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THE EFFECTS OF CREEP ON LATERALLY LOADED PILES

LES EFFETS DU FLUAGE SUR LES PIEUX CHARGES LATERALEMENT

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SYNOPSIS: PILATE is a computer program which solves the lateral-load-on-a-pile problem. PILATE is based on analytical solution rather than finite differences, and assumes the soil to be non-linear elastic. PILATE can be made to take creep of the soil into account; an example is given here of the procedure. Alternately, a new program, PILATEF can be used, as is illustrated by a secǒnd example. While frozen soil is used for both examples, the methods can be applied to unfrozen plastic clays and to ice.

PILATE est un programme d'ordinateur qui résout le problème du pieu sous charge latérale. PILATE est basé sur une solution analytique, plutoôt que sur les différences finies et suppose que le sol est élastique non linéaire. PILATE peut prendre en compte le fluage du sol; un exemple de la procédure à suivre est donné ici. Un nouveau programme, PILATEF, peut être utilise comme solution alternative. Ceci est illustré sur un second exemple. Bien que les deux exemples concernent des sols gelés, les méthodes peuvent être appliquées aux argiles plastiques non gelées et à la glace.

INTRODUCTION

PILATE is a computer program developed by the Laboratoire Central des Ponts et Chaussées (LCPC) which is widely used in France to predict the behaviour of piles subjected to lateral loads (Frank and Romagny, 1990). In its general form, PILATE can consider the case where the soil around the pile is moving for some external reason. Two examples are: i) solifluction, in which a shallow layer of soil moves down a slope around a pile or a group of piles, and ii) piles in a soft soil at the toe of a newly constructed embankment. In the form discussed here, PILATE considers a pile which is embedded in a material which does not move except as a result of an external force applied to the above-ground head of the pile. However, the solutions presented here can be extended to the general case without difficulty.

PILATE, in its simplest form, is a member of a small family of programs which treat a laterally loaded pile as an elastic beam on an elastic foundation. Even in this simple form, PILATE considers the foundation to be non-linear elastic. The program is based on finite elements rather than the more usual finite differences

One intent of this contribution is to illustrate how PILATE can be used to predict the behaviour of piles which are embedded in a material which creeps (that is to say, a material with time-dependent behaviour). In this case, it is warm, ice-rich permafrost that leads to time-dependent behaviour, but the material in which the pile is embedded could be also clay or ice, for example. Creep can be accommodated by PILATE by making the non-linear elastic foundation have elastic properties which are time-dependent. In other words, the material will become less stiff with time as creep deformation occurs.

A new computer program, PILATEF, built on the basic concepts of PILATE, assumes the soil has visco-elastic properties. In rheological terms, the foundation material is considered to be of the Maxwell type in which a spring and a dashpot are in series.

Examples of both PILATE and PILATEF procedures are given in what follows. First, however, the basic features of PILATE are described. It is assumed that the reader has an understanding of current procedures for analyzing laterally loaded piles. Such procedures are found in most modern foundation engineering textbooks. Details about the PILATE computer program are found in user's manuals which are available in either English or French from the first author.

PILATE WITHOUT CREEP

The application of a lateral load to a pile is illustrated in Figure 1(a). The embedded portion of the pile is subjected to a shear force T_o and a moment M_o at the ground line, as shown in Figure 1(b). Both shear, T_p, and moment, M_p, are considered at the toe of the pile when applicable.

