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Displacement of piles under dynamic loads in frozen soils

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The effect of a small alternating load superimposed on a static load on the displacement rate of piles in a frozen sand and a frozen natural soil has been studied at −2.2°C. An alternating stress as small as 3 per cent of the static stress caused an increase in rate of displacement in the region where the displacement rate was decreasing with time, and doubled the steady-state displacement rate of both wood and concrete piles. Under dynamic loads the design life of pile foundations calculated on the basis of allowable settlement will be reduced or, alternatively, the bearing capacity of piles for dynamic loads will be smaller than the bearing capacity for static loads.

On a étudié l'effet d'une petite charge périodique ajoutée à une charge statique sur la vitesse de déplacement de pieux dans un sable gelé et dans un sol naturel gelé, à une température de −2,2°C. Une contrainte périodique représentant aussi peu que 3 pour cent de la contrainte statique a fait augmenter la vitesse de déplacement dans la région où elle diminuait en fonction du temps et a fait doubler la vitesse de déplacement en régime permanent pour des pieux en acier et des pieux en béton. La durée de vie de fondations en pieux soumis à des charges périodiques, calculée d'après le tassement admissible, est réduite, c'est-à-dire que la capacité portante de pieux soumis à des charges périodiques est plus faible que celle de pieux soumis à des charges statiques.

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Introduction

Piles supporting buildings in permafrost areas are subjected to slow settlement under the loads imposed on them. Bearing capacity is usually calculated from the adfreeze strength between a pile and frozen soil, determined from long- and short-term creep tests under static loads. In field situations an alternating load is often superimposed on the static load due, for example, to vibrating machinery (turbines, power generators, and compressors) or travelling loads (cranes and fork lift trucks). Shock and transient vibrations are also caused by machinery (stamps, forges, pile drivers, and heavy vehicles), nearby blasting operations, and earthquakes.

In many viscoelastic materials such as metals, polymers, frozen soils, and ice, it has been observed that the steady-state creep rate is enhanced by a superimposed alternating stress. This indicates that an alternating load superimposed on a static load can increase the rate of settlement of piles in frozen soils and hence lower their bearing capacity below the values calculated from static load alone. This effect must be taken into consideration in design.

The effects of alternating stresses on the strength and dynamic properties of ice and frozen soils have already been studied to some extent (Czajkowski and Vinson 1980; Kaplar 1969; Stevens 1975; Vinson and Chaichanavong 1978; Vinson *et al.* 1978). No detailed studies, however, have been reported on the effect of alternating loads on the rate of settlement of piles in frozen soils.

Laboratory studies have been undertaken at DBR/NRCC to provide information on the behaviour of piles in frozen soils under various conditions of load and temperature. Results of long-term creep tests under static loads were reported earlier (Parameswaran 1979, 1980). In this paper the author describes the equipment and method used in studying the effect of a superimposed vibratory load on the rate of settlement of small-scale model piles, and gives some results.

Equipment and Test Procedure

A schematic diagram represents the apparatus used for the study of creep under a superimposed alternating load (Figure 1). Each pile (A), made either of wood, concrete, or steel pipe and each having a smooth surface, a diameter of 76.2 mm and a length of 305 mm, was embedded in frozen sand or soil. The sand used was Ottawa sand, ASTM C-109, with average grain diameter of 0.2 to 0.6 mm, mixed with 14 per cent water by weight. A natural silty sandy soil with average grain diameter of 0.02 to 0.1 mm, containing about 10 per cent clay and mixed with 20 per cent water by weight, was also used. Either sand or soil was compacted around the pile to a height of 190 mm inside a Plexiglas box (305 × 305 mm^2 inside dimensions) and allowed to freeze inside a cold room at −2.2 ± 0.1°C. Following complete freezing, which took a few days, the box was transferred to the creep frame in the cold room and the pile then subjected to a static load by weights (W). An alternating load of magnitude equal to about 3 per cent of the static load was superimposed on the pile by an electrodynamic shaker (E). A load cell (C), BLH type U3L1, with capacity 45.45 kN and capable of high frequency response, monitored the static and dynamic loads. D is a direct-current differential transducer

