Terrestrial photogrammetry for measuring pile movements

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Terrestrial photogrammetry was used to monitor movements of previously driven piles during the installation of 116 concrete piles in sensitive marine clay. The technique and the equipment used are described and the sources of error discussed.

La photogrammétrie terrestre a été utilisée pour mesurer, durant la mise en place de 116 pieux de béton dans l'argile sensible, les mouvements de pieux déjà battus. La technique et l'équipement utilisés sont décrits et les sources d'erreur sont discutées.

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Introduction

This note describes photogrammetry, a technique by which geometrical information is derived from photographs. Although its best known application is in topographic mapping, it is being applied to an increasing extent to a variety of scientific and engineering measurements such as monitoring engineering structures affected by pile driving operations. For instance, photogrammetry was used to study movements of model piles affected by the installation of additional piles (Massarsch 1974) and to measure movements induced in a stone masonry wall because of pile driving at an adjacent site (Massarsch 1975). The effects produced on adjacent pile foundations by driving a large group of piles in marine clay have been studied using this technique (Bozozuk *et al.* 1978).

Terrestrial Photogrammetry

Two camera stations were established 10.0 m apart on stable ground about 14 m outside the piling area. The cameras were supported by scaffolds 3.7 m above the original ground surface in order to photograph as many piles as possible. Six control points consisting of painted crosses, well defined joints, and bolts (points 3 and 6, 1 and 4, and 2 and 5 respectively in Fig. 1) were established on an existing silo immediately behind the construction area. The control points and camera stations were used to define the reference coordinate system and provide information on the accuracy of the photogrammetric measurements. Their X-, Y-, and Z-coordinates were determined at the start of construction by surveying with a T2 theodolite. The X-direction of the coordinate system was parallel to the camera base with the coordinates increasing from the left- to the right-hand camera station. The Y-axis was horizontal and normal to the base with the coordinates increasing from the cameras to the piling area, and the positive Z-axis pointed vertically upwards.

A photographic target consisting of a white cross on a black background and identified by a number was painted on each pile after it was driven (Fig. 1). The line thickness forming the targets was about 25 mm.

A Wild P-31 camera with a 100 mm focal length lens and an image format of 117 mm × 83 mm was used alternatively at each camera station. It was aimed at the centre of the piling area in order to cover the entire area of interest on the photographs. This resulted in a convergence angle ϕ of about 15° between the two camera axes. The photographic exposures were made on 3.3 mm thick aerographic plates at 1 week intervals for 5 weeks during the pile driving operations.

The concrete piles installed in the 2.5 m deep excavation projected about 5 m above the floor. In many cases the piles in the foreground obscured targets on other piles. After all piles had been driven, only 30% of the total and 18% of those driven the previous week could be stereoscopically

