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Technical Note

Estimation of Settlement of Footings from Load Tests on Capillary Sand Beds

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Introduction

The plate load test resembles closely the prototype situation of a footing foundation and gives a direct measure of in-situ compressibility. Therefore, inspite of many limitations, its use for the estimation of settlement and allowable soil pressure of footings resting on sand deposits is quite popular, especially in India. In Indo-Gangetic plains of Northern India, the soil generally encountered consists of fine sand/silty sand and the water table occurs at shallow depth (Fig. 1). In such cases, the soil above the position of water table to a considerable height is affected by capillary action (Lambe and Whitman, 1969; McCarthy, 1977). The capillarity affects the engineering properties of soils such as shear strength and compressibility. As a consequence, a test plate resting on capillary bed exhibits a smaller settlement for a given load intensity as compared to a test plate resting on a similar deposit of dry sand of same relative density (Fig. 2). The results of such load tests lead to unsafe prediction of settlement of prototype foundations (Terzaghi and Peck, 1967). However, no method is yet available to estimate, quantitatively, the effect of capillarity on settlement of test plates/footings. Therefore, a comprehensive experimental investigation consisting of load tests on 30cm × 30cm plates resting on prepared capillary sand beds was carried out. The paper presents the details of the tests carried out and a procedure of moderating the results of load tests conducted on capillary beds to enable a satisfactory estimate of settlement of footings.

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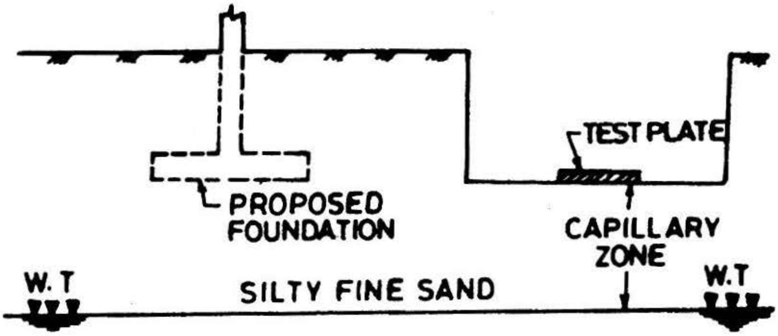

FIGURE 1 : A Typical Load Test Situation

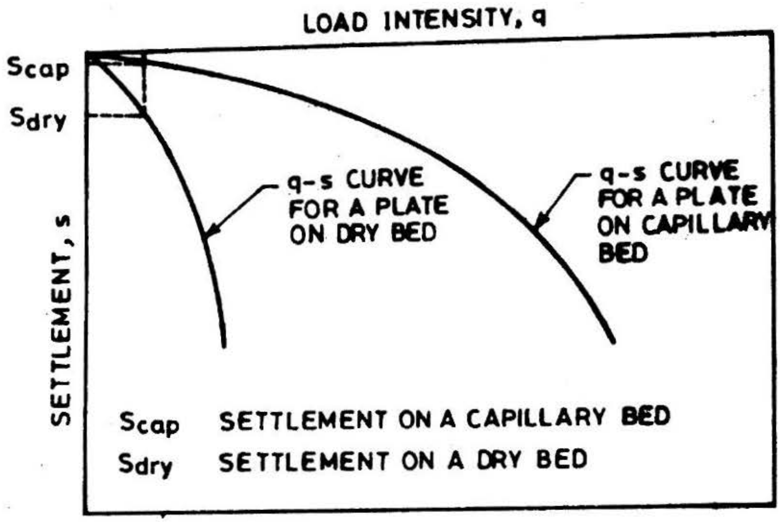

FIGURE 2 : Load – Settlement Curve for Plate on Capillary and Dry Beds

Experimental Investigations

The set-up consists of a large testing tank, 1.5m × 1.5m in plan and 1.5m in depth, in which the test bed was prepared (Fig. 3). On either side of the tank, there are two small tanks 0.5m × 0.6m × 1.5m each, connected to the large tank through a pipe at the bottom to facilitate raising, lowering, or maintaining a desired water level in the testing tank. A loading frame consisting of four columns and cross beams is built around the testing tank to provide reaction against jack loading of the test plate. A calibrated proving ring is used to measure the load applied and dial gauges, fixed at the four comers of the test plate, are used to measure the settlement of the test plate.

