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IMPROVEMENTS IN INSTRUMENTATION OF STATIC PILE LOAD TEST

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ABSTRACT: The performance of pile load test has been improved by introducing electronic devices in order to automate data acquisition system. Shortcomings of previously used instruments such as load and displacement measuring devices and acquisition system (manual type) are enumerated showing the importance of modification. An inner load-cell assembled with an electronic transducer is used to measure error-free load transferred to pile directly. Two displacement transducers are used to replace displacement dial gauges so as to make the acquisition system computer-controlled. As a result of these modifications, pile load testing has been proved to easier, load and displacement measurements become more accurate and above all, physical involvement during a test gets reduced.

KEYWORDS: Load test, load cell, transducer, auto-control, data acquisition

INTRODUCTION

The need for piles under a foundation is self-evident. Load tests are carried on piles, however, to develop the design data, to establish the installation criteria, to verify the design and installation criteria, to confirm the required capacity of pile, or to verify the combination of some of these reasons. Load–test programs to develop design data, including the selection of the pile type, are conducted before the foundation is designed and often involve several pile types (i.e., geometry, configuration and material). Tests to verify or establish the installation criteria or to verify the design capacities are usually conducted just before the installation of production piles gets under way. Tests to confirm a pile capacity may be made at any time during the project. Piles may be tested individually or in-group.

Pile capacity can also be evaluated by utilising bore log of subsoil report (Bowles, 1996), or by other methods such as dynamic method (Goble, 1975), wave method (Bowles, 1996), etc. The former one is the most popular method, in which correlation between SPT values and the strength parameters are to be used for estimating pile capacity. Uncertainties and limitations are often associated with such correlation. On the other hand, important and/or high rise structures that often

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require deep foundation need pile performance be evaluated by full-scale pile load test in the site.

Since critical decisions are often made on the basis of load-test results, careful planning, reliable equipment and instrumentation, the proper set-up and conduct, and accurate recording and reporting of the data are essential. The results of pile load tests are applicable only to similar types of piles installed with the same equipment and methods as used for the test pile, or with comparable equipment and methods, and under essentially similar subsoil conditions.

The practice of instrumentation and data logging system during pile load test in Bangladesh, recent modification/improvement and their advantages over the prevailing technique are presented in this paper. Many researchers already used instrumented and advanced load-testing procedure. Bond et al. (1991) performed load test on laboratory instrumented pile (known as Imperial College Instrumented Piles). Lehane (1992) and Bond and Jardine (1995) extended the technology to full-scale experimental investigation of displacement piles in field.

EXISTING PRACTICE IN LOAD-TEST

Piles can be tested in compression (bearing), in tension (uplift), laterally, or under combined loading. Of them, compression test on a single is popular in Bangladesh. The details for conducting such tests are usually governed by ASTM D1143 (1989) and Bustumante (1982), which cover all aspects of pile load testing. Interpretation of the test results can be made using Davisson (1975), Kaniraj (1998) and many others. Current status of static pile load test in Bangladesh has been reported by Ansary et al. (1999).

Testing system includes test loads, load-transferring system, the reaction measuring devices and a data acquisition system. For bearing tests, loads can be applied directly to the test pile or pile group with objects of known weight. Or, they can be applied with a hydraulic-jack-ram acting against a suitable reaction such as a weighted-platform or a steel frame tied to the reaction piles or other types of ground anchors. If possible, the application of load with hydraulic jack is a usual practice. The platform, against which the jack-ram is acting, is loaded with sandbags. The surcharge is imposed based on the anticipated maximum load to be applied on the test pile. This load also includes the weight of test beams, girders and joists of platform and ram, base plate, etc. The loading system is calibrated for the complete jack-system (i.e., the ram, pump and pressure gauge inclusive) to an accuracy of at least 5%.