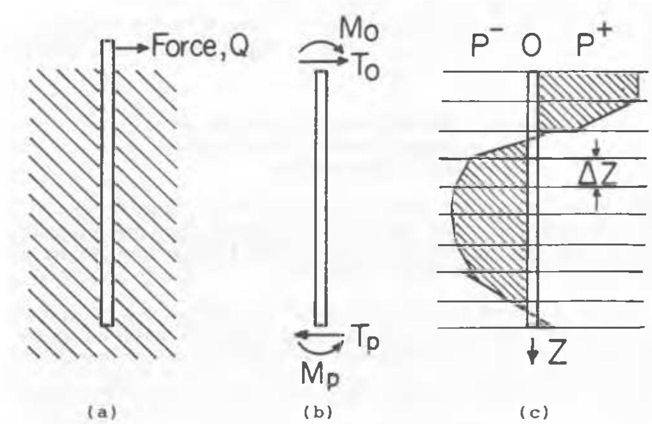

Fig.1. The laterally loaded pile problem

PILATE gives the exact analytical solution to the case of the pile being considered as a beam which is subjected to the distributed loads shown in Figure 1(c). The loads are the soil reactions (Winkler springs or reaction curves). They are specified to be of magnitude P per unit length of pile (for example, kN/m). It is in this way that PILATE differs from well-known finite difference computer programs (Morin et al., 1991 and 1992). In the finite difference solution, the soil reactions consist of a series of point loads which are spaced a finite distance apart.

Values of P are based on non-linear soil reaction curves of the sort illustrated in Figure 2, in which P = f(y), where y is the horizontal displacement of the soil by the pile. A reaction curve is required for each soil type, and for each significant change of stiffness properties within a soil type. The interrelationship of P and y is complex in that the pile deforms, rotates and translates as a result of the P forces (in addition to T and M), yet the P forces themselves are dependent on the movement of the pile. Hence, a solution to the problem requires an iterative approach. (If the soil reaction curves happen to be linear, an iterative solution is not required.)

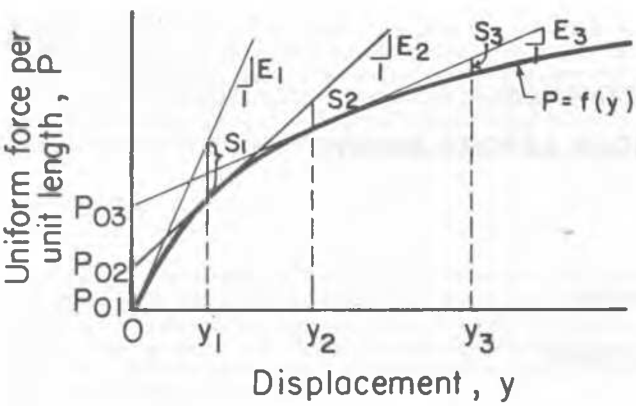

Fig.2. Reaction curve and convergence process

The iterative procedure used by PILATE is illustrated in Figure 2. For the first calculation, the soil is assumed to have moduli of reaction E_1 which are given by the initial tangent to the P,y curves. This means that the reaction curves are linearized. It is then straightforward to determine the distribution of P and y along the pile. The values at the middle of the layers, P_1 and y_1, are noted. The calculated P_1 values are then compared to the real values of P for the displacement y_1, using the real reaction curves. If the difference s_1 is greater than a certain small percentage of P (specified by the user; usually 0.1%), a tangent is drawn to the curve at y_1. The computer now calculates P_2 and y_2 using the equation $P = P_{o2} + E_2{*}y$. Once again, the difference in P values, in this case s_2, is calculated and compared to the amount which is acceptable. The procedure is repeated until convergence is reached (at s_3 in Figure 2).

PILATE calculates the distribution of P and y using the closed form solution for the equilibrium equation:

$$E_p I_p \frac{d^4 y}{dz^4} + E_i\, y + P_{oi} = 0 \qquad (1)$$

where E_p = elastic modulus for the pile material
I_p = moment of inertia of the pile section
i = number of the iteration

This is done for each layer, that is to say for each P = f(y) reaction curve. The continuity in y, y' (the rotation), M (the bending moment), and T (the shear) at the interfaces between layers, as well as the ground line and toe conditions provide the integration constants.

If the soil is homogeneous but non-linear, or if changes in P,y curves are infrequent, it is necessary to arbitrarily break up the soil profile into layers. This is to ensure that the stiffness of the soil is allowed to change frequently to reflect the changes in y. Usually a minimum of ten to fifteen layers is sufficient. Difficulties with convergence may be due to an insufficient number of layers.

