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APPLICATION NOTE

INSTRUMENTATION FOR MONITORING CONSOLIDATION OF SOFT SOIL

1 INTRODUCTION

Considerable settlement may occur when constructing projects such as highway embankments, bridge approaches, dikes, dams, large storage areas, tanks, airport runways or buildings on soft compressible soil, due to the consolidation of soil under the superimposed load. To avoid serious and potentially expensive problems due to such settlement, it is desirable to cause the consolidation to occur at the outset of the project, and in the shortest possible time during construction period.

Construction of a facility on top of a soft soil foundation will normally be delayed until there is assurance that it will not be damaged by settlement that occurs during subsequent consolidation. If the predicted delay is not acceptable, the time required for consolidation can be reduced by surcharging and/or by installation of vertical drains.

1.1 Consolidation

In case a saturated soil experiences a steady pressure due to the weight of overlying soil or pre-loading from an embankment, its volume will decrease with time. Soil particles as well as the water in the voids being almost incompressible at the pressures encountered, any change in volume can only occur if the water between the voids is forced out. This reduces the size of the voids enabling the solid particles to become wedged closer together. The process is illustrated in figures 1.1 and 1.2 below:

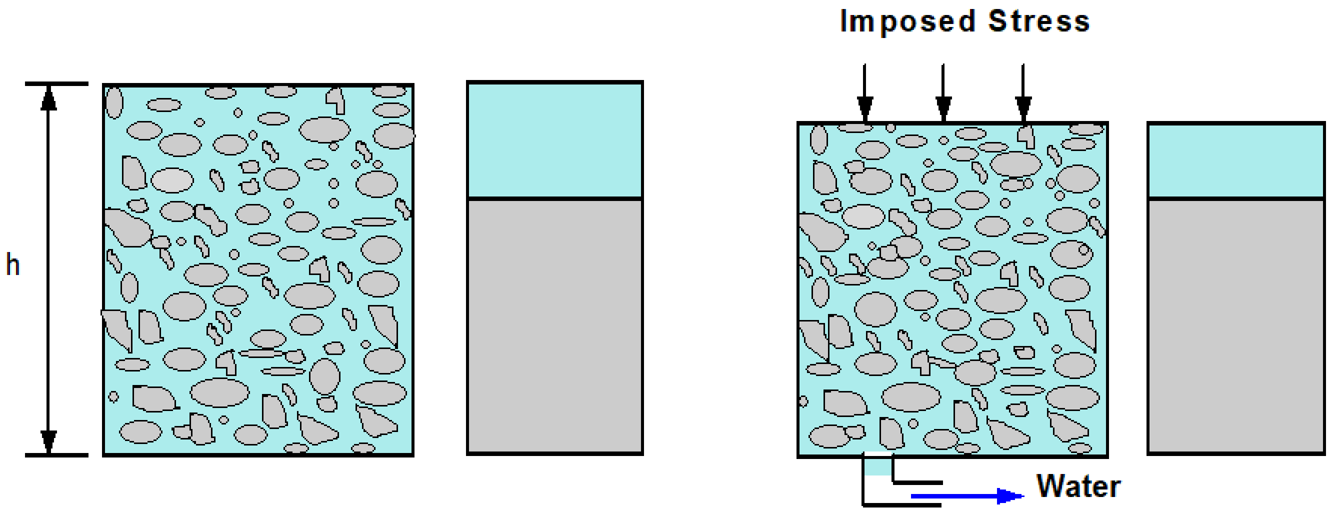


Figure 1.1

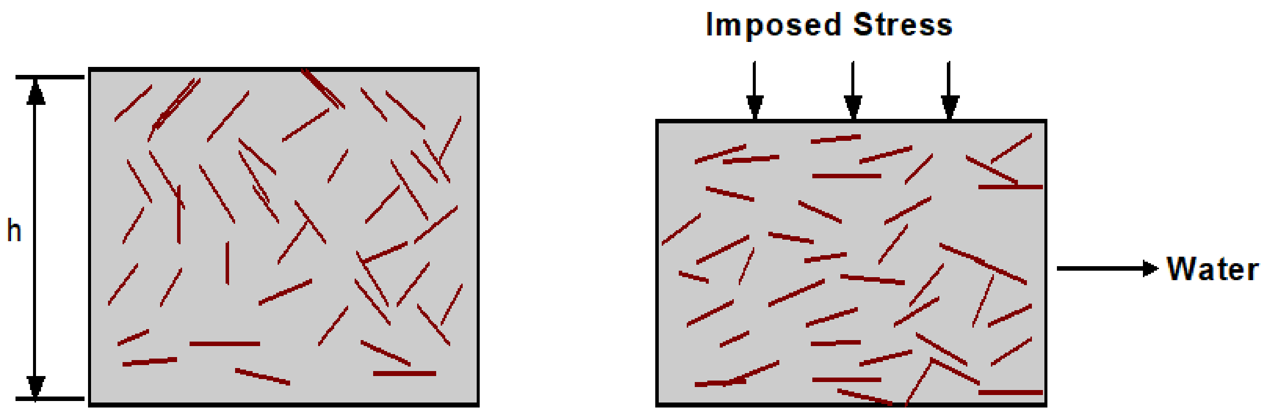


Figure 1.2

Surcharging (or pre-loading) involves placement of fill materials to a level higher than that required for the foundation or embankment, so that consolidation proceeds more quickly. The fill material is removed later on.

