PREDICTION OF LONG-TERM SETTLEMENT OF SOFT CLAY USING THE CONTINUOUS SURFACE WAVE METHOD & DAMPING MEASUREMENT

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ABSTRACT: This paper presents a method of calculating long-term settlement of a loaded pad on soft clay at a site in Klang, which is situated on the west coast of Peninsular Malaysia. In this study, the soil model was treated as an inelastic material of viscoelastic property. An elastic shear modulus G from shear wave velocity and damping ratio D at known strain were initially used as the input. The elastic settlement was first found from G. The additional time-dependent primary settlement was obtained by applying the seismic settlement equation based on the generalised theory of viscoelasticity. The value of D used was appropriate for the strain produced by the elastic settlement. Good agreement with observation was obtained. Comparisons were also made with other established methods of settlement prediction Finally, a revised seismic equation parameter was proposed to suit Malaysian soft clay soils. The revised parameter was able to reduce the difference between observed and predicted long-term settlement to an average of 10%.

Keywords: soft clay; shear modulus; damping; elastic settlement; time dependence

1. INTRODUCTION

Ground settlement is a common problem in areas of soft clay deposits found widespread throughout the coastal areas of Malaysia. This problem is mainly due to large deformation of the very soft clay material of the subsurface under long-term loading of engineering superstructures. As such, reliable and relatively simple methods of predicting settlement and deformation on the very soft clays found in Malaysia are needed.

This paper reports the application of a method of calculating these movements by treating the clay as an inelastic material. Immediate settlement can be calculated from elastic shear wave velocities by finding the elastic settlement. This is then multiplied by a factor to add the effect of viscoelastic creep due to consolidation process. The settlement so obtained has been applied to stiff clays for periods of about 24 hours (Abbiss, 1986). This method has also been extended to long-term settlement predictions observed for loaded pads on chalk (Abbiss, 1979) and landfill sites in Britain (Abbiss, 2007). The long-term settlement is calculated from an analytical expression involving the measured damping at known strain. In both cases, the initial elastic settlement is taken as the starting point.

2. PHYSICAL MODEL

The physical model used is that of the generalised viscoelastic solid as described in Abbiss (1986) and Lomnitz (1974). This has a semi-random array of springs and dashpots that can respond to an applied stress with a range of time constants. These form the relaxation or retardation spectrum that characterises the time dependence. In this calculation, the spectrum is assumed to be constant with time at a given strain.

3. AT THE KLANG SITE

3.1 Ground Profile

The underlying ground condition is of soft clay as described from the Geonor field vane shear test result shown in Fig. 1.

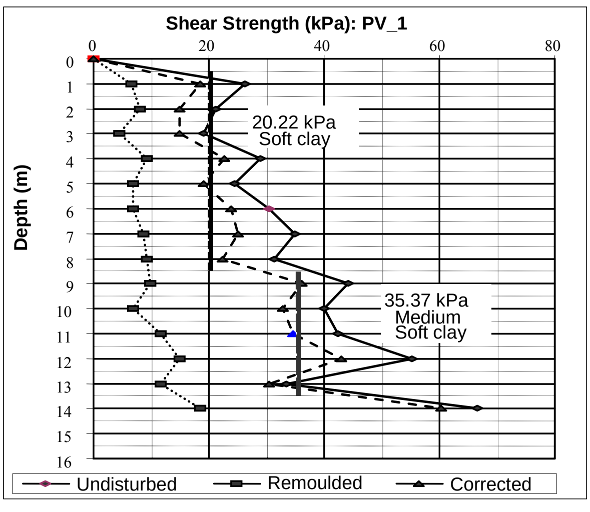

Fig. 1. A typical field vane profile at the Klang site

The subsoil at the test site can be divided into three layers: very soft clay layer with average s_u of 10 kPa (0.0 - 1.0 m), soft clay layer with average s_u of 20.36 kPa (1.0 - 8.5 m) and medium soft clay layer with average s_u of 34.21 kPa (8.5 - 15.5 m).

3.2. Shear Wave Velocities

Shear wave velocities are measured in the soft clay by the Continuous Surface Wave (CSW) method conducted with a total of seven survey measurements. Their close agreement gives a good value of the shear modulus as a function of depth. It also indicates that the material is isotropic. The low average velocity of 56.13m/s with a standard deviation of about 2.3 corresponds to an RMS error of 4.1%. Fig. 2 and Fig. 3 illustrate the layout and set up of the CSW survey lines, respectively.

