement calculations based on the tangent modulus concept. Three guest lectures at Moscos State University.

Janbu, N., (1969). The Resistance Concept Applied to Deformations of Soils. Proc. 7th Int. Conf. on Soil Mech. and Found. Engr., vol. 1, 191-196.

Kane, H., (1973). Confined Compression of Loess. Proc. 8th Int. Conf. on Soil Mech. and Found. Engr., vol. 2, 115-122.

Kezdi, A., (1974). Handbook of Soil Mechanics. vol. 1.

Lambe, T.W., (1964). Methods of Estimating Settlement. ASCE Conf. on Design of Foundations for Control of Settlement, 47-71.

Lambe, T.W., (1967). Stress Path Method. Journal of the Soil Mechanics and Foundations Division, ASCE, vol. 93, 309-331.

Lambe, T.W. and Marr, W.A., (1979). Stress Path Method: Second Edition. Journal of the Geotechnical Engineering Division, ASCE, vol. 105, 727-738.

Lambe, T.W. and Whitman, R.V., (1969). Soil Mechanics. John Wiley, New York, N.Y.

Lutenegger, A.J., (1983). Engineering properties and zoning of loess and loess-like soils in China: Discussion, Canadian Geotechnical Journal, vol. 20, 192-193.

Milvoc, D., (1969). Some Engineering Properties of Loess. Specialty Session No. 5, Proc. 5th Int. Conf. on Soil Mech. and Found. Engr.

Peck, R.B., and Ireland, H.O., (1958). Discussion of Experiences with Loess as Foundation Material, by W.A. Clevenger. Trans. ASCE, vol. 123, 171-179.

Schmertmann, J.H., (1970). Static Cone to Compute Static Settlement over Sand. Journal of the Soil Mechanics and Foundations Division, ASCE, vol. 96, 1011-1043.