PILATE WITH CREEP

Figure 3(a) illustrates the 2.5m by 2.5m by 2m deep, frozen soil test facility at the University of Manitoba. Refrigeration panels are mounted on the walls and floor. An enclosure is refrigerated separately and controls the air temperature. A tubular steel pile, 150 mm square and 1800 mm long, was installed in frozen sand kept at a temperature of -3°C. Nine rectangular (150 mm wide by 125 mm high) steel plates had been mounted on the front face of the pile. The plates could measure the force that each would apply to the soil when a horizontal load, Q, acted on the pile at a distance of 100 mm above the soil surface (see Domaschuk et al., 1991, for details). The plates were separated, one from the other, by 15 mm. Figure 3(b) illustrates how the force plates were located with reference to the soil surface.

Loads of 36, 61, and 114 kN were applied incrementally. Each load was maintained until displacement stopped. This required 18, 40, and 162 days respectively. Finally, a 146 kN load was applied. After about 70 days, the rate of pile displacement started to increase regularly and the load was reduced to zero after 140 days. The total elapsed time was 360 days.

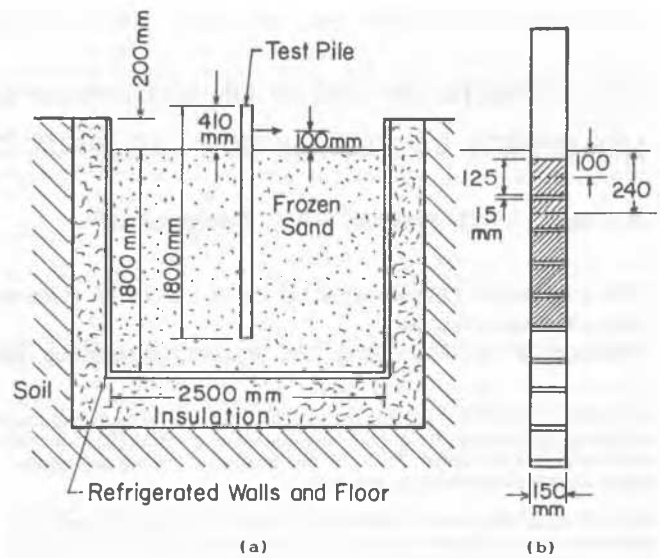

Fig.3. The refrigerated pit and the instrumented pile

Of interest here are the reaction-displacement curves for the force plates. It was possible to analyze the test results to produce the curves which are shown in Figures 4(a) and 4(b) for the plates at 100 mm and 240 mm respectively. Note that both an initial and a final curve are plotted, corresponding to the cumulative displacement immediately on application of a load, and to the cumulative displacement at the end of the load increment (made up of both immediate displacement and creep).

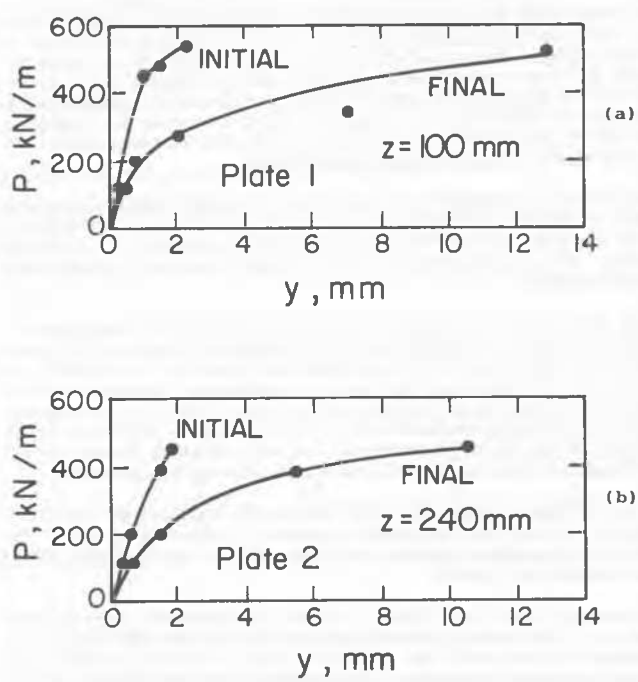

Fig.4. P,y curves from the two force plates

Thus it was possible to create four P,y curves for the frozen sand. Two of the curves are for the immediate reaction of the soil; two of the curves incorporate creep. In fact, it would be possible to create P,y curves for any intermediate stage, that is to say, at any specified time after a load was applied.