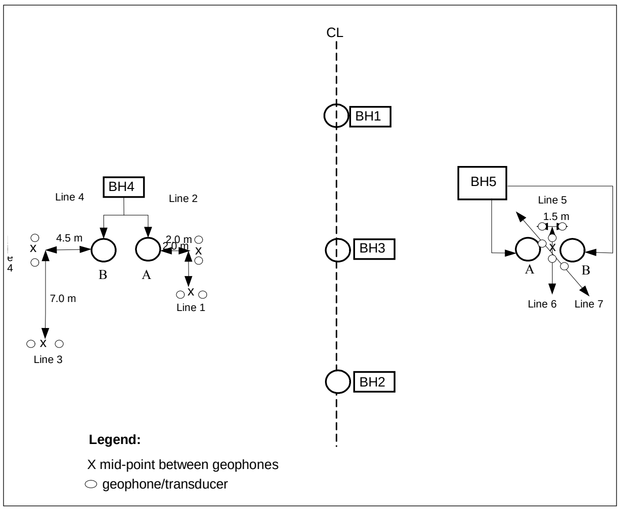

Fig. 2. Layout of the CSW survey lines

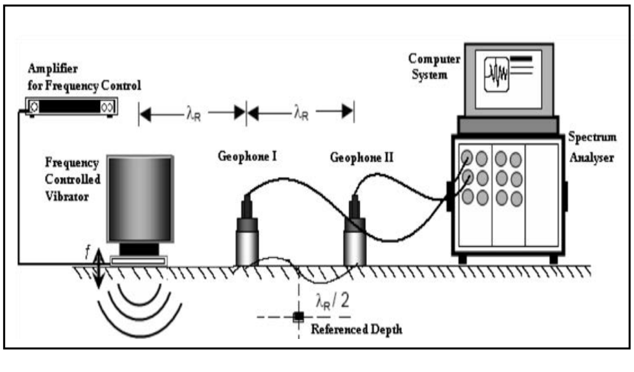

Fig. 3. Set-up of the geophones and vibrator of a CSW survey line

3.3. Damping Measurements

Damping is found directly from the hysteresis loop observed in the plot of surface load intensity against vertical strain for the first cycle of loading and unloading of five plate load tests. The energy absorbed during the cycle is the area of the loop ΔE, as shown in Fig. 4, which was measured with a planimeter.

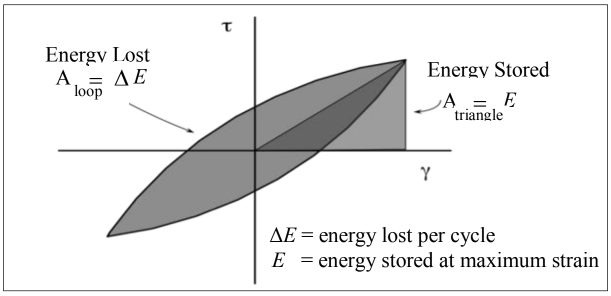

Fig. 4. Damping from cyclic loading

Five readings of the half loop geometrical area from the first loading and unloading cycle of the small plate load tests are used to find D. The energy stored during a cycle is E, the triangle with vertices at the origin and one end of the loop. The damping ratio D is calculated as $\Delta E/(4\pi E)$ = 0.15, the mean of five tests, with a standard deviation of the mean of ±8%. The strain that this corresponds to is the maximum excursion strain ε = 0.00581 ±4%. This is fairly close to the strain experienced by the soil under the pad during the loading test. The input data for the settlement prediction of the loaded pad is summarised in Table 1.

Table 1 Input data for settlement prediction

Shear wave Velocity V_s (m/s)	56.1
Mass Density ρ (Mg/m^3)	1.328
Damping Ratio D	0.15 at 0.00581 strain
Load Intensity q (kPa)	27.8
Equivalent Pad Radius b (m)	1.26

3.4. Long-term Settlements

Standpipe piezometers and pneumatic piezometer are installed at the experimental sites to monitor the ground water level and their pore pressures. Settlements are observed under a loaded pad measuring 2 m by 2.5 m with a pressure of 27.8 kPa placed on soft clay. They are measured by means of precise levelling of targets set on a concrete pad and from magnetic extensometers. Readings are taken for 10 months or 300 days. Layout of the pad (skip tank) and the instrumentations installed is shown in Fig. 5.

The predicted long-term curve of settlement against time from the seismic method (Abbiss, 1986) is shown in Fig. 6 and plotted against the logarithmic scale of time in Fig. 7. The immediate settlement after one day was 22.56 mm, increasing to 30.24 mm after an elapse of a ten-day period. The curve is similar to an exponential decay versus time that corresponds to an almost linear plot against log time. As would be expected the settlements are relatively large in the case of soft clay.