The reaction evaluation system consists of instrumentation for measuring pile head movements and magnitude of load transferred/mobilised to the pile. For bearing tests, at least two dial gauges are used, and they are mounted equidistantly on opposite sides of the pile from its center. The sensitivity of such a strain gauge is 0.1 mm, while readings up to 0.2 mm are sufficient for pile load testing (Fellenius, 1975 and Fuller, 1983). Gauges are mounted so as to measure movements at the sides of the pile near the butt in relation to an independent reference system. Gauges should not be mounted to bear on the test plate on the top of the pile unless the plate is welded to the pile, or instrumentation is provided to measure the movement of the plate in relation to the pile as test loads are applied. For accurate readings, dial gauge stems are aligned with the direction of the load and bear against a smooth surface such as glass or polished stainless steel.

Load of the weighed platform can be transferred to the test pile by using either of four procedures (Fellenius, 1975): slow maintained-load, the constant rate of penetration, the Swedish cycling and quick maintained-load tests. However, the procedure used in Bangladesh is derived from the methods described by ASTM D1143 (1989) (slow maintained-load type) and Bustumante (1982) (quick maintained type). Loads are applied in a series of steps, starting at about 1/8th of the maximum anticipated load but reducing progressively to a smaller increment as failure is approached. Each load is maintained for a minimum holding period unless the settlement rate ceases to 0.25 mm/hr or elapses 30 minutes for a load increment, while the maximum pause would be at most 2 hours if either of the above conditions does not satisfy. Experience shows that the minimum holding period varies from 10 min (for a few initial increments) to more than an hour as creep rate gets larger as load on pile approaching failure. The progress of each test is monitored by the change in displacements with time being plotted for each loading step. Once failure occurs, hydraulic jack is pumped continuously to keep the pile moving at a steady velocity (approximately 3 mm/min) until 12 mm post peak displacement has occurred.

While jacking to transfer load on pile, pressure inside the pump oil is increased accordingly. The oil chamber of pump has two out-let channels—one is directly connected to the pressure gauge and the other is connected to a leak-proof chamber of ram. Any change in the oil pressure (as a result of jacking) is reflected directly in the deflection of the dial indicator of pressure gauge, while concurrently the same pressure is exerted upward on the bottom surface of ram. This results in the upward movement of piston against the platform so as to get the equivalent reaction load from the weighted-platform. Thus the load of platform is gradually transferred to the test pile as the increments pile up. The magnitude of the transferred load is the product of gauge pressure (i.e., oil pressure of ram chamber) and the cross sectional area of ram. The calibration of hydraulic jack can be used instead of evaluating ram load from gauge pressure. The relative deflection of dial indicator is the measure of relative increase in oil pressure.

HAZARDS IN THE EXISTING PRACTICE

As mentioned earlier, the reaction-load is theoretically the product of gauge pressure and ram area. It is so, only when an ideal situation prevails during the test. That is, when the ram is perfectly vertical (during compression test) seating over pile top and friction between the piston and the wall of guiding cylinder is negligible. In real sense, it is difficult to obtain and maintain a perfectly smooth interface condition between ram and guide. So, there will be some frictional loss (F_{fl}), which is a portion of the total hydraulic load (F) applied by jacking as shown in Eq. 1.

$$F = F_{f1} + F_p = p * a + F_{f1} \tag{1}$$

where, p is hydraulic pressure exerted at any instant, a is cross-sectional area of ram, and F_p is the apparent total load transferred on pile measured by pressure gauge. In fact, F_p is component of the actual total load F transferred on pile. If interface friction is ignored (i.e., by using calibration of pressure gauge only), the value of F_p, instead of F, will be considered as the load acting on pile, resulting in the under-estimation of pile capacity. However, using a proper lubricant in the interface can minimise friction (F_{f1}). To overcome such an error confidently, the use of calibration of the entire jack-ram system can be a better solution than that of using pressure gauge only.

In calibrating the entire jack-ram system, the ram is jacking up against a system of proof load, which is a universal testing machine of 1680 kN capacity. The proof load is calibrated against pressure gauge reading. This proof load exhibits the actual load acting on pile, excluding the interface friction of any magnitude.

