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FLUID SETTLEMENT PROFILER: ERROR ANALYSIS FOR INSTALLATION AT BLACKSTRAP, SASKATCHEWAN

by S.S. Tao

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Fluid settlement profiler: error analysis for installation at Blackstrap, Saskatchewan¹

S. S. TAO

Prairie Regional Station, Division of Building Research, National Research Council of Canada, Saskatoon, Sask., Canada S7N 0W9

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The accuracy of settlement measurement at the base of a man-made ski hill, using a fluid settlement profiler, has been analysed. Owing to the great length of the installation, changes in ambient temperature and barometric pressure contributed most to overall error. Other factors, such as probe positioning, level reference to benchmark, and transducer system reproducibility also affected accuracy. At the centre of the settlement profile the possible error was found to be 11.2 mm or 0.87% of the observed settlement.

On a analysé la précision des mesures de tassement faites à l'aide d'un appareil hydraulique de mesure du profil de tassement à la base d'une colline artificielle. Du fait de la grande longueur de l'appareil les variations de température ambiante et de pression barométrique ont constitué la majeure partie de l'erreur totale. D'autres facteurs, tels que la localisation de la sonde, la relation au niveau de référence et la répétitivité du système de capteur de pression ont également affecté la précision. Au centre du profil de tassement on a établi que l'erreur possible était de 11.2 mm ou 0.87% du tassement observé.

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Introduction

The fluid settlement profiler was first used by Bozozuk (1969). The method has since been applied at the Prairie Regional Station as the only means of measuring the settlement of two more structures. The first case measured settlement under the Ski Hill at Blackstrap Provincial Park, Saskatchewan, a conical fill having a base diameter of 176.8 m (580 ft), installed in 1969. The second case measured settlement under a 61 m (200 ft) diameter oil storage tank in Edmonton, Alberta, constructed in 1970. This note is prepared for those who may be interested in sharing the results of this particular area. Owing to variability of the installations, mainly to length, the accuracy quoted is for the Blackstrap case only.

Brief Description of the Fluid Settlement Profiler

A fluid settlement profiler basically consists of two major components: a semi-rigid, 2.54 cm (1 in.) diameter polyvinyl chloride (PVC) pipe filled with fluid, and a high-sensitivity pressure transducer housed in a torpedo that can be pulled through the PVC pipe. The pipe is buried under the foundation of the structure to be studied and will follow the movement of the soil as settlement takes place. A mixture of 60% ethylene glycol and 40% water (referred to

as fluid hereafter) is poured into the pipe until it is completely filled. The pressure transducer is pulled through the fluid-filled pipe for settlement measurements. Pressure readings are obtained for desired points periodically. The elevation of a point can be calculated by

$$[1] \quad H_p = H_{BM} + H_L - P_i/\gamma$$

where H_{BM} = elevation of the reference benchmark; H_L = height of liquid surface in reservoir from reference benchmark; γ = unit weight of fluid; and P_i = pressure reading for the point from the pressure transducer. Figure 1 is a schematic diagram showing the installation at Blackstrap, Saskatchewan.

Identified Sources of Error

As indicated by [1], error can be introduced from two major sources. One is the surveying error incurred when relating the fluid-level elevation to the benchmark elevation. The second comes from the last term in the equation and is related to the unstable ambience to which the transducer system is subjected, namely, the variations in temperature, barometric pressure, and fluid density. To a certain degree the transducer system is affected by these changing factors, and inaccuracy is introduced in converting transducer readings to fluid heads. Minor errors may also originate from torpedo pulling, which causes fluid movement and inaccurate torpedo

¹This paper is a contribution from the Division of Building Research, National Research Council of Canada and is published with the approval of the Director of the Division.

FIG. 1. Schematic diagram of fluid settlement profiler at Blackstrap, Saskatchewan.

positioning. At Blackstrap the combined error from the second source was much greater than that from the first source.

In optical level surveying, the limit of accuracy can be easily defined. According to Davis and Foote (1940), for precise leveling

$$\delta = 0.02(D^{1/2})$$

where δ is the possible error in feet and D is a number equal to the length of the circuit in miles. For the Blackstrap case, the permanent benchmark is 115.8 m (380 ft) from the reference benchmark in the terminal hut at the east side of the Ski Hill. The predicted error due to surveying is 1.6 mm (0.064 in.).