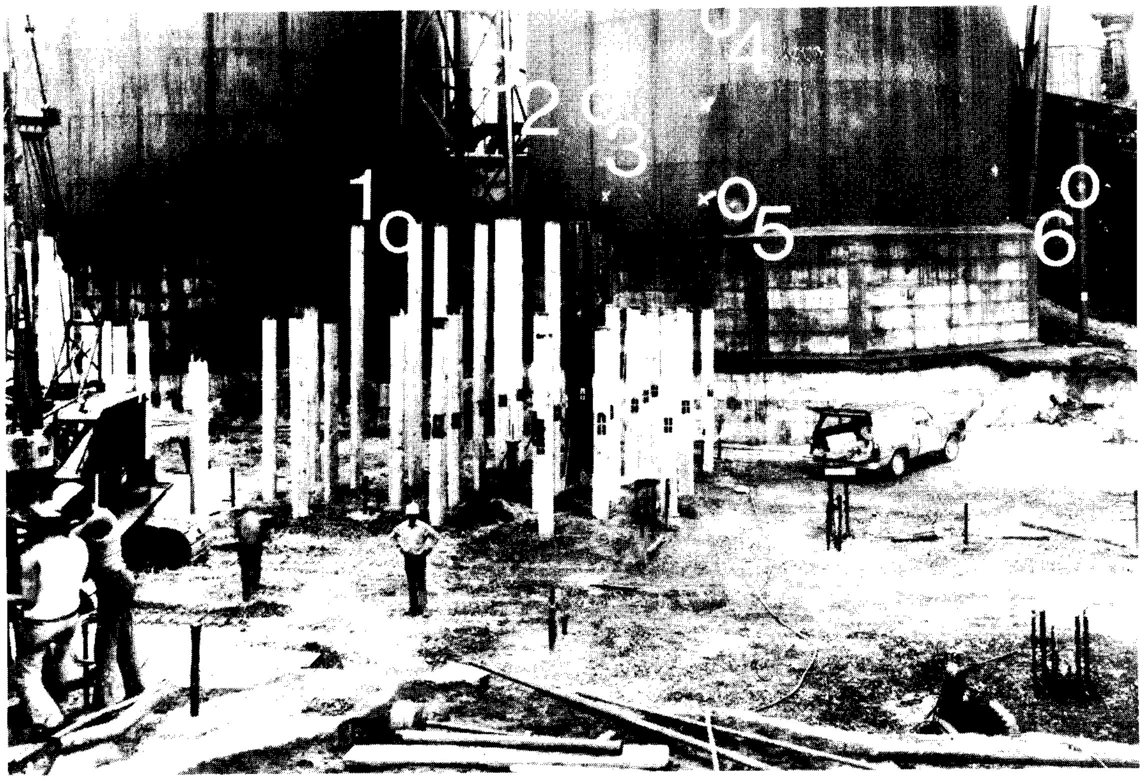

FIG. 1. Control points (1–6) and targets (crosses) for terrestrial photogrammetric measurements. (Photo: M. C. van Wijk, Division of Physics, National Research Council of Canada.)

interpreted on the photographs. These percentages, however, were considered sufficient to assess the overall movements of the piles.

A Zeiss Jena Stereocomparator 1818, equipped with an Instronics Gradicon readout system, was employed for the photogrammetric analysis using the original negative plates. Photo coordinates were measured for the following points, which were automatically recorded on magnetic tape: (1) fiducial marks, for defining the camera coordinate system; (2) points near the edges of the stereo overlap, required for relative orientation; (3) six control points, used for absolute orientation; and (4) pile targets.

The photo coordinates were transformed to coordinates corresponding to 'normal case' photographs, where the camera axes are parallel to each other and normal to the base, by means of the following equations:

$$x' = f\frac{f\sin\phi + x\cos\phi}{f\cos\phi - x\sin\phi} \qquad [1]$$
$$y' = \frac{fy}{f\cos\phi - x\sin\phi}$$

where x, y = actual coordinates measured in the convergent photographs; x', y' = transformed coordinates, corresponding with 'normal case' photography; ϕ = convergence angle; and f = focal length of the camera.

The same convergence angle, measured to an accuracy of 1 or 2°, was used for all photographs taken during the pile driving operations. The precise camera orientation and the spatial target coordinates were computed from the transformed coordinates, using the computer program, for relative orientation of near-normal case photographs (Schut 1973). The spatial coordinates were then transformed to the control coordinate system by means of the XYZ transformation program (Schut 1967).

Pile movements were determined from the differences of the X-, Y-, and Z-coordinates, which were derived from photogrammetric surveys obtained at different stages of the pile driving program. To illustrate these measurements, Fig. 2 shows the magnitude and direction of horizontal movements observed on installed piles as piling was subsequently completed in each designated zone.