On the other hand, if the surface of the pile top is not perfectly horizontal (which occurs frequently), it will reduce the efficiency (defined as the ratio of load transferred to pile to that applied on piston) of jacking load. In such a case, the ram load possesses a lateral (normal to the axial direction of pile) component F_2 (normal to the axial direction of pile) of mobilised load (F_p). Since F_2 component increases load in the direction normal to surface of interface contact, it will increase frictional resistance of quantity $f * F_2$ (where, f is coefficient of friction at the interface) in addition to F_{f1} (Eq. 1). It will further reduce the reaction load (F_p') transferred to pile as shown in Eq. 2.

$$F_1 = F_p * Cos\,\alpha \quad \text{(acting along pile axis)} \tag{2a}$$

The contact force acting normal to the ram-guide is:

$$F_2 = F_p * \text{Sin}\alpha \tag{2b}$$

The magnitude of load transferred to the pile is:

$$F_p' = F_1 - F_2 * f = F_p * (\text{Cos}\alpha - f * \text{Sin}\alpha) \tag{2c}$$

where, α is the deviating angle (angle of non-coherence) of piston axis from the vertical direction. Note that the actual load transferred to pile is F_p' (for which the jack is not calibrated), while the measured value that can be obtained by using the calibration of entire hydraulic jack-ram system is F_p. In such case, the accuracy of reaction load measurement is $F_p' / F_p = Cos\alpha - fxSin\alpha$ as can be obtained from Eq. 2c. The occurrence and magnitude of non-coherence, α, in the field is uncertain. Besides, the value of f depends on many factors, such as surface roughness, materials of piston and guide, lubricant type (if used) in interface. Therefore, the system cannot be calibrated to rectify or avoid the error. Thus, errors due to non-coherence and friction loss that resulted from non-horizontal surface of pile-top remain as a potential shortcoming in load measurement. In most cases, it over-estimates the pile capacity, and hence eventually reduces the factor of safety. The degree of over-estimation can be assessed from Fig. 1, which shows the relation between F_p' / F_p and f and α.

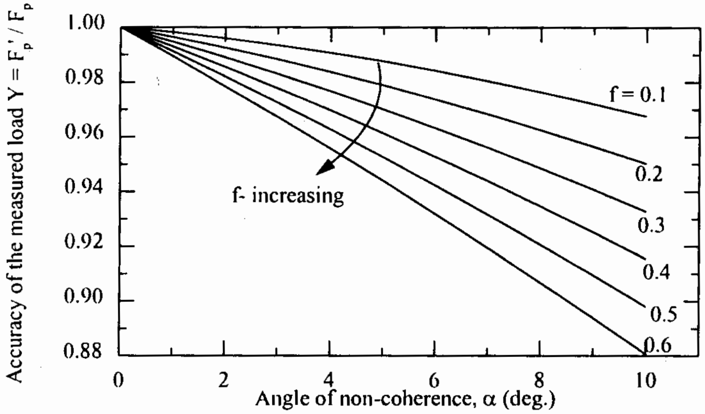

Fig 1. Typical relationship between F_p'/F_p and the angle of non-coherence due to non-horizontal pile cap

Data logging is done manually. That is, while jacking (by involving at least one person) to apply a load increment, two persons are involved in

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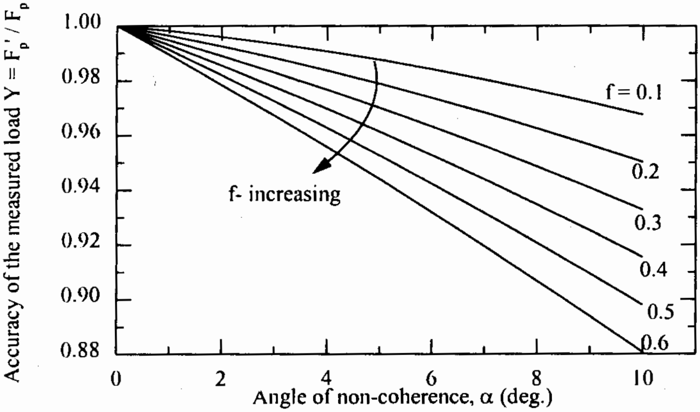