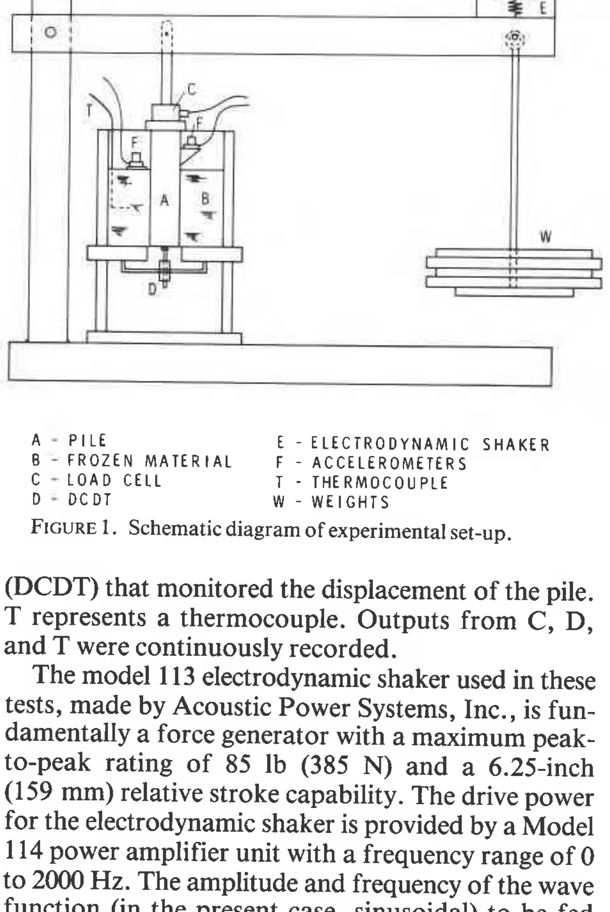

FIGURE 1. Schematic diagram of experimental set-up.

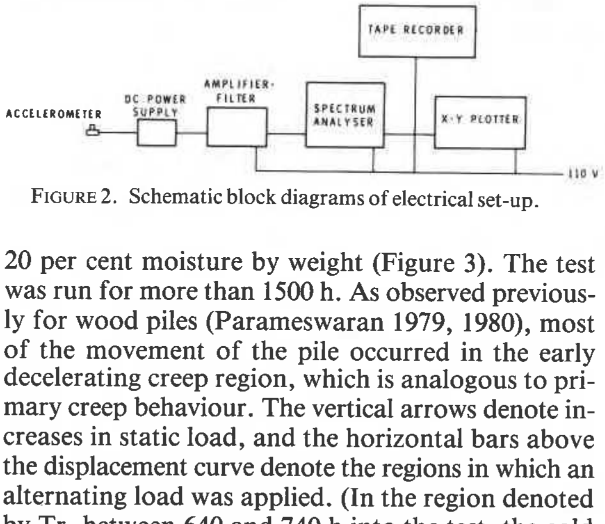

FIGURE 2. Schematic block diagrams of electrical set-up.

(DCDT) that monitored the displacement of the pile. T represents a thermocouple. Outputs from C, D, and T were continuously recorded.

The model 113 electrodynamic shaker used in these tests, made by Acoustic Power Systems, Inc., is fundamentally a force generator with a maximum peak-to-peak rating of 85 lb (385 N) and a 6.25-inch (159 mm) relative stroke capability. The drive power for the electrodynamic shaker is provided by a Model 114 power amplifier unit with a frequency range of 0 to 2000 Hz. The amplitude and frequency of the wave function (in the present case, sinusoidal) to be fed into the shaker is controlled by a Wavetek Model 182 function generator with a frequency range of 2 mHz to 2 MHz. The frequency can be continuously varied in this range. The frequency of loading used in the present series of experiments was 10 Hz. The output can be either 2 or 20 V peak-to-peak, with continuous amplitude control.

In some experiments a pair of accelerometers (F) were used to monitor the amplitudes and frequencies of vibration of the pile and the top of the frozen soil. The outputs from the accelerometers were fed through an amplifier-filter to a spectrum analyser and an *x-y* plotter. Schematic block diagrams indicate the electrical set-up (Figure 2).