Surveying from the permanent benchmark to the reference benchmark was carried out with a Wild N2 metric level read to the nearest 0.01 mm. Statistics of the closure errors for all such surveys gave an error of 0.7 mm at the 68% confidence level. A metre stick was used to determine the elevation of the fluid in the feed-end reservoir with respect to the elevation of the reference benchmark and was read to the nearest millimetre. This could add a further 0.5 mm error to the $H_{BM} + H_L$ elevation, thus bringing the possible error for the reference liquid level to 1.2 mm.

A field installation is always under the influence of changing temperature. Part of the fluid in the pipe may go through a wide range of temperature change in a year. As demonstrated by Fig. 2, the density of the fluid can vary as much as 1.5% when the temperature drops from 30 to 0°C. Although for a deeply buried pipe the fluid may be kept at a fairly constant temperature, the situation is different in the sections within 6 m of the ends where the fluid temperature may vary considerably. For practical reasons, changes of fluid density with temperature cannot be easily considered when reducing pressure readings to

pressure heads. It is therefore assumed that for the full length of the pipe fluid temperature is always at 4.4°C (40°F).

This assumption is fair except in dealing with the 6 m lengths at each end, where fluid temperatures change in yearly cycles. In 1977, a year of moderate climate, three sets of temperature readings were taken along the pipe for a distance of 30 m inward. The observed temperature profiles have been plotted in Fig. 3, which shows that at the end, temperature variation could be as great as 20°C, but that at 6 m from the end, it was only 3°C.

When the fluid temperature is higher than 4.4°C (40°F), fluid density is lower than the assumed value and the elevations of a point will be overestimated. At Blackstrap, a point 6 m from the end lies approximately 1.2 m below the liquid surface and the first 0.5 m vertical decline is in air. Using 12 and 2°C to represent summer and winter temperatures of the 1.2 m fluid column, a point 6 m from the end may

FIG. 2. Temperature versus density (60% ethylene glycol - 40% water solution).

FIG. 3. Temperature profiles in fluid-filled pipe.

have its elevation overestimated by 4.4 mm (0.17 in.) in summer and underestimated by 2.0 mm (0.08 in.) in winter.

Barometric pressure on the fluid surface varies from time to time. The variation takes place in two ways. One is the moderate and gradual change during the day. This kind of variation is believed to have very little effect on the reading obtained with the differential pressure transducer since the transducer is vented through the jacket of the conductor cable to the atmosphere. The adequacy of ventilation was checked in the laboratory. It was found that an artificially induced pressure increase can be equalized in less than 15 min. Another possible source of pressure variation is wind. The windward terminal would experience a pressure higher than that of the leeward terminal. The differential pressure changes in an unpredictable manner. There has, however, been no surging of fluid level observed even with a pressure difference of 15 mm fluid head. This is attributed to the viscous and frictional characteristics of the fluid in the PVC pipe, and hence the pressure difference is assumed to be distributed along the pipe with a uniform gradient, i.e., zero at the feed end and the full amount at the reel end.

Stationing of the torpedo is done by referencing to marks on the conductor cable jacket as the torpedo is pulled through the PVC pipe. Occasionally, when the torpedo is going around bends, the cable may have to be guided at the feed end so as to reduce the resistance to pulling. There is no other precaution taken to ensure the accurate positioning of the torpedo. It was estimated for the worst case that the torpedo may be located 150 mm (6 in.) away from the desired position because of a lack of consistent cable tension, air temperature effects on the cable

before it entered the fluid, and stretching (178 mm or 7 in.) of the PVC pipe due to soil settlement. If the torpedo is 150 mm away from its expected position and in a portion of the pipe that has a slope of 2° from the horizontal, the error in elevation will be

$$150 \text{ mm} \times \sin 2^\circ = 5.2 \text{ mm}$$

The probable error in the near-horizontal central portion of the centre of the casing is thought to be much smaller and may in reality be insignificant. The stationing error may be most significant near the reel-end reservoir. In hindsight, it seems reasonable that calculations could have been done prior to each new set of readings to select appropriate stationings to ensure that elevations were being measured at the same plan locations. Laying the pipe with minimum initial slope or perhaps with an initial camber to compensate for later deflections could also reduce this source of error.

