7. Plate loading tests

7.1 PRINCIPLE OF THE PLATE LOADING TESTS

The plate loading tests were performed in order to check the applicability of different methods of estimating bearing capacity and settlements for shallow foundations on clay till. The tests were performed as a series of tests on square plates with dimensions chosen in such a way that ultimate bearing capacity failure was expected to be reached for at least the smallest plate and with such variations that the effect of the stresses extending to various depths could be studied. The largest plate also had dimensions similar to an ordinary foundation.

Foundations in Sweden are made so deep that they are unaffected by frost action, which normally means a foundation level 1.1 – 2.5 m below the ground surface, unless special precautions are taken. In the plate loading tests, it was also desired to lay the plates on top of fairly homogeneous soil below the top soil and desiccated crust in order to facilitate interpretation of the results. In ordinary foundations, part or all of the excavation for the foundation is often back-filled after the foundation work has been completed.

Much of the loading equipment is standard for this type of test, which sets limits on possible dimensions and maximum loads. The loading equipment consisted of a system of beams, ground anchors and hydraulic jacks and pumps. The main beams consisted of three 17 m long steel profiles which could be bolted together. Such beams are kept in Swedish National Rail Administration depots distributed throughout the country for use in temporary emergency repairs of railway lines and can often be made available for loading tests. Because of the high loads, a secondary system of beams was placed across and on top of the main beams over the largest plate. The ends of the beams were placed on supports consisting of wooden rafts of the type normally used to support excavators on soft ground. In this case, they were used to provide firm and level bases, and the number of rafts at the ends can also be adjusted to place the beams in a horizontal position. The required reaction force can be provided by dead-weights or by ground anchors. In this case, it was considered unsuitable to use dead-weights and a system of eight ground anchors was installed. The ground anchors consisted of tie rods, which were lowered in pre-drilled holes down to 10 metres in the bedrock and then fixed by pumping in cement grout. The ground anchors were placed in pairs, one on each side of the ends of the beam systems, and extended well above the beams. Shorter beams were placed across the ends of the beam systems and were tied down with a pre-stress in the tie rods in order to secure the system.

The dimensions of the reaction system made it possible to install three plates measuring 0.5 x 0.5 m, 1 x 1 m and 2 x 2 m in a row along the main beams without significant interference in terms of the same soil mass being affected by the different load tests. The distances between the plates and the loading sequence were also adjusted to minimise the influence from a preceding load test on the results from the following load tests. Thus, the smallest plate was placed at one end of the row, the largest plate was placed approximately in the middle but somewhat closer to the smallest plate, and the intermediate plate was placed at the other end of the row. The plates were then tested in a sequence with the smallest plate first and the largest plate last.

No large amount of backfill was put in place after the plates had been installed. The plates were installed 0.2 m deeper than the rest of the excavation and only the gaps left after removal of the moulds were filled in.

The load on the plates was provided by hydraulic pumps and jacks. According to Swedish practice, the load in tests on friction soils is normally applied in steps with a duration long enough to enable a study of the creep rate of the deformations (Bergdahl et al. 1993). For cohesive soils, a longer duration is required to permit for full dissipation of excess pore pressures and related consolidation if the drained properties are to be studied. A minimum of ten steps is normally used to enable evaluation of both load settlement curves and failure loads. In tests on friction soils and in undrained tests on clays, a duration for each load step of about 8 minutes is normally considered sufficient. In the present series of tests, the tests were performed in steps with durations that were determined with respect to the measured pore pressures and time settlement curves. The durations of the load steps were therefore somewhat shorter for the first load steps and then increased at higher loads as the time-settlement relations changed. The durations were thus mainly 2 hours for the 0.5 m square plate, 4 hours for the 1 m square plate and 6 hours for the 2 m square plate. The duration of the load steps in the unloading and reloading loops was only about 12 minutes for each step. The pore pressure in the soil below the plate was measured during the tests in order to verify that full excess pore pressure dissipation was achieved.

Different systems for application of both constant static loads, cyclic loads and dynamic loads by hydraulic jacks have been developed at the Institute. In this case, an electronically operated system was used in which the load was measured and regulated by means of an electronic load cell. Because of the high loads and pressures and the long duration of the tests, a back-up system for maintaining oil pressure was installed which was automatically engaged if the pressure should drop. This proved to be well-advised, since the first oil pump failed at the end of the series of tests.

7.2 INSTALLATION OF PLATES AND INSTRUMENTATION

The reinforced concrete plates were to be cast in place at the bottom of excavated pits. The ground water observations in previous years had shown that the free ground water level would normally be about 2 m below the ground surface in summertime. However, the spring this year was wet, with a ground water level at the ground surface, and no significant lowering of the ground water was observed during the period of the investigations and subsequently. An attempt was made to lower the ground water locally by excavating large holes to 2 metres depth at the ends of the intended excavation for the tests and pumping out the water from the bottom of these. This continued for a couple of weeks, but no effect was observed at the observation points in the test area. Time was then running short and it was decided to perform the excavation and to try to keep the water out and preserve the soil properties at the bottom of the excavation in the usual way. This entailed the excavation of ditches and pumping at the bottom of the excavation, while minimising the length of the periods between excavation and reloading by installation of the plates.