Since it was not possible to generate P,y curves for all nine load plates (mainly because the displacements were too small), a demonstration of how PILATE can be used to model creep was run using the P,y curves for the uppermost plate given in Figure 4(a). The soil was assumed to be homogeneous with these non-linear reaction properties. Ten equal intervals of Δz were specified. The point of the pile was assumed to be free. Figure 5 illustrates the results. They are indeed encouraging.

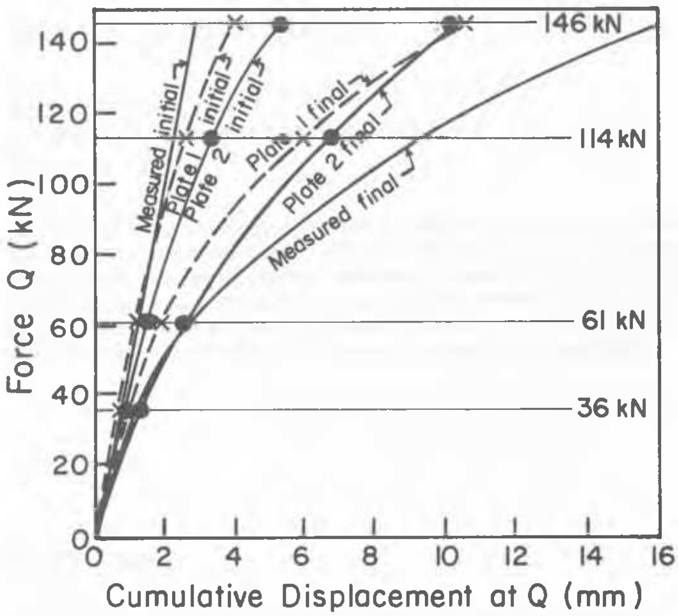

Fig.5. Predicted versus measured displacements

Using 20 soil layers did not change the results. Specifying the point of the pile to be fixed rather than free reduced the immediate displacement at 146 kN by 2% and the long term displacement by 15%. Using the P,y curves for the second plate rather than the first plate led to a worse fit in the immediate case and a better final fit (as illustrated in Figure 5).

PILATEF

It is convenient to refer to a paper by Neukirchner and Nixon (1987) to illustrate the way that PILATEF can take creep into account directly using a Maxwell model. Neukirchner and Nixon describe the situation illustrated in Figure 6. It is possible for PILATEF to back-calculate a short-term linear reaction modulus E from the data for the 1-day pile displacement (see Figure 7). The value of E is 513 MPa . This means that the initial, distributed load P along the pile will be given by P = E*y = 513*y, with y in metres and P in MN/m.

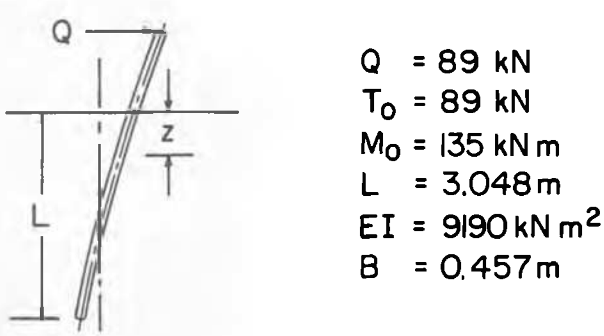

Fig.6. Neukirchner and Nixon's example problem

It is also possible to represent the rate at which y will change due to secondary creep in the frozen soil (Neukirchner and Nixon consider only secondary creep, assuming, probably, that primary creep will be relatively insignificant). The modified Glen's Law for secondary creep given a pressure p on the soil equal to P/B (where B is the diameter of the pile) is:

$$\dot{y} = I * B/2 * \beta/N_\beta * p^n \tag{2}$$

where:
- I = a shape factor = 0.2
- β/N_β = a creep constant β, and a relative creep stiffness parameter, N_β, which can be combined = 10^{-8} years^{-1}kPa^{-n} for ice-rich soil at -5°C
- n = a creep constant = 3