Results and Discussions

Displacement was plotted against time for an uncoated wood pile in frozen natural soil containing 20 per cent moisture by weight (Figure 3). The test was run for more than 1500 h. As observed previously for wood piles (Parameswaran 1979, 1980), most of the movement of the pile occurred in the early decelerating creep region, which is analogous to primary creep behaviour. The vertical arrows denote increases in static load, and the horizontal bars above the displacement curve denote the regions in which an alternating load was applied. (In the region denoted by Tr, between 640 and 740 h into the test, the cold room malfunctioned and the DCDT showed erratic displacements.) The stress at the pile–soil interface resulting from static load alone is shown in Figure 3. The alternating load, as measured by the load cell, was 25.4 kg peak-to-peak, corresponding to an alternating stress of 5.5 kPa at the pile–soil interface. This amounts to 2.81 per cent of the static stress at the lowest load and 1.74 per cent at the highest static load.

Increasing rate of displacement due to the alternating stress is evident (*see* Figure 3), especially in regions 5, 7, and 9 where the displacement rate was

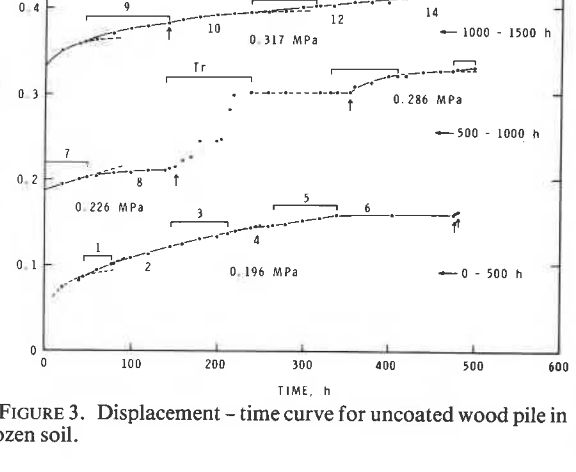

FIGURE 3. Displacement – time curve for uncoated wood pile in frozen soil.

TABLE 1. Displacement rates for a wood pile in frozen soil, with and without superimposed alternating stress

Without Alternating Stress			With Alternating Stress		
Region	Period (h)	Displacement rate (mm/min)	Region	Period (h)	Displacement rate (mm/min)
			(11)	1240–1315	1.78×10^{-6}
(12)	1315–1360	7.41×10^{-7}			
			(13)	1360–1416	1.49×10^{-6}
(14)	1420–1480	5.56×10^{-7}			
			(15)	1480–1533	2.20×10^{-6}

decreasing continuously, and in regions 11, 13, and 15 where the displacement rate was constant under static load. Since the steady-state displacement rates are the ones that are of interest in design calculations, the effect of an alternating stress on these rates is considered. Displacement rates calculated in the steady-state region with and without superimposed alternating stress are shown in Table 1. The displacement rate with superimposed alternating load is about twice that under static load alone; between regions 14 and 15 the rate increased by a factor of 4 when alternating stress was applied.

The displacement–time curve was plotted for an uncoated B.C. fir pile in Ottawa quartz sand containing 14 per cent moisture by weight (Figure 4). The test was carried out for 600 h; stress at the pile–soil interface from static loads before and after the load increment were 0.238 and 0.270 MPa, respectively. The alternating load imposed an additional stress of 5.5 kPa (peak-to-peak), corresponding to 2.31 and 2.04 per cent, respectively, of the static stresses. The displacement rate of the pile decreased continuously throughout the test. Superimposition of the alternating stress, however, caused an increase in displacement rate as shown in regions A, B, and C.

The displacement–time curve was also plotted for a concrete pile in frozen natural silty/sandy soil containing 20 per cent moisture by weight (Figure 5). The displacement rate is almost constant from 320 h onwards. The effect of an alternating stress is clear. Static stress at the pile–soil interface during the steady displacement rate regime was 0.179 MPa. The superimposed alternating stress (peak-to-peak) was 5.5 kPa, which amounted to 3.07 per cent of the static stress.

The region beyond 300 h is expanded in Figure 6; the displacement rates in regions 1 to 7, with and without alternating stress, were calculated (Table 2). It may be seen that even a small alternating stress of 3 per cent of the static stress causes a pile displacement rate that is twice that under static stress alone.