The excavation work was started using an excavator to about 0.2 m above the foundation level. A 1.3 metre deep pit with base dimensions of about 13 x 5 metres was thus excavated. The slopes at one of the long sides had an inclination of about 1:1 but the slopes at the other sides were steeper. Care was taken to perform the last part of this excavation smoothly without excessive deepening of the pit in the separate digging operations. At two opposite corners of the excavation, holes were dug to 2 metres depth and the pumps were lowered into these. Ditches were then dug along the sides of the excavation. The further 0.2 metre of excavation for the tests plates was carried out manually, *Fig. 81*. The prefabricated moulds were then put in place.

After the excavation work, part of the instrumentation below the plates was installed. This consisted of settlement gauges. In this stiff soil, the

Fig. 81. Excavation for the plates at Tornhill.

installation required the drill rig to be lowered into the excavation. This required great care with installation of rails for the rig to run on in order not to disturb the bottom of the excavation.

The instrumentation under each of the plates was to consist of three settlement gauges placed at different depths and one piezometer. However, the disturbance at installation appeared to be relatively large and therefore only one settlement gauge was installed under the smallest plate. The settlement gauges consist of short augers, which are screwed down into the soil. The rods are encapsulated in a plastic tube and the annulus is filled with grease. When the auger has been screwed into place, the plastic tube is retracted over a distance corresponding to the intended range of measured settlements. The rods and protecting tubes are extended to pass through the concrete plate.

The settlement gauges were placed close to three corners of the plates in the so called "characteristic point" for stresses and settlements, i.e. at a perpendicular distance of 0.13*b* from adjacent sides of the plate (where *b* is the width of the plate). One gauge for each plate was placed with its centre at a depth of about 0.15 metre below the base. The reason for this was to obtain a check on possible excessive deformations resulting from disturbance of the bottom of the pit in spite of the careful excavation. The other two gauges were placed at depths within the depth interval down to 2*b* below the plates.

After installation of the instrumentation, reinforcing bars were placed in the moulds and concrete was pumped in. Apart from the settlement gauges below the plates, the total settlements of the plates were measured on rods fixed in the concrete at each corner of the plate.

The work of installing the moulds, instrumentation and, reinforcement, in addition to pouring the concrete, was a fight against time owing to water seepage. The pumps and ditches needed constant monitoring since parts of the slopes continuously collapsed as water continued to seep in on the lower parts of the slopes. There was also a rain shower during this period. The bottom of the excavation was checked carefully just before the concrete was poured to estimate the extent of the softening. Although the surface itself was then very soft, the obvious effect extended only to about 10 mm depth below. The ground water conditions were measured with tensiometers and pore pressure probes below the excavation and in the slopes. The free ground water level in the slopes was found to be about 1 m below the ground surface. Below this level, water seeped into the excavation and above it the pore pressures were negative, corresponding to negative hydrostatic pressures from this level. Below the bottom of the excavation, the pore pressures were slightly artesian and thus there was an upward gradient with water seeping very slowly up towards the surface.

Piezometers were installed beneath the plates in order to check that the tests were drained and that all excess pore pressures had dissipated at the end of each load step. The piezometers were electrical and were intended to be installed at depths where the pore pressures could be expected to be highest with consideration to stress increases and drainage paths. The piezometers were pushed in at the corners where no settlement gauges had been installed and with such inclinations that they would be positioned centrally beneath the plates. After pushing the piezometer into place, the drill rods were retracted, leaving only the piezometer connected to a wire and the signal cable in the ground. However, this operation had to be performed with the drill rig standing on the slope of the excavation and the resistance of the soil was so great that the intended depths could not always be fully reached.

The concrete plates were 0.5 metre thick. One day after casting the plates, the moulds were removed and the gaps between the plates and the surrounding soil in the excavation were filled in with excavated soil. The work with setting up the reaction, loading and measuring systems was then commenced.

7.3 INSTALLATION OF THE REACTION SYSTEM

The eight ground anchors had been installed by PEAB Grundteknik about one month in advance. The ground surface at each pair of ground anchors was now scraped off and levelled. A number of wooden rafts, or “excavator mats”, were then stacked and adjusted in such a way that the top surfaces of the stacks were at the intended levels and horizontal. The three railway bridge beams were placed side by side with the ends resting on the stacks at the ends of the excavation and then bolted together. Their common centre line was carefully aligned with the centre line of the row of plates. Two short beams were then placed on top and across the ends of the large beams, and were connected to the tie rods from the ground anchors. Above the centre of the largest plate, two other beams were placed on top of and across the railway bridge beams with their ends resting on the two stacks of excavator mats at the sides of the excavation. The ends of these beams were connected to the corresponding tie bars in the same way as the ends of the long beams. The tie rods were pre-stressed and the whole reaction system was thereby fixed, *Fig. 82*.

Fig. 82. Reaction system being mounted.