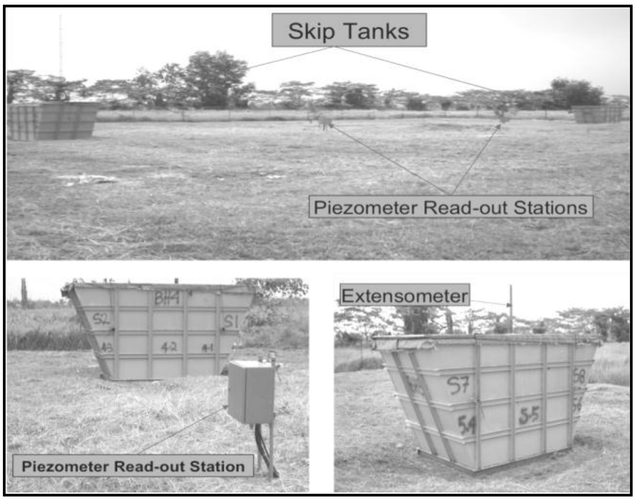

Fig. 5. Layout of the skip tank and the instrumentations installed

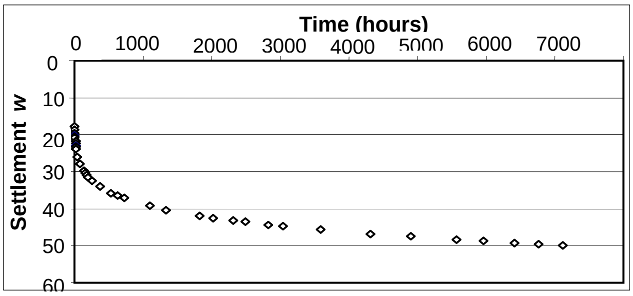

Fig. 6. Predicted long-term settlement against time

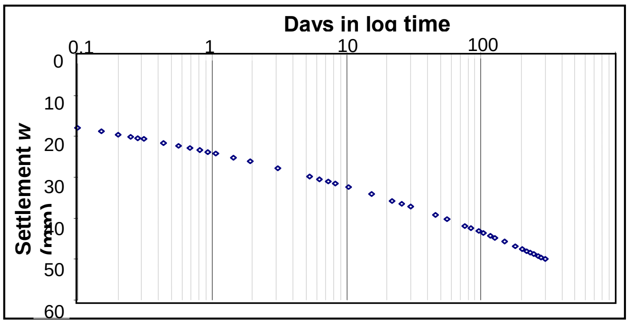

Fig. 7. Predicted long-term settlement against log of time

4. CALCULATION OF LONG-TERM SETTLEMENT

4.1. Calculation of Elastic Settlement and Strain

The test pad measuring 2.0 m x 2.5 m is equivalent to a circular pad of radius b of 1.26 m. The analytical elastic solutions of Brown and Gibson (1972) are used to find the elastic settlement. The pad is founded at a depth of 0.6 m. The average properties for the calculation are most significant at a depth of about one radius below the founding level, so the shear wave velocity Vs required is that at a depth of 1.86m with a value of 56.13 m/s. The mass density ρ is 1328 kg/m^3 (from a unit weight value 13.0 kN/m^3). The elastic shear modulus G is then calculated from

$$G = \rho(Vs)^2 \tag{1}$$

assuming at this stage that the dynamic and static moduli correspond to a low elastic stiffness of the ground with a value of 4.18 MPa. The site is known to be isotropic so no corrections for anisotropy are required. However there may be a small increase in stiffness with depth.

The settlement w of a pad of radius b with a load pressure of q (in Pa) on an ideal elastic uniform half space of shear modulus G is

$$w = qb/(2G) \tag{2}$$

for a Poisson's Ratio ν of between 0.3 and 0.5. Brown & Gibson (1972) give graphical corrections to this value from analytical solutions for varying Poisson's Ratio with increasing shear modulus with depth. For this soil and dynamic calculation, it is a reduction in w by about 5%. The dynamic ν in clays can be 0.47 (ideally 0.5). The factor of 0.9 is used in this calculation to give an elastic settlement w of 3.77 mm. The elastic strain is then $w/(2b)$ = 0.0015.