After 800 h of test a flat Fourier spectrum with frequencies between 0 and 50 Hz was fed to the shaker from the random noise output of a spectrum analyser. When the responses of the pile and the soil were monitored by two accelerometers (*see* F in Figure 1), it was found that the relative amplitude of displacement between pile and soil was a maximum at a fre-

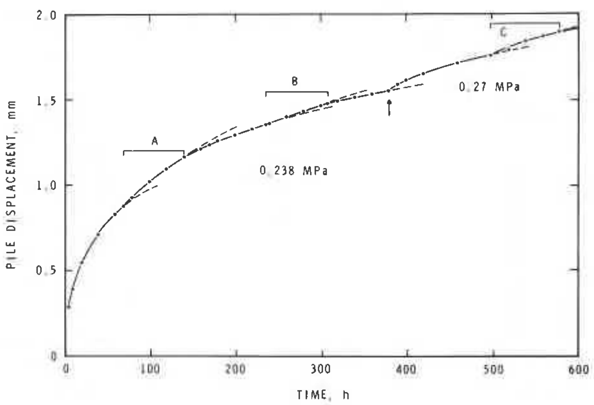

FIGURE 4. Displacement – time curve for an uncoated wood pile in frozen sand.

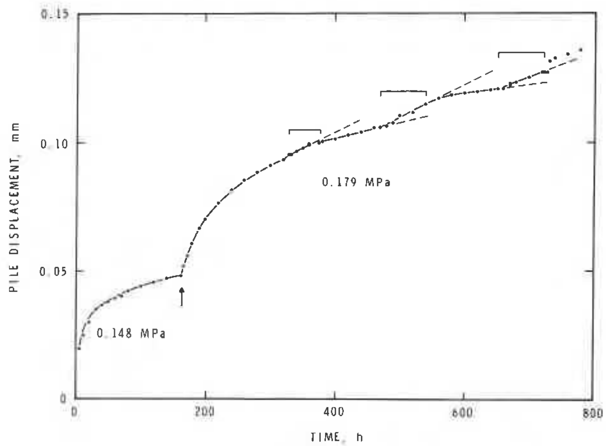

FIGURE 5. Displacement – time curve for concrete pile in frozen soil.

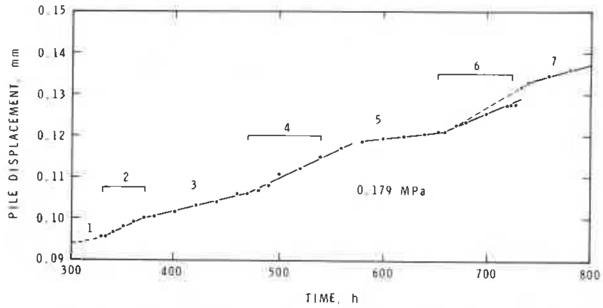

FIGURE 6. Displacement – time curve for concrete pile in frozen soil, region beyond 300 h expanded.

quency of 8.72 Hz. This indicates that for this particular set-up (a concrete pile in frozen silty/sandy soil) 8.72 Hz is the critical frequency at which the superimposed alternating load causes the maximum increase in displacement rate. It should be emphasized, however, that the critical frequency is typical for each test set-up, and that the critical frequencies for full-scale piles embedded in permafrost may be entirely different from those determined in the laboratory for small-scale model piles.

Implications for Design

In practice, pile foundations are designed to withstand the static load of the superstructure with an allowable settlement of, say, 1 inch (25.4 mm) in 25 years. This corresponds to a steady-state displacement rate of about 2×10^{-6} mm/min. If the alternating stress doubles the displacement rate, the allowable settlement is attained in half the time, i.e., in 12.5 years. To reduce the displacement rate to the allowable value, the static stress along the pile–soil interface must be reduced. Earlier the author reported (Parameswaran 1979) that the displacement rate $\dot{\ell}$ can be related to the stress along the pile–soil interface τ by an empirical equation of the type:

[1] $\tau \alpha (\dot{\ell})^m$

or

[2] $\dot{\ell} \alpha (\tau)^n$

where $n = \dfrac{1}{m}$.