Fig 1. Typical relationship between F_p'/F_p and the angle of non-coherence due to non-horizontal pile cap

Data logging is done manually. That is, while jacking (by involving at least one person) to apply a load increment, two persons are involved in monitoring continuously readings of strain dial gauges in naked eyes, or through theodelite or binocular. After the application of a load-increment, settlement readings (from dial gauges) are to be taken until average settlement rate ceases to 0.25 mm/hr while maintaining constant total load on the test pile. During this period, settlement readings are recorded (by involving yet another person for keeping records) in 5-minute interval. Thus, at least four persons are to remain in hurry in this process until the test completes. At the end, data entry to computer for analysis intensifies the agony. The manual data logging is, therefore, tedious, intensive and above all, less accurate.

RECENT DEVELOPMENT IN INSTRUMENTATION

Steps are taken to improve the performance of load tests. Major shortcomings of existing method are sorted out as:

1. Accurate measurement of load transferred to pile that should be free from all sort of frictional error. That is, we need an independent but direct system of load measurement.
2. Manual data acquisition system, which is primitive way of data logging in the present era of computer technology, should be replaced with a modernised system that will save human involvement (since error prone), but improve the accuracy dramatically.

To materialise the above-mentioned objectives, a load cell, often called as load column, is used just above the ram, but below the test beam. Due to jacking, the load that applies on the load column (as a reaction from the weighted-platform) is the load in excess to frictional loss. Eventually, this magnitude of load is applied on the test pile. As it works independently, frictional loss of jack pressure (the measure of load mobilised to pile in the existing testing method) due to rough interface and non-horizontal surface of pile top will play no role in the measured pile capacity.

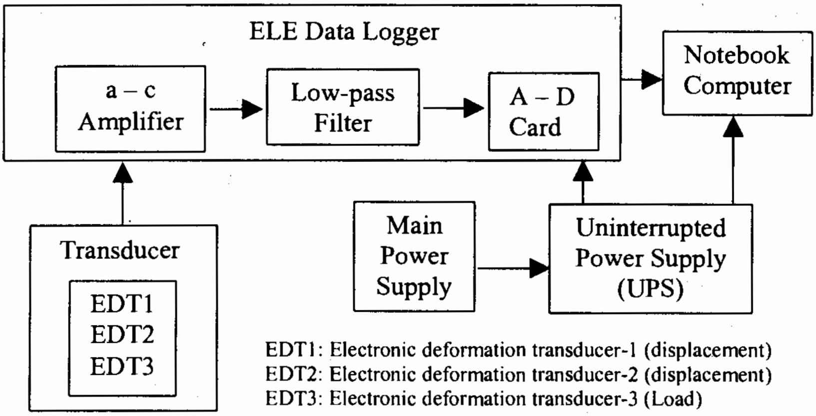
Load-column (manufactured by ELE International, USA) is a split-type load cell of capacity of 150 Ton. The maximum gap of the split, known as run, is about 2 mm. That is, the entire run will just be closed when 150 Ton load is applied axially (i.e., normal to the split direction) on the load-column. Imposed load on intermediate magnitude is directly proportional to the deformation in split. That is, the magnitude of split gap at any instant during loading is the measure of the load acting on it axially. To circumvent the change in deformation (in split gap) due to change in loading on it, the load-column is assembled with an electronic deformation transducer (EDT). The EDT is connected to load-column in a way that the run of the EDT is just same as that of split-gap of load-column. Any change in load on the load-column (and hence on the pile) causes an equivalent change in electronic signal (i.e., voltage) in EDT. At a given instant during test, such signal can be digitised (i.e., reading data electronically) through a computer via an analogue-to-digital (A-D) converter card. Data reading electronically is possible only using a computer aided data acquisition system (discussed later), which has been introduced recently in Bangladesh University of Engineering and Technology, Dhaka.

Similarly, to computerise the data logging system, dial gauges to measure pile settlement are also replaced with a pair of electronic deformation transducers (EDT). Working principle of these EDTs is similar to that use with load-column.