In pulling the torpedo through the pipe, part of the fluid is displaced by the cable coming into the pipe. Fluid also moves with the advancing probe. The up and down surges and the duration of the pendulation have been a concern. Random readings taken within 10 min of the advancement of the torpedo indicated a variation equivalent to 3.5 mm fluid head in excess of the transducer system error. This was thought to be attributable to the surging effect. Analysis of mass oscillation in buried pipe of the size used at Blackstrap, however, indicated that the magnitude of readings taken at or after 5 min was not significantly affected by the surge of the fluid.

The remaining source of error is within the pressure transducer system. Many types of transducer are available. The lowest pressure range satisfying the needs of the installation is the best. A 5 psid

FIG. 4. Voltage comparator for ESI bridge.

differential pressure transducer, Model PM131TC 5-350, made by Statham Instruments, has been used. It is read with a Model PORTAMATIC PVB300 bridge unit made by Electro Scientific Industries. To minimize the effect of unstable excitation voltage a tightly controlled power supply ($\pm 10 \mu\text{V}$) was devised. Instead of calibrating the pressure against the output voltage from the transducer, the pressures were correlated to the ratio of output voltage to excitation voltage. This was done by means of a voltage comparator (shown in Fig. 4). Lead-wire resistance is nullified by a six-wire arrangement. Using this readout system and the transducer, 156 laboratory observations showed that the transducer system has a reproducibility of 4.1 mm of fluid head at a 68% confidence level.

The probe has certain temperature-compensating capabilities. The manufacturer-quoted values for thermal zero shift are less than 0.01% of full scale per $^{\circ}\text{F}$ and the thermal sensitivity shift is less than 0.01% per $^{\circ}\text{F}$. Considering a 10°C (18°F) temperature change and a 3 m head, the combined transducer error resulting from the temperature change should be within 11.7 mm fluid head. In the laboratory the sensor error attributable to temperature change was found to be 5.6 mm fluid head for a temperature change of 20°C (36°F).

Summary

The sources of error have been identified for the Blackstrap installation. By estimating some parameters, possible error from each source is tabulated below.

TABLE 1.

Cause	Error value (mm of fluid head)
Probe positioning	5.2
Level survey to fluid surface	1.2
Barometric pressure difference at two ends	1.5
Fluid density change (summer)	4.4
Transducer system error	4.1
Transducer error due to temperature change ($0 - 20^{\circ}\text{C}$)	5.6

The simple summing of all items has little meaning, however, because a condition under which error of a certain source is enhanced the most would not cause the maximum error from other sources. Comparing data from two consecutive runs in 2 days with 29 stationing points in each run, the average discrepancy was found to be 16 mm.

The reliability of measurement at the centre of the pipe is probably the most interesting. For that particular point in the Blackstrap installation the following errors are probable.

TABLE 2.

Cause	Error value (mm of fluid head)
Probe position error	0.0
Level survey to fluid surface	1.2
Barometric pressure difference at two ends	7.5
Fluid density change (summer)	4.4
Transducer system error	4.1
Transducer system error due to temperature change (summer extreme)	5.6
Combined error (square root of sum of squares)	11.19

NOTE: the combined error, as compared with the measured settlement of 1281.9 mm (50.47 in.), is 0.87%.

In more recent installations, Bozozuk has installed a regular ground-movement gauge at a point beside the fluid pipe where there will be little temperature change, say 6 m from the end. Optical survey determines the actual movement of this gauge. The difference in elevation at this point, determined by the fluid settlement profiler and the ground-movement gauge, is the elevation correction for all inner points.

If the advancement of the torpedo does not disturb the fluid too much, a large portion of temperature error can be accounted for and better accuracy can be obtained.

Bozozuk, M. 1969. A fluid settlement gauge. *Canadian Geotechnical Journal*, 6(3), pp. 362-364.

Davis, R. E., and Foote, F. S. 1940. *Surveying, theory and practice*. 3rd ed. McGraw-Hill Book Co., New York, NY.