Vertical drains (or band/wick drains) are highly permeable columns of high quality flexible polypropylene, installed at close intervals within the foundation soil. A typical vertical drain is approximately 100 mm wide, 6 mm thick, and comes in rolls up to 300 m in length. A continuous sand blanket is placed over the tops of the drains, so that the drains communicate with the blanket and allow pore water pressures to dissipate more rapidly, thus minimizing the time required for consolidation. Alternatively, prefabricated strip drains similar to vertical drains may be used for horizontal dissipation instead of the sand drainage blanket.

1.2 Consolidation of soft foundations through flexible vertical drains

For many years, civil engineers are faced with a big challenge to design structures on soft compressible soils which include soft clay, silt and peat foundations. Consolidation of water-saturated, fine-grained soil occurs very slowly because the low permeability of these soils impedes the escape of pore water from the soil voids. Such soils have poor drainage and strength properties. Even under large temporary surcharge loads, settlement can take years because of this slow water movement and the great distance the water must move to exit the soil. The installation of prefabricated vertical drains greatly reduces the distance the water must move to reach a free drainage path, and therefore greatly increases the settlement rate. Drain spacing may be adjusted to match the required settlement time. No construction activity can take place without soil stabilization as long term settlement is usually uneven and unpredictable.

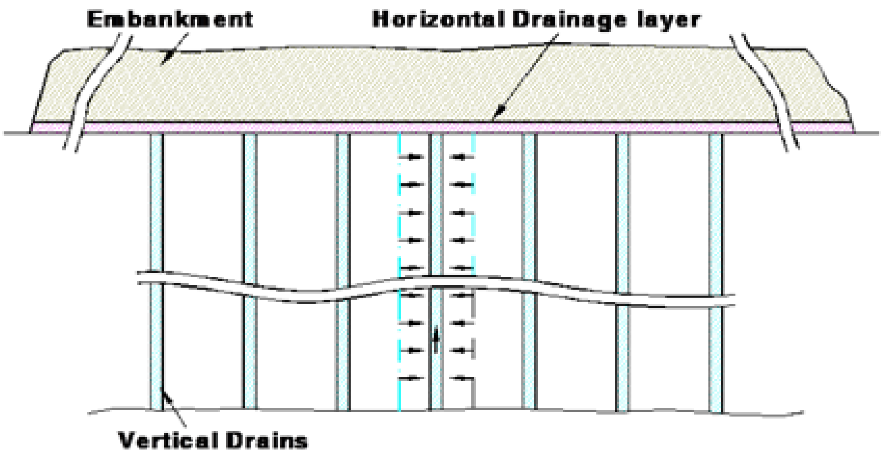


Figure 1.3

Flexible vertical drains made of polypropylene, also known as polypropylene vertical drains (PVD) can greatly reduce settlement time and accelerate the consolidation process. PVD are installed in regular spacing into the full depth of the compressible soil layers to create artificial and shorter horizontal drainage paths. This enables the pressurized water to flow horizontally towards the nearest drain and escape freely though the longitudinal grooves on both sides of the vertical drain core. Usually PVD are used in conjunction with pre-loading the surcharge with soil or vacuum pressure to further accelerate the consolidation process. See figure 1.3.