AUTOMATED DATA ACQUISITION SYSTEM

In this Figure 2 shows the block diagram of the data acquisition system being presently in use for load tests. Any change in gauge-length in a deformation transducer is responded internally as an equivalent electronic signal change. Transducers are continuously sending electronic signals in terms of voltage through electric wires towards the data logger (DL). The DL is armed internally with an a-c amplifier, a low-pass filter and an A-D card. The a-c amplifier receives continuous signals (in terms of voltage), which is controlled by the gain (i.e., the amplification ratio of incoming voltage). The gain should be set at a proper value so as to obtain the optimum resolution depending on the maximum axial deformation (tension or compression) to be measured. Note that load on pile is also measured from the deformation in split-gap of load-column. In order to eliminate unwanted high frequency noise components involved in the input signals to computer (via A-D card), the a-c amplifier is armed with a built-in low-pass filter to increase the signal-to-noise ratio. This eventually increases the accuracy of test data. Finally, data are fed into a 16-bit laptop-computer through the 16-bit A-D card, which is set for a voltage range of –5 V to +5 V.

The transducers are energised by 3V d.c. supply from data logger. Both DL and computer are connected to main electric supply. Load test continues for several hours to complete, and we are having load-shading problem in Bangladesh frequently. To perform a load test uninterruptedly, an electronic device for uninterrupted power supply (UPS) is used as the power source of computer and data logger, which is eventually energised from main power supply. During load shading, the UPS can supply energy for running the data acquisition system for four hours continuously.



EDT1: Electronic deformation transducer-1 (displacement)
EDT2: Electronic deformation transducer-2 (displacement)
EDT3: Electronic deformation transducer-3 (Load)

Fig 2. Block diagram of the auto-control data acquisition system

A software program, written in Q-basic, is developed to guide data logging process. Key functions of the software required to control data logging are as follows:

- Data logging can be intermittent or continuous. In case of intermittent logging, a finite time interval Δt (may be called sampling interval) is intricate with the control so that the computer control, after each sampling, will enjoy a pause for time Δt before going for the next sampling. The value of Δt can be changed at any time during the test.
- After each sampling, the computer updates the following. a) The current settlement and load by converting the corresponding voltages using the respective calibration factors; b) The settlement rate while maintaining a constant load-state (the settlement rate dictates the time for the next step of load increment); and c) Different plots such as time-settlement, time-load and load-settlement curves. These plots are important to monitor whether the testing proceeds and/or the electronic devices work in the desired direction. If not, the operator can stop the testing and restart if necessary.

RESOLUTION OF DATA ACQUISITION

The evaluation of the resolution (and hence sensitivity) of acquisition system is an essential but painstaking task as the system incorporates various electronic devices such as transducers, an a-c amplifier, an A-D card and a computer, all of which have their own resolutions. However, it is not necessary to devise resolution of each device. Rather resolution of transducer is prime important, but as signals from it pass through data logger unit (Fig. 2), resolution of entire data logger is also important. Eventually, final data are read/digitised into computer. The resolution of computer is, therefore, to be considered. As mentioned earlier, computer and A-D card are of 16-bit devices and A-D card is set for a voltage range of –5 V to + 5 V (i.e., total 10 V). The smallest resoluble voltage in A-D card, hereafter designated as RV, is 10 V/(2^{n-1}-1) (where, n is bit number, i.e., n=16) $\doteq$ 0.3052 mV. The 16-bit computer can also recognise a value as small as 1 *RV*. Therefore, either transducer or data logger (Fig. 2) must govern the resolution of entire system.