7.4 INSTALLATION OF THE LOADING SYSTEM

The loading system used for the tests at Tornhill consisted of a hydraulic pump and electronically operated regulation valves, two hydraulic jacks for different load ranges, corresponding load cells for measuring the load and providing the signal for regulating the hydraulic pressure, and a computer for data collection and regulation of the loading process. A back-up system for the hydraulic pressure was also installed.

For the two smaller plates, a circular stress distribution plate was centred directly on the concrete. The load cell and the jack were then positioned on this plate and on top of them further plates were laid as required to fill the gap up to the reaction beams. For the largest plate, an additional square stress distribution steel plate covering a large part of the top surface was laid in position before the above mentioned assembly was put in place. In order to distribute the load on the reaction beams evenly, a short beam was fixed under and across them at the loading point.

Measuring system

The measuring system consisted of the computerised data collection and load regulation system, the load cells, the piezometers and the displacement transducers. The displacement transducers were fixed on special measurement beams (ladders), whose ends rested on the ground outside the area affected by the particular test. The displacement transducers measured the movements of the top of the plate and the settlement gauges in relation to this ladder. The whole system was protected from sun and weather by tarpaulins, using the reaction beams as a ridge. The measurement beam was supplied with a fixed vertical scale and was continuously levelled by a high precision instrument in order to check that the reference level was stable, *Fig. 83*.

Fig. 83. Installation of the measuring system.

Loading procedure

The load tests were to be performed in steps with maintained constant loads. In order to ascertain that all excess pore pressures would dissipate during the time for each load step, a number of preliminary calculations were made using somewhat conservative assumptions. On the basis of these calculations, a tentative schedule was set up where each load step for the smallest plate was to be applied for 2 hours. The corresponding times for the middle and the largest plates were 4 hours and 6 hours respectively.

Preliminary calculations of the bearing capacity had given widely differing results depending on which strength parameters were used. However, the preconsolidation pressure in the upper part below the plate was estimated to be at least 650 kPa and the calculated bearing capacities were somewhat or much higher than this value. For the first test plate, which was the smallest 0.5 x 0.5 metre plate, it was therefore decided to start with load steps of 25 kN, corresponding to 100 kPa, which would give the desired minimum of eight load steps.

The first load test resulted in failure after ten load steps and it was decided to make the steps somewhat smaller in the next test. The 1 m x 1 m plate was thus loaded in steps of 75 kN corresponding to 75 kPa. No direct failure was obtained in this test, but the frequently used failure criterion of the settlement being equal to 10 % of the plate width was approached.

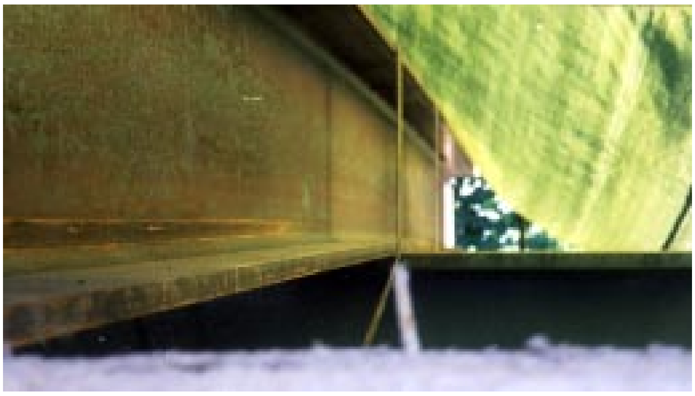

Fig. 84. Deflections in the reaction beams at the end of the loading test on the largest plate.

The maximum design load for the reaction system varied depending on where the load was applied. The tie rods were designed to take a maximum force of 500 kN each, However, this force could not be mobilised simultaneously in every rod and it was difficult to estimate the interaction within the beam system. For the 1 m x 1 m plate, the load was applied about midway on the free span of the large beams between their ends and the crossing beams above the 2 m x 2 m plate. The pair of tie rods at the ends of the beams would have to take about half of the applied load and with a possible imbalance in the system, one of them might have to take more than the other. The loading of the 1 m x 1 m plate was therefore stopped at a load of 1350 kN.

For the 2 m x 2 m plate, the main load would be taken by the crossing beams and their tie rods. A contribution would also be obtained from the long railway bridge beams, but this would require a fairly large deflection because of the long span. The crossing beams and their tie rods were designed for a maximum load of 2000 kN. The loading of the large plate was applied in steps of 200 kN, corresponding to 50 kPa, and no failure was expected. The loading was continued up to a total load of 2800 kN, where it was stopped because of large and permanent deflections in the crossing reaction beams, *Fig. 84*.

The settlements and pore pressures were studied continuously during the load steps. During the initial steps of each test, the settlements essentially stopped within a short time. The time-settlement curves then showed straight-line relationships between log time and settlement, with very low creep rates. At the same time, the piezometer readings showed that no or only very small excess pore pressures developed and that these appeared to dissipate rapidly. It was thus possible to shorten the first load steps in each series. The time settlement curves then gradually changed in such a way that the time required to reach a straight-line settlement-log time relationship increased and the duration of the load steps was increased. However, the times in the preliminary schedule did not have to be exceeded.