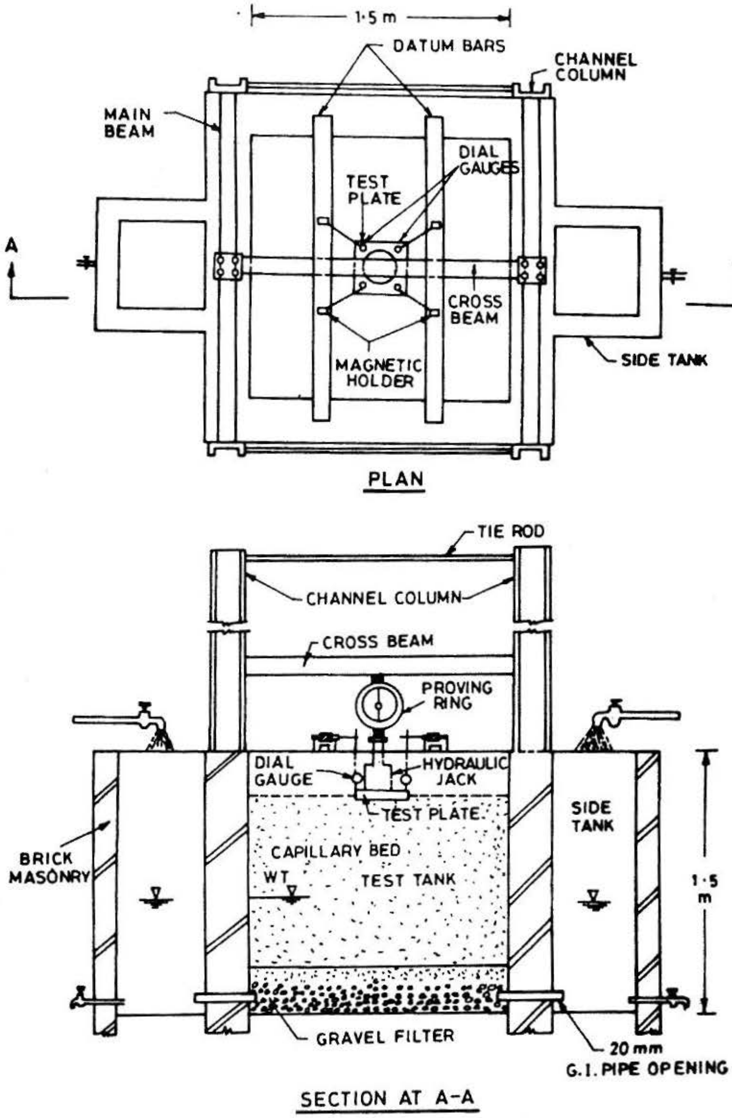

FIGURE 3 : Test Set-up

Soil Used

The load tests were conducted on two different types of soil, viz., (i) locally available Solani river sand (fine sand) and (ii) silty fine sand obtained by mixing Solani river sand and Ganga canal silt in equal volume. The physical and other relevant properties of the soils used are shown in Table 1.