Firstly, an attempt was taken to make out the resolution of data logger. Electronic-devices controlling resolution of DL are an A-D card with having resolution of 1 *RV* and an a-c amplifier. Usually, an a-c amplifier possesses a very high resolution (Hoque et al., 1997), which is far below than 1 *RV*. Note that a higher resolution means a smaller value to be read out (i.e., smaller than 1 *RV* in this particular case). Figure 3 shows the variation of the voltage output with time at an arbitrary setting of a transducer (arbitrarily chosen) at a standstill condition. The output voltage was expressed in terms of *RV* number. The normalised voltage (i.e., the actual output voltage divided by the value of 1 *RV*) is always an integer and varies within a range of 0 to +1 *RV* (or, -1 to 0 *RV*). In other words, the DL exhibits a resolution of 1 *RV* with an accuracy of ≠1 *RV*. The values of resolution and accuracy are exactly the same those for A-D card according to the manufacturer. As A-D card governs the resolution of DL, so the a-c amplifier possesses a resolution higher than or at least equal to 1 *RV*, which can be set by adjusting the gain. A similar result was reported in Hoque et al. (1997).

In any case, the resolution of entire system (comprising a transducer, a DL and a computer) would be n*RV*, where, n ≥ 1 (an integer). The excitable bridge (i.e., an electric bridge, e.g., a Wheatstone bridge) installed in the transducer may possess an infinite resolution, even though one cannot get a value of n less than unity. Figure 4 shows typical time-histories of settlement after the second increment of loading during load test. Load test was performed on a R.C.C. precast pile (25 ft long and 7"x7" cross-section) of the proposed District Jail Project under Public Works Department, Moulvibazar, Sylhet. The reason for using such short piles is to replace wooden piles in the foundation of 3 to 4 storied buildings. Wooden piles are susceptible to decay due to alternating and wetting. The project would use similar short piles of huge number. A total 16 pile was tested. Test piles had been driven two weeks before load testing. Subsoil was consisted of: a) a silty-clay layer of 10-ft depth at the top, loose to medium density, SPT being varied from N=1 to 7 blows/ft penetration); b) followed by an organic clay layer of 6 to 7 ft thick (N value was varied from 3 to 4 blows/ft) with high moisture content; and c) a 10-ft layer of medium to coarse sand of

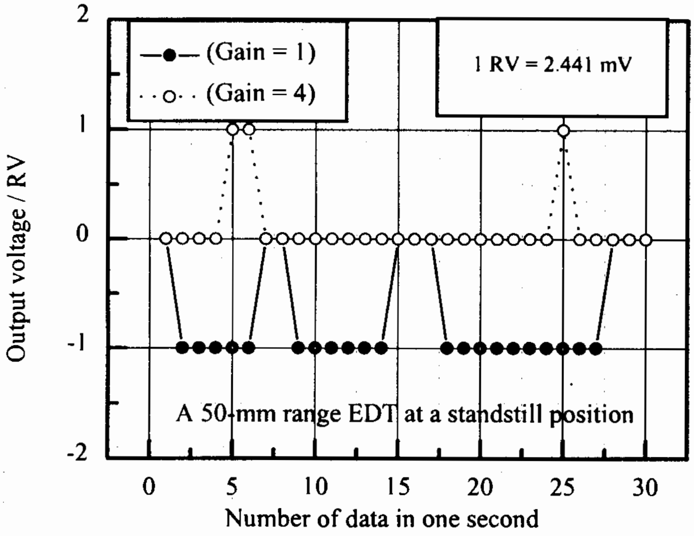


Fig 3. Resolution of the data logger armed with an a-c amplifier, an analogue-to-digital card and a filter