The way PILATEF handles this information is as follows. The total displacement, y, is split into an 'elastic' component, y_e, and a 'creep' component, y_c. The distributed load in each layer becomes:

$$P = f(y - y_c) \tag{3}$$

and Equation (1) becomes:

$$E_p I_p \frac{d^4y}{dz^4} + E_i \cdot y + P_{oi} - E_i y_c = 0 \tag{4}$$

where E_i = E, is constant, and $P_{oi} = 0$ if linear elasticity is assumed (the common assumption for visco-elastic models for ice or ice-rich permafrost), and y_c is the creep displacement of the mid-point of the layer.

The creep term, $E.y_c$, is treated as a simple second-member term. That is to say that $E.y_c$ does not change the stiffness of the system. At each time t, the value of y_c is obtained from:

$$y_c = \int_0^t \dot{y}\,dt = \int_0^t g(p,t)dt \tag{5}$$

The function g is time-dependent in the case of primary creep and time-independent in the case of secondary creep. For the law considered by Neukirchner and Nixon:

$$g(p) = I * B/2 * \beta/N_\beta * p^n \tag{6}$$

Discretization with time is done in the following way:

$$y_c = \sum_{i=1}^{n} g\left(\frac{p(t_{i-1}) + p(t_{i-1} + \Delta t_i)}{2}\right)\Delta t_i \tag{7}$$

This means that the creep rate is determined in the middle of the time step. An iterative procedure is required if p varies, that is to say when there is load redistribution.

This time integration scheme was chosen because it allows longer time steps (with a concomitant reduction in computer time) and an increase in precision.

The thickness of the layers, Δz, is chosen bearing in mind that 1) $E.y_c$ is calculated at the mid-height of the layer, and 2) $E.y_c$ must represent the whole layer. In the present example, 20 layers were used.

A comparison between the PILATEF results and the Neukirchner and Nixon results is made in Figure 7. The fit is excellent.

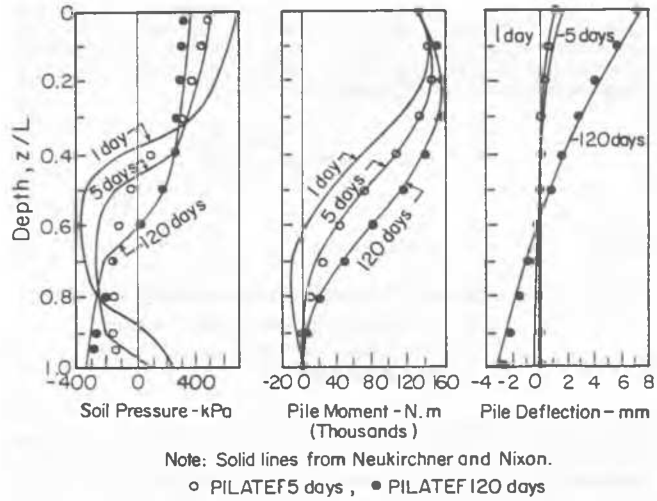

Fig.7. PILATEF versus Neukirchner and Nixon numerical results

CONCLUSION

The computer program PILATE can be used for frozen soil, that is to say the program can consider creep by making the soil P,y curves time dependent. PILATEF represents the soil by means of a Maxwell model. The spring in the model is the non-linear P,y curve for the short term behaviour of the frozen soil - say, for the first day after loading. The dashpot can represent either primary or secondary creep.

ACKNOWLEDGEMENTS

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