Basically the drain comprises of a drain body and a filter jacket. The drain body is a central continuous plastic core specially designed to provide high discharge capacity and high tensile & compressive strength. The core functions as a free-draining water channel. The filter jacket, surrounding the drain body is a strong and durable non-woven polypropylene filter with high tensile strength, high permeability and effective filtering properties allowing free access of pore water into the core while eliminating the movement of soil particles and preventing piping. Combining both the features of the core and filter jacket, the PVD provides an effective, fast and reliable drainage system for soil improvement. PVD are available in different core configurations and filter fabrics to suit various soil conditions and engineering practices.

2 ROLE OF INSTRUMENTATION

Instrumentation for embankments of soft ground is frequently used to monitor progress of consolidation and to determine whether the foundation is stable. For example, instrumentation is used to monitor progress of consolidation beneath a single-stage embankment, a surcharged embankment or staged construction, so that construction schedules can be determined. When vertical drains are installed, instrumentation will normally be used to evaluate whether it is effective in accelerating consolidation. Instrumentation may also be installed to provide a warning of any instability, thereby allowing remedial measures to be implemented before critical situations arise.

If construction feasibility is in doubt or if uncertainties in the selection of soil parameters are unacceptably great, it may be appropriate to construct a test embankment and monitor various geotechnical parameters with the help of instruments. Instrumentation data play an essential role in evaluating the performance of such a test embankment.

1.3 Instrumentation for determining initial site conditions

Conventional site investigation procedures, often supplemented by in situ testing are used to determine the initial site conditions. However, performance monitoring instrumentation do play a role. For example, initial ground water pressure and fluctuations must be determined for design purposes. Piezometers can be installed well before the start of filling, to define the pre-construction groundwater pressure regime, including any perched or artesian water. In case piezometers are installed sufficiently early, seasonal variations can be defined. Settlement measurements may also be required to establish pre-construction settlement behavior.

1.4 Instrumentation for test embankment

As mentioned earlier, test embankments are sometimes constructed to resolve uncertainties in the selection of soil parameters; to examine alternative construction methods or to demonstrate construction feasibility. The goal of instrumentation in these tests will generally be to provide an indication of incipient failure and/or to evaluate the progress of consolidation. In addition, instrumentation may be installed to permit a back-analysis for determining the engineering properties of the underlying soil. In all cases, the primary parameters of interest are vertical and horizontal deformations and pore water pressure.

Depending on the specifics of the case, instrumentation for a test embankment will include any or all of the monitoring methods discussed in this application note. The quantity of instrumentation will usually be greater than for a prototype embankment (one that is part of the constructed project), so that maximum information is gained from the test.

1.5 Instrumentation for monitoring the consolidation process

When surcharging with vertical drains employing staged construction or otherwise, instrumentation is used to indicate the progress of consolidation. Instrumentation data allow schedules to be determined for surcharge removal and for placement of stages during staged construction and also allow an evaluation of the effectiveness of vertical drains.

Both settlement and pore water pressure measurements are normally made when evaluating progress of consolidation beneath a single-stage embankment, a surcharged embankment or staged construction. In case piezometers are installed in the vicinity of the embankment, reference piezometers should also be installed, remote from the embankment, to monitor any variation in groundwater pressure that may result from other causes. A predictive extrapolation can be made from a plot of pore water pressure versus time because the equilibrium piezometric level corresponding to full consolidation is known to be equal to the reference value remote from the embankment (see figure 3.3).

Refer to the table on the next page for selecting instruments for monitoring the progress of consolidation. The list is not exhaustive or exclusive. Selection among the various options will depend on the feasibility of extending instrument pipes and leads up through the embankment without risk of damage and the need for redundancy. In all cases predictions should be made of maximum vertical foundation compression and horizontal spreading, and a special effort must be made to select instruments that are both capable of surviving the deformations and capable of providing reliable data as deformation occurs.