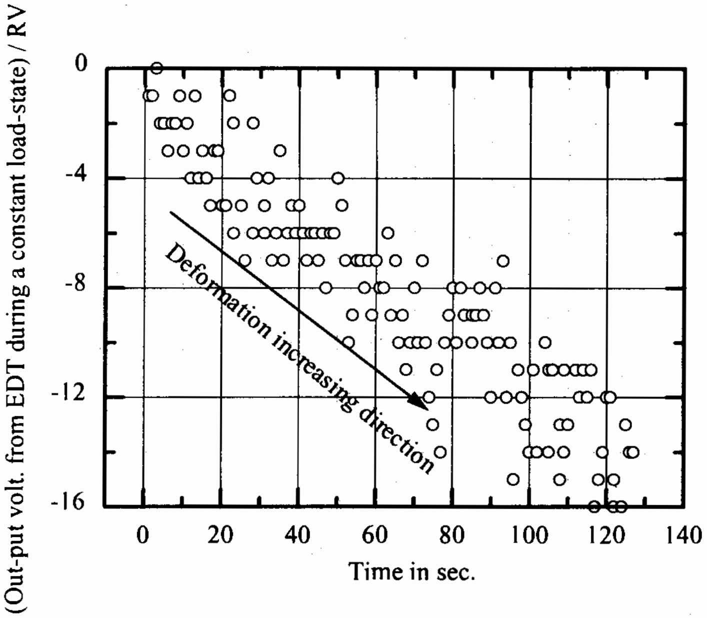


Fig 4. Typical time-history of pile settlement-in-voltage / RV while maintaining a constant load-state on pile after the second increment of loading

medium density (N-value was varied from 7 to 9), in which tip of pile was rest. Water table was 6-ft below the ground level. For convenience, time histories were plotted directly against settlement of each transducer in terms of voltage. Arbitrary zero shifting has been made in both axes directions. The shift values were, for instance in Fig. 4, +950 *RV* along the vertical axis, and 35 seconds along horizontal axis. It can be seen that the EDT was able to respond to very small increments of settlement. As the settlement rate was small after the very second increment of loading, continuous data were sampled (throughout the time-history of the particular increment) at the interval of 1 *RV* (Fig. 4). At a given second in time axis, the output voltage expressed in RV was varied in the range between 2 *RV* to 4 *RV*. Such a wide variation was due not only to the resolution of A-D card, but also to the scatter in load axis at the same time. While maintaining steady load-state after a load increment, axial load on pile might change in a very slow rate due to the re-orientation of soil particles in contact. As data pass through an A-D card, which has an accuracy of ±1 *RV*, one may expect two dissimilar (unequal) data at a particular standstill position of the transducer (Fig. 3). Considering this, it can be said that an EDT, and hence the acquisition system, can respond to a displacement equivalent to at least 2 *RV*. With this resolution, the smallest displacement one can measure is 2 *RV*x50 mm = 2x0.3052x10^{-3}x50 mm = 0.03052 mm. Since the EDT used for load-column has a run of 2 mm for 150 Ton load capacity, so the smallest load one can realise is 2 *RV*x150 = 0.09156 Ton. These resolutions are far better than those are considered sufficient for load test (Fuller, 1983; Chellis, 1961 and Fellenius, 1975), and also better than those were available in manual logging system. A better resolution can be obtained by resetting 'Gain' of data logger for a higher value (provided EDTs can make it out).

TYPICAL RESULTS

Figures 5a to c show typical test results of the pile described in Fig. 4. Time-histories of settlement after each load increment until settlement ceased to the minimum value were shown in Fig. 5a. Both time and settlement axes were initialised to zero at the start of a given load increment. The shift values were also noted with their respective curve in the plot. As load-state approaching failure, settlement rate increased and more time was required to reach a settlement rate less than the minimal (specified earlier). Figure 5b shows the time-histories of all load increments. Slight variation was observed in the time-histories while maintaining a constant load-state after a given load increment. It was observed relatively at higher load-state near failure. Since settlement rate was higher at such a load-state, very often stress relaxation was occurred in the pile. There was a time gap between