Table 1 : Physical Properties of Soils

S.No.	Description	Soils used	
		Fine sand	Silty fine sand
1.	Dry unit weight of the test beds (kN/m^3)	16.4	15.9
2.	Relative density (%)	83.0	70.0
3.	Effective size, D_{10} (mm)	0.15	0.03
4.	Specific gravity of soil grains	2.65	2.62
5.	Angle of internal friction	38°	36°
6.	Classification as per IS:1498-1070	SP	SM

Preparation of Test Bed

The tank was filled with dry sand by adopting the rainfall technique. The water level in the tank was allowed to rise to the top of the sand bed, then lowered and maintained at a predetermined elevation by controlling the water level in the side tanks. Thus a capillary zone was created between the water table and the top of the sand bed. The thickness of the capillary zone was varied and limited to about 1.0m (as the total depth of the test tank is 1.5m) and kept well within the height of capillarity observed for the type of sand under test (Lambe and Whitman, 1969). This was also confirmed by making measurements of water content within the capillary zone. Lambe (1951) and Kezdi (1974) define the height of capillarity, h_c as the height from water table to a point 'A' where the depth vs. water content distribution curve tends to be vertical as shown in Fig. 4. Accordingly, the measured water content values were plotted for each of the test beds and it was confirmed that the thickness of capillary zone is less than the height of capillarity, h_c as obtained from the above definition.

Testing Procedure and Observations

The test plate (30cm × 30cm) was centrally placed on the test bed. A hydraulic jack for loading, a proving ring for measurement of load and dial gauges for settlement observations, were used. The tests were carried out in accordance with the provisions of IS:1888-1971.

A number of load tests were carried out on fine sand and silty fine sand beds by varying the thickness of capillary zone. A summary of tests carried out are given in Table 2.

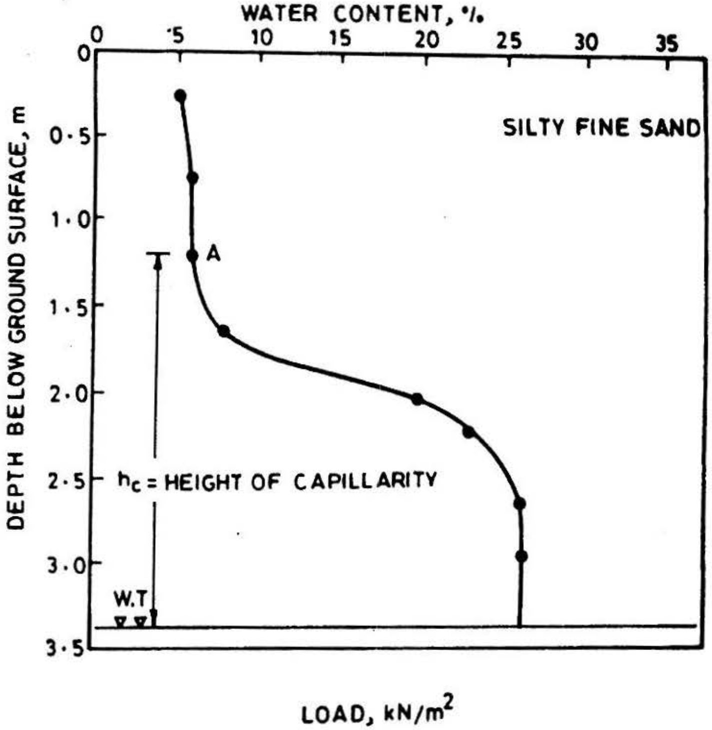

FIGURE 4 : Determination of Height of Capillarity, h_c

Table 2 : Load Tests Conducted

Type of soil	Type of bed	Thickness of Capillary zone (m)	No. of tests
Fine sand	*Submerged*	—	1
	Dry	—	1
	Capillary	0.30	1
		0.60	1
Silty fine sand	Submerged	—	1
	Dry	—	1
	Wet	—	1
	Capillary	0.30	1
		0.60	2
		0.90	2
		1.05	1

Results and Discussions

Effect of Capillarity on Settlement

The load-settlement plots obtained for the tests conducted on fine sand are given in Fig. 5 and those of tests on silty fine sand are given in Fig. 6. These plots show that the plate resting on capillarity bed undergoes much less settlement than that of a plate resting on submerged bed. For example, under a load intensity of 100 kN/m^2 (Fig. 6), the settlement of the plate resting on 90cm thick capillary bed is 5.5mm whereas for the same load intensity, the settlement of the plate resting on submerged bed is 22mm. Thus, the increase in settlement due to submergence is about four times. In the design practice usually adopted, the observed settlement of a test plate on sand deposits is doubled to account for the effect of submergence. Therefore, the present practice will lead to severe underestimation of settlement, if the test bed is affected by capillarity. The plots in Figs. 5 and 6 also show that, for a given load intensity, the magnitude of settlement decreases with the increase in thickness of capillary zone.