MEASUREMENT	INSTRUMENTATION
Vertical deformation of constructed and new ground surface	Surveying instrument
Vertical deformation of original ground surface	Encardio-rite model EPL-37 full profile liquid level gage with pressure sensor and water filled tube
	Settlement platforms/buried plates
Vertical deformation and settlement of subsurface	Encardio-rite model EDS-91 magnetic probe extensometer
Horizontal deformation	Encardio-rite model EAN-20 inclinometer system
Groundwater pressure	Encardio-rite model EPP-10 porous tube piezometer
	Encardio-rite model EPP-30/36V vibrating wire piezometer

1.6 Instrumentation for monitoring the stability of embankment

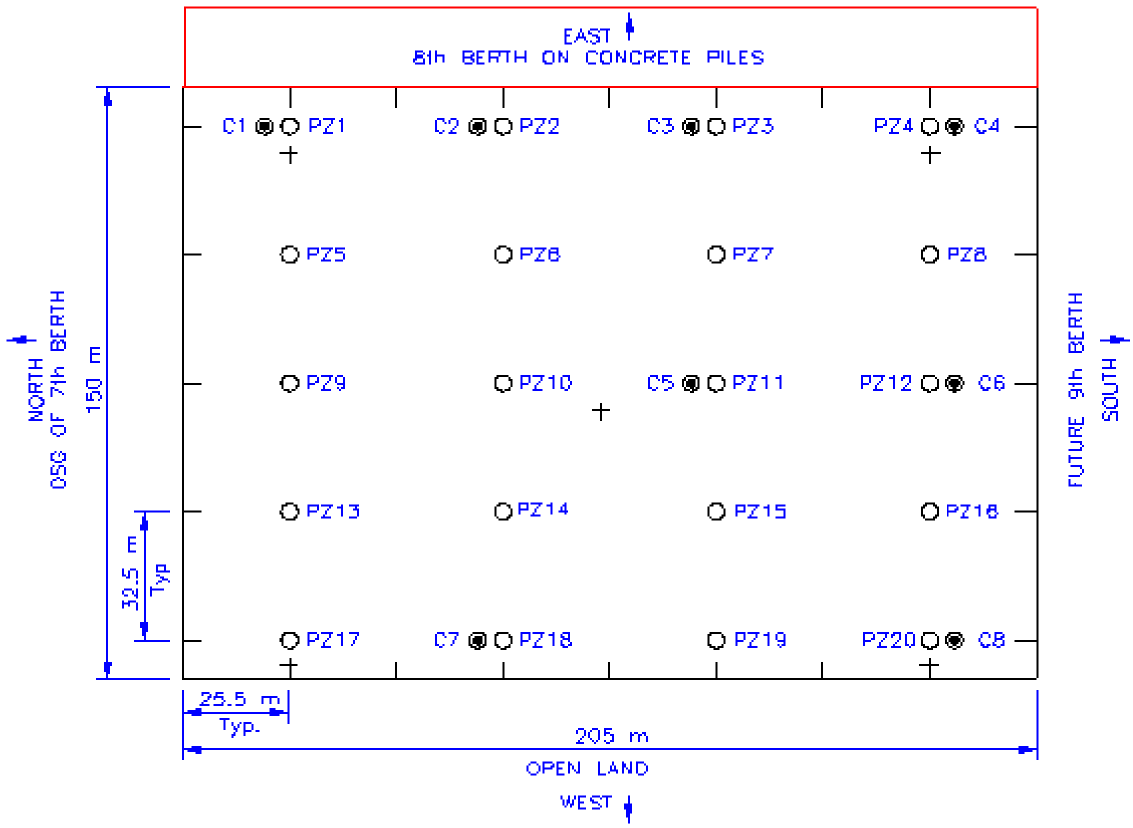
A monitoring program is generally required to provide a forewarning of lateral instability of the embankment, thereby allowing remedial measures to be implemented before critical situations arise. Remedial measures may include a waiting period to allow the foundation material to increase in strength as pore water pressures dissipate and/or the construction of stabilizing berms or the removal of some fill.

In case the monitoring program is required to provide an indication of incipient failure, horizontal deformation measurements will normally provide