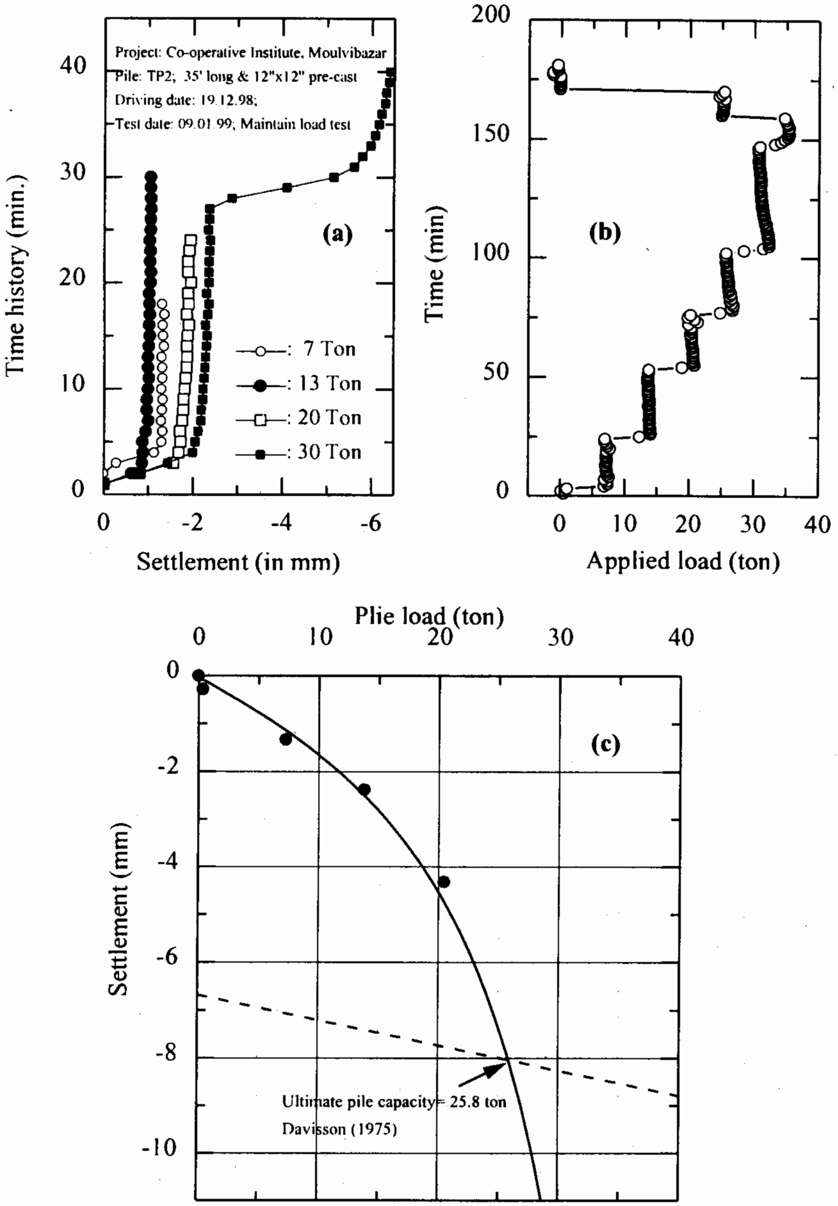


Fig 5. During load-test in maintain load condition, (a) typical time-history of settlement, (b) typical time-history of load, and (c) relationship between load and settlement

observing a decrease in load in computer and the subsequent load adjustment. Finally, Fig. 5c shows load-settlement relationship. The ultimate capacity of the pile was indicated on the plot according to Davisson (1975) method. In evaluating elastic shortening of pile, which is required to calculate net settlement under test load, elastic modulus of pile concrete was estimated as $E_c = 57{,}000\sqrt{f_c'}$ (Winter and Nilson, 1983), where, $f_c' = 3000$ psi.

CONCLUSIONS

The performance of static pile load test in compression has been improved by bringing about changes in instrumentation and data acquisition system. The previous data acquisition system was manual type. Therefore, testing was labour intensive and tedious. No independent and direct load-measuring device was available. The load-measuring system was not capable of excluding friction error of any sorts that might be incorporated due to interface roughness of piston movement and non-horizontal surface of pile top.

In order to avoid friction error of any sorts, an independent load cell, called load-column, coupled with an electronic gauge is installed just above the ram of hydraulic jack to measure directly the load transferred to pile. The displacement dial gauges are replaced with a pair of electronic deformation transducers. The data acquisition system is made computer controlled with the use of electronic transducers and a high-resolution data logger. The new system makes data logging operations much simpler during the entire test.

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