The value of the exponent n was found to be between 6.7 and 9.1 for various piles in frozen sand. From pile pull-out tests carried out in the field in permafrost areas in Gillam and Thompson, Manitoba, Johnston and Ladanyi (1972) found values for n of 8.05 and 7.50.

If $\dot{\ell}_1$ is the displacement rate under a static stress τ_1 with a small superimposed alternating stress, and $\dot{\ell}_2$ ($= \dot{\ell}_1/2$) is the allowable displacement rate during the design life of the structure, the stress τ_2 corresponding to $\dot{\ell}_2$ can be determined from equation 1:

[3] $(\tau_2/\tau_1) = (\dot{\ell}_2/\dot{\ell}_1)^m = (1/2)^m$.

Using an average value of $n = 8$ in equation 2 or $m = 1/8$ in equation 1, from equation 3

[4] $\tau_2 = 0.917\,\tau_1$.

Thus, in the present experimental set-up, the allowable stress under dynamic loads is about 8.3 per cent less than that under static loads alone. If the displacement rate under dynamic loads is increased by a factor of 4, as was observed in the steady displacement rate region for wood and concrete piles, it will be necessary to decrease the stress by about 16 per cent to maintain the same rate as for static load.

Conclusions

An alternating stress, having a frequency of 10 Hz, superimposed on a static stress increases the rate of settlement of piles in frozen soils tested at −2.2°C in the regions in which the displacement rate continuously decreases with time (analogous to primary

TABLE 2. Displacement rates for a concrete pile in frozen soil, with and without alternating stress

Without Alternating Stress			With Alternating Stress		
Region	Period (h)	Displacement rate (mm/min)	Region	Period (h)	Displacement rate (mm/min)
(1)		8.33×10^{-7}			
			(2)	328–370	1.98×10^{-6}
(3)	370–470	1.0×10^{-6}			
			(4)	470–560	2.04×10^{-6}
(5)	580–660	4.58×10^{-7}			
			(6)	660–730	1.83×10^{-6}
(7)	740–800	1.11×10^{-6}			

creep in materials) as well as in the regions where the displacement rate is constant (analogous to steady-state or secondary creep). An alternating stress as small as 3 per cent of the static stress causes a doubling of the displacement rate of uncoated wood and concrete piles in frozen sand and soils.

In usual design practice the displacement of pile foundations is limited to an allowable value (say, 1 in. in 25 years). As alternating stresses increase the displacement rate, their effect must also be taken into consideration in determining the load per pile to ensure that the allowable displacement will not be exceeded.

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References

Czajkowski, R.L. and Vinson, T.S. 1980. Dynamic properties of frozen silt under cyclic loading. J. Geotech. Eng. Div., ASCE, vol. 106, no. GT 9, pp. 963–980.

Johnston, G.H. and Ladanyi, B. 1972. Field tests of grouted rod anchors in permafrost. Can. Geotech. J., vol. 11, no. 2, pp. 176-194.

Kaplar, C.W. 1969. Laboratory determination of dynamic modulii of frozen soils and of ice. U.S. Army, Cold Regions Res. Eng. Lab., Research Report 163, 48 p.

Parameswaran, V.R. 1979. Creep of model piles in frozen soil. Can. Geotech. J., vol. 16, no. 1, pp. 69–77.

Parameswaran, V.R. 1980. Adfreeze strength and creep of frozen soils measured by model pile tests. *In:* Proc. 2nd Int. Symp. Ground Freezing, Trondheim, Norway, pp. 157–164.

Stevens, H.W. 1975. The response of frozen soils to vibratory loads. U.S. Army, Cold Regions Res. Eng. Lab., Technical Report 265, 103 p.

Vinson, T.S. and Chaichanavong, T. 1978. Dynamic behaviour of ice under cyclic axial loading. J. Geotech. Eng. Div., ASCE., vol. 104, no. GT 7, pp. 801–814.

Vinson, T.S., Chaichanavong, T., and Czajkowski, R.L. 1978. Behaviour of frozen clay under cyclic axial loading. J. Geotech. Eng. Div., ASCE, vol. 104, no. GT 7, pp. 779–800.