3.2. Calculation of Damping at Elastic Strain

A correction is applied to adjust the value of D to that corresponding to the elastic strain experienced under the pad due to elastic settlement alone. The formula used is that of an "s" curve for D as a function of log time as given in Abbiss (2001). This is inverted as discussed in that paper to obtain the value of the "characteristic strain", ε_c. For this site,

$$\varepsilon_c = [2\varepsilon/(e - 1)][\exp(D_{max}/D - 1) - 1] \tag{3}$$

With D_{max} = 0.33, the measured value for D is 0.15, and the corresponding values of ε and ε_c are 0.00581 and 0.01569, respectively. From the equation for the "s" curve of damping,

$$D(\varepsilon) = D_{max}/\{1 + \mathrm{Ln}[\,1 + (e - 1)\varepsilon_c/(2\varepsilon)]\} \tag{4}$$

So for an elastic strain of 0.00149, D = 0.0999. This value is used in the viscoelastic formulae given herein.

4. ANALYTICAL EXPRESSION FOR LONG-TERM VARIATION OF STRAIN

4.1. Primary Part

Previous work with the generalised viscoelastic theory (Abbiss, 1986) has used an expression for modulus that is equivalent to a relation for strain ε at constant stress as a function of time in the form of

$$\varepsilon(t) = \varepsilon_0(t/t_0)^{(4D)/(\pi)} \tag{5}$$

D is the damping factor related to the quality factor Q by $1/Q = 2D$, and ε_0 is the initial strain. D is the value corresponding to that initial elastic strain.

4.2. The First 24 Hours

The average period t_0 of the surface waves used to measure dynamic stiffness G is approximately 0.0667 s corresponding to a frequency of 15 Hz at the effective depth of shear wave velocity measurements. The period of settlement t of 24 hours is equal to 86,400 s. The settlement w is proportional to the strain ε. Substituting these values in Eq. (5) with D of 0.0999 as found above, $\varepsilon(t)/\varepsilon_0$ is 5.985. Thus the settlement after 24 hours is found to be 3.77 mm x 5.985 = 22.57 mm compared with 13.50 mm observed.

4.3. After One Month

The further primary part is found by multiplying the 24-hr value of w by 180 raised to the same power as in the previous calculation and equals 32.36 mm. The calculated values are produced in tabular form and plotted for the curve of settlement against time from 1 to 300 days.

The summary of results calculated for Klang is summarised in Table 2. The calculated settlement curve against time compared to the experimental observation curve from 1 to 300 days is shown Fig. 8. Comparisons are also made with other established methods of settlement prediction.

Table 2. Settlements in mm for Klang site (0.067 s is period of surface wave)

Time	Klang Calculated (mm)	Klang Observed (mm)
0.067 s (elastic)	3.77	---
1 day	22.56	13.50
30 days	34.77	33.00
45 days	36.62	33.80
248 days	45.50	36.02
300 days	48.00	36.50

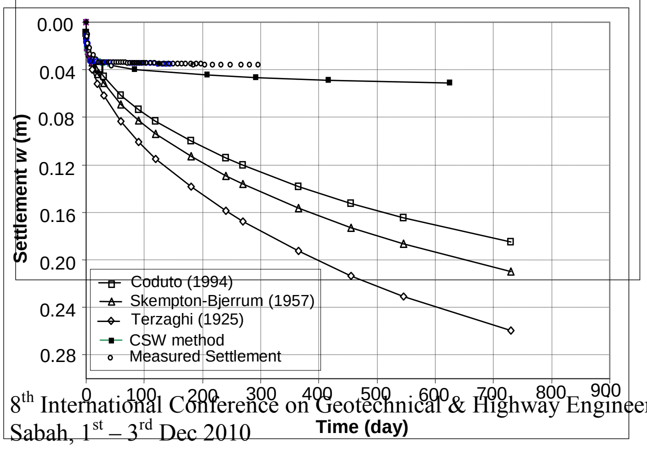

Fig. 8. Measured settlement compared with calculated settlements from various methods of prediction

5. PROPOSED REVISED SEISMIC EQUATION PARAMETER

The seismic settlement equation proposed by Abbiss (1986) is written as

$$w = w_0(T/T_0)^{\beta D/\pi} = w_0(T/T_0)^{4D/\pi} \tag{6}$$

where w_o is the elastic deformation factor from Brown and Gibson (1972), T is settlement time of interest, T_o is period of seismic measurements (*1/frequency*), β is the constant value "4" (Abbiss 1986), and D is damping ratio.

A parameter of the settlement equation as proposed by Abbiss (1986) is revised by the author in order to derive the form of equation which is able to produce better predictions of long-term settlement compared to the actual observed settlement. The constant "4" in the equation is revised and a β value of 3.25 is proposed. Thus, Eq. (6) can be rewritten as

$$w = w_0(T/T_0)^{3.25D/\pi} \tag{7}$$

A comparison of the statistical parameters of RMS and ratio of difference for the revised seismic equation and other settlement prediction methods with the monitored settlement data shows that the revised parameter is able to provide a closer agreement with the observed settlement than the other methods especially for the long-term settlement of soft clay at the site in Klang.