The standard error of the photogrammetric

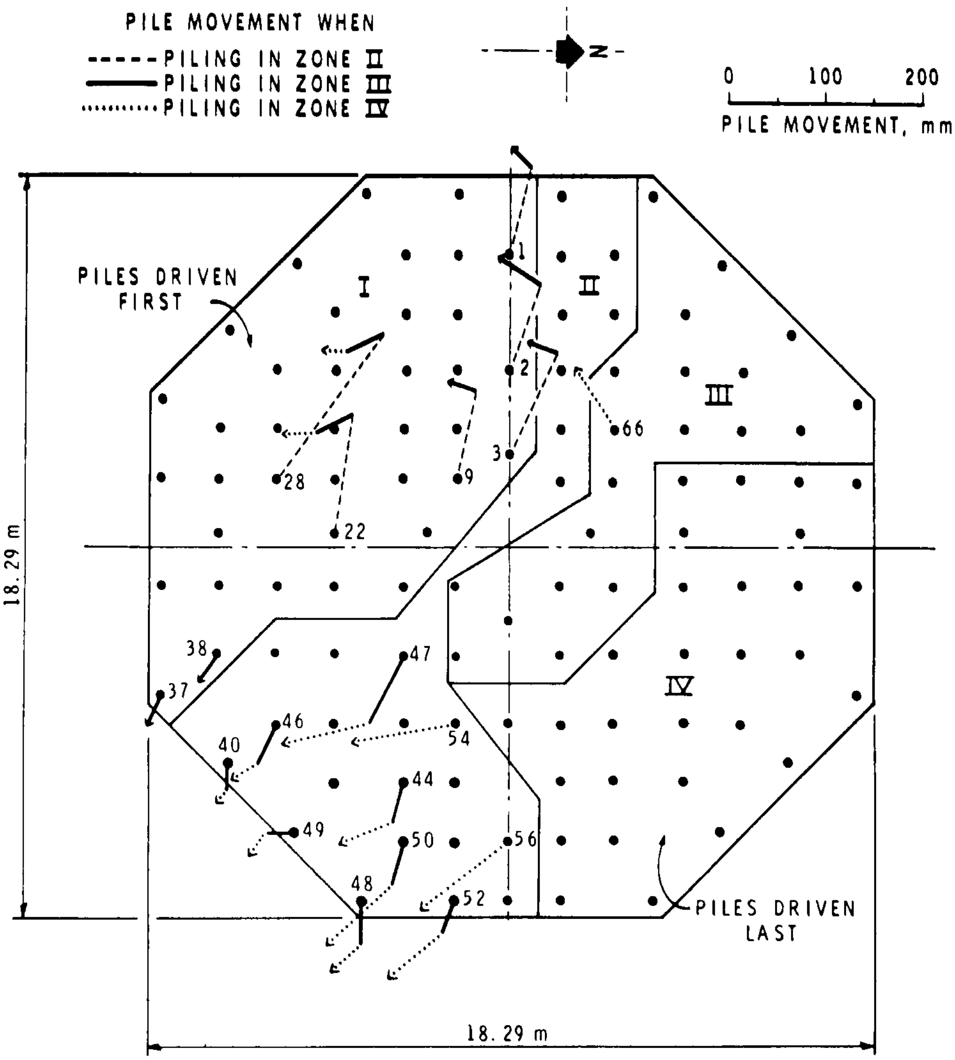

FIG. 2. Photogrammetric measurements of horizontal pile movements due to pile driving in successive zones.

coordinates was obtained by comparing the photogrammetrically determined coordinates of the control points and the camera stations with corresponding values from field surveys, using the equation:

$$m = ((\Delta\Delta)/n)^{\frac{1}{2}} \qquad [2]$$

where m = standard error in photogrammetric coordinates, Δ = differences between photogrammetric coordinates and those obtained from field surveys, and n = number of points.

The following coordinate standard errors were calculated by analysing the stereo pairs of photographs taken at five different times during the project: $m_x = 11$ mm; $m_y = 14$ mm; and $m_z = 4$ mm. Since the piles were located between the control points and the camera stations, the standard errors of the pile coordinates are within the above values. Considering, however, that the movements of the piles are calculated from the change in their coordinates, the standard errors then become $\sqrt{2}$ times the above coordinate standard errors or: $m_{\Delta x} = 15$ mm; $m_{\Delta y} = 20$ mm; and $m_{\Delta z} = 5$ mm.

Summary and Conclusions

Terrestrial photogrammetry proved to be a useful technique for recording the movements of driven piles. Because the piles projected about 5 m above the floor of the excavation, the cameras were elevated about 3.7 m above the original ground surface on scaffolds in order to photograph as many piles as possible. Thus the movements of 30% of the 116 piles driven on the site were recorded. The accuracy of the measured movements was

$m_{\Delta x} = 15$ mm, $m_{\Delta y} = 20$ mm, and $m_{\Delta z} = 5$ mm with respect to an orthogonal coordinate system. The technique has many advantages for field use. The photographs can be obtained quickly and if carefully planned, many observations can be easily obtained as construction progresses, without interfering with construction activities.

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BOZOZUK, M., FELLENIUS, B. H., and SAMSON, L. 1978. Soil disturbance from pile driving in sensitive clay. Canadian Geotechnical Journal, **15**(3), pp. 346–361.

MASSARSCH, K. R. 1974. Jordundanträngning vid pålslagning. Resultat av model försök. Royal Swedish Academy of Engineering Sciences, Commission on Pile Research, Report No. 43. (In Swedish.)

——— 1975. Deformationsmätningar vid slagning av pålar. Resultat av stereofotogrammetriska mätningar. Royal Swedish Academy of Engineering Sciences, Commission on Pile Research, Report No. 49. (In Swedish.)

SCHUT, G. H. 1967. Block adjustment by polynomial transformations. Photogrammetric Engineering, **33**(9), pp. 1042–1053.

——— 1973. An introduction to analytical strip triangulation, with a FORTRAN program. Revised edition. National Research Council of Canada, Division of Physics, (NRC 13148), P-PR 44. 82 p.