Settlement Correction Factor

In a situation as shown in Fig. 1 (water table not far below the proposed depth of foundation), it can always be expected that the water table would rise to the base or above the base of the foundation sooner or latter and the foundation design has to account for the same. Therefore, the probable settlement of the test plate if it were to rest on a submerged bed is of interest

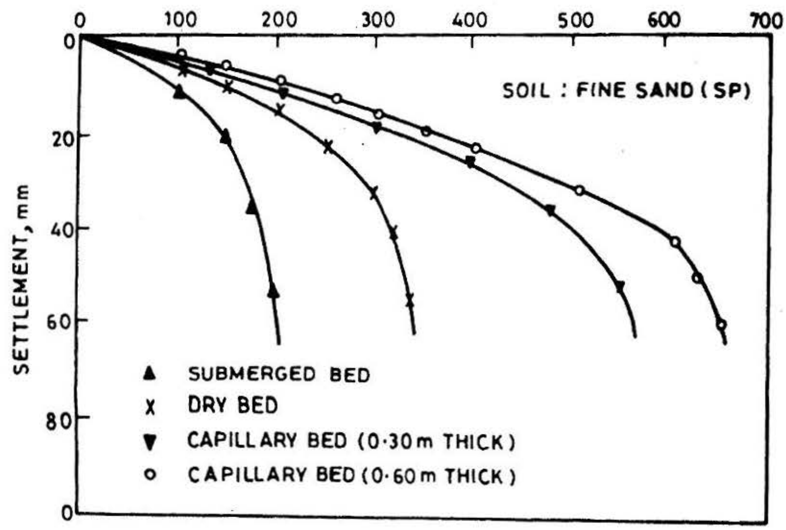

FIGURE 5 : Load – Settlement Curves for Plate on Fine Sand

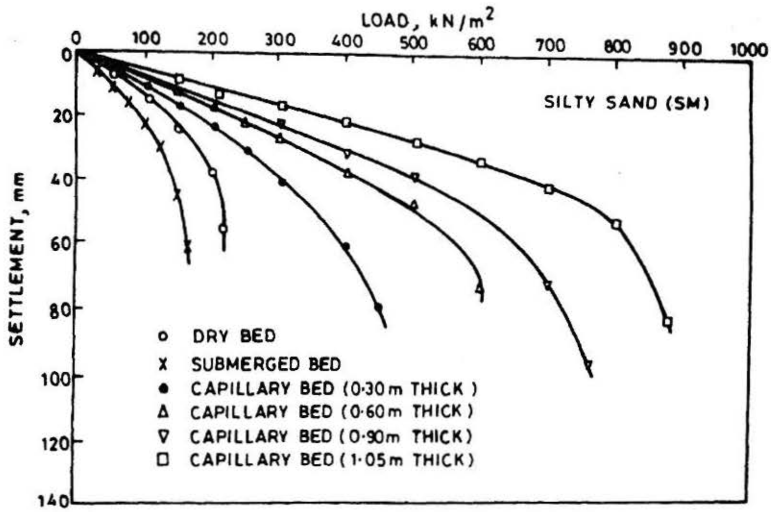

FIGURE 6 : Load – Settlement curves for Plate on Silty Sand

to the designer. To enable estimation of the increase in settlement due to submergence of test bed, an expression for the ratio of settlement of the test plate on submerged bed to that of the plate on capillary bed, termed as settlement correction factor, has been derived.

The settlement, S of a test plate or foundation can be considered to be inversely proportional to the elastic modulus, E of the soil. The elastic modulus can be related to the mean of the principal stresses (Lambe and Whitman, 1969) and accordingly, the settlement can be expressed as,

$$S \propto \frac{1}{E} \propto \left[\frac{1}{\sigma'_v\left(\frac{1+2K_0}{3}\right)}\right]^n \tag{1}$$

where, σ'_v = effective vertical overburden stress

K_0 = coefficient of earth pressure at rest

n = a constant; may vary from 0.4 to 1.0 (Lambe and Whiteman, 1969)

The variation of effective vertical overburden stress below the base of the test plate, in a capillary and a submerged bed, is linear and as shown in

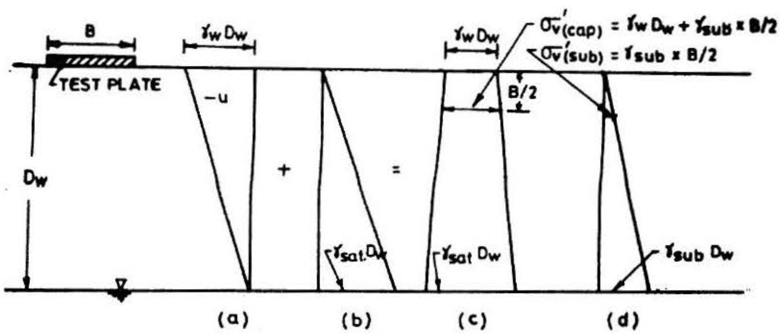

FIGURE 7 : (a) Pore Water (b) Total (c) Effective Stresses in a Capillary Zone and (d) Effective Stress in a Submerged Zone

Fig. 7. Therefore, the value of σ'_v at the mid point of the seat of settlement can be used in Eqn. 1. The seat of settlement is usually taken to extend upto a depth equal to the width of footing/plate, B below the base of the footing/ plate (Peck et al., 1974; Perloff and Baron, 1976). Settlement observations made on the test plate during the rise of water table in the present investigations also confirm the above. In view of this, the seat of settlement is assumed to be equal to the width of the test plate.

The effective vertical overburden stress at a depth B/2 below the plate in a capillary bed (Fig. 7), is obtained as,

$$\sigma'_v(\text{cap}) = \gamma_w D_w + \gamma_{sub} \frac{B}{2} \tag{2}$$

Similarly, the corresponding effective vertical overburden stress in submerged situation is give by,

$$\sigma'_v(\text{sub}) = \gamma_{sub} \frac{B}{2} \tag{3}$$

where γ_w = Unit weight of water

γ_{sub} = Submerged unit weight of soil

D_w = Depth of water table below the test plate, i.e. the thickness of capillary bed

From Eqns. 1, 2 and 3, the settlement correction factor, K can be written as,

$$K = \frac{S_{sub}}{S_{cap}} = \left[\frac{\sigma'_{v(cap)}\left(1+2K_0\right)/3}{\sigma'_{v(sub)}\left(1+2K_0\right)/3}\right]^n \tag{4}$$

Substituting the values of $\sigma'_{v(cap)}$ and $\sigma'_{v(sub)}$ from Eqns. 2 and 3 in Eqn. 4 and simplifying,

$$K = \left(1+\frac{2D_w}{B}\cdot\frac{\gamma_w}{\gamma_{sub}}\right)^n \tag{5}$$

An appropriate value of 'n' for use in Eqn. 5 is determined based on the results of plate load tests on capillary and submerged beds reported in Figs. 5 and 6. It is found that the value of n in Eqn. 5 can be taken as 0.7.

Validation of the Expression for 'K' using the Experimental Data

The values of 'K' for various values of thickness of capillary zone (D_w/B) are computed from Eqn. 5 for n = 0.7. In these computations, the unit weight of submerged sand, γ_{sub}, is taken to be equal to the unit weight of water, γ_w (γ_{sub} is generally close to 10 kN/m^3). Finally, K versus D_w/B plot is presented in Fig. 8.

It can be seen from Fig. 8 that the settlement correction factor, K, can be as high as 5 when the thickness of the capillary zone is about 1.5 m (i.e., for D_w/B = 5 and for a test plate with B = 30cm). Whereas, in practice, a factor of 2 is applied to account for the increase in settlement due to submergence. This clearly brings out the possible level of under-estimation of

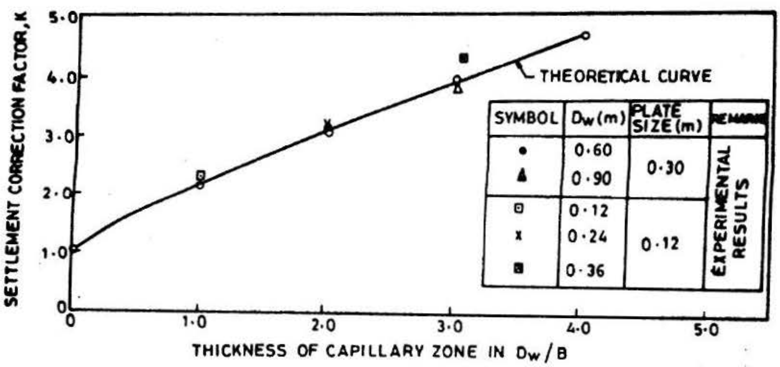

FIGURE 8 : Settlement Correction Factor, K vs. D_w/B Plot.

settlement that could occur if a load test is conducted on a capillary bed.

A few load tests on 30cm × 30cm plate were conducted wherein the plate was initially placed on a capillary bed, loaded upto a safe load intensity and the settlement recorded. Subsequently, the water table was raised upto the base of the plate, maintaining the load and the final settlement recorded. Thus, the values of settlement of the plate on capillary bed and submerged bed were noted. From these observed settlement values, the settlement correction factor, K, is computed for the test situations. A similar exercise is carried out on the results of tests on 120mm diameter circular plate reported by Ramasamy et al., (1986). The values of K, thus predicted are compared with the values computed using Eqn. 5 for n = 0.7. The comparison is shown in Fig. 8. It can be seen from Fig. 8 that the analytical results agree reasonably well with the results obtained experimentally.

Suggested Procedure of Moderating the Results of Load Tests conducted on Capillary Sand Beds

Based on the analysis and the results of the experimental investigation, the following procedure is recommended for the estimation of settlement of footings on sands from the results of load tests conducted on capillary beds.

Step 1 Obtain samples from ground level to water table at close depth intervals, preferably every 200mm. for water content determination. Plot depth versus water content curve. Obtain h_c as outlined in Fig. 4. Confirm that $D_w < h_c$ where D_w is the depth to water table from the base of the plate. The present analysis is valid only for situations where $D_w < h_c$.

Step 2 Draw the load-settlement curve for the load test conducted on the capillary bed.

Step 3 From the load-settlement curve, find the settlement corresponding to the design foundation pressure. This is S_{cap}

Step 4 Using Eqn. 5, obtain the settlement correction factor, $K = S_{sub}/S_{cap}$, taking n = 0.7.

Step 5 Multiply the observed settlement, S_{cap}, by K to obtain, S_{sub} for the plate.

Step 6 Use the extrapolation relationship given by Terzaghi and Peck (1967) or that suggested by Bjerrum and Eggestad (1963) whichever is considered acceptable for obtaining settlement of the foundation from the settlement of the plate estimated in Step 5.

Conclusions

1. Capillarity in Silty sands/Fine sands reduces the settlement of a test plate substantially, the order of reduction being dependent on the thickness of capillary zone.

2. An expression for the settlement correction factor, K, which is the ratio of the settlement of a plate on submerged bed to the settlement of the plate on capillary bed has been developed. The expression has also been validated by the results of load tests.

3. Based on the analytical and experimental evidence presented in the paper, a procedure for the estimation of settlement of footing foundations using the results of a load test conducted on a capillary bed has been outlined.

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