Fig. 9 and Fig. 10 show the ratio of difference and the values of RMS, respectively, for the revised seismic equation in comparison with those from other settlement prediction methods. The revised seismic equation is shown to be able to reduce the difference between observed and predicted long-term settlement to about 10%.

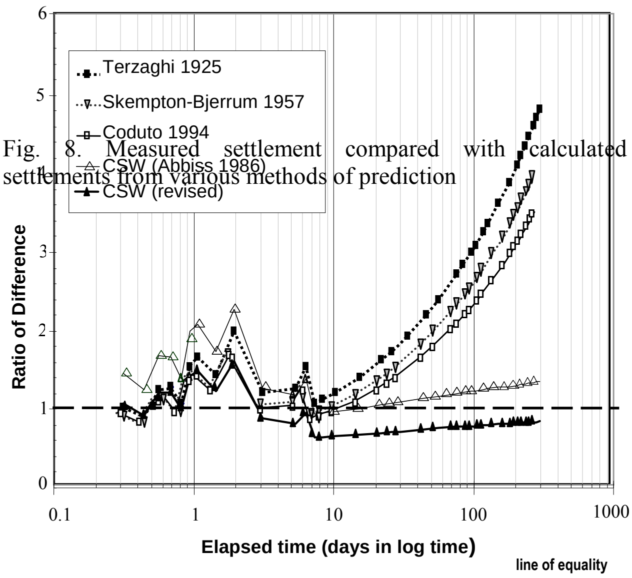

Fig. 9. Ratio of difference of settlement prediction using the revised parameter for CSW compared to various settlement prediction methods

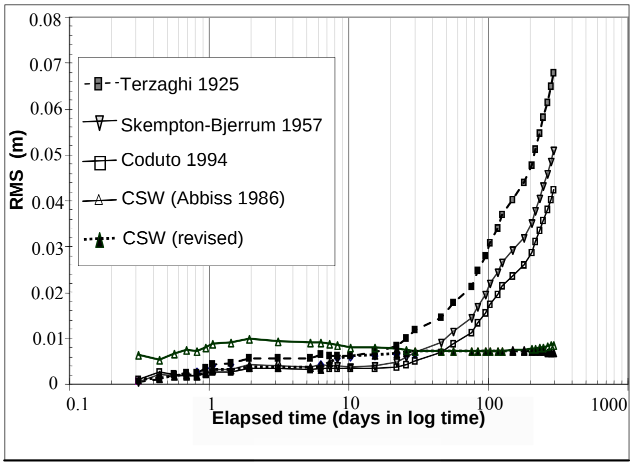

Fig. 10. RMS of settlement prediction using the revised parameter for CSW compared to various settlement prediction methods

6. DISCUSSION

Treating the soft clay at Klang as an inelastic material makes possible the calculation of long-term settlement under load. Low elastic stiffness was immediately apparent by measuring the shear wave velocity, with *G* proportional to the square of the velocity. Damping at known strain is found from hysteresis loops during the load-unload cycles of the plate load pad tests. Long-term settlements are calculated based on the behaviour of a generalised viscoelastic solid. The actual value of the damping used in the calculation is that corresponding to the elastic strain experienced under the foundation.

Two separate formulae are then used to find the correct value of *D* needed: Eq. (4) to obtain the characteristic strain ε_c to the damping at a measured strain $D(\varepsilon)$ observed, and Eq. (5) to find the damping at elastic strain $D(\varepsilon_{el})$ from ε_c and the elastic strain. The reason why the damping has to correspond to the elastic strain is that both the primary viscoelasticity and any further creep movements are probably driven by the elastic energy stored in the material during the elastic strain.

Evaluation of long-term settlement with this method depends on the input data to minimise the error in calculation. The higher the accuracy that is required, the higher must be the accuracy of the input parameters.

7 CONCLUSIONS

The prediction of long-term settlement using the method proposed by Abbiss (1986) has given good prediction results when applied on Klang soft clays. The results from the seismic method have shown a considerably closer prediction of long-term settlement prediction to the actual observed settlement compared to traditional methods. Overall, the seismic method has proven to be a fast, cheap and reliable method for the prediction of long-term settlement. Additionally, this geophysical method is non-destructive, non-intrusive and more representative in ground investigation compared to the conventional methods where soil samples suffer from considerable disturbance during drilling, sampling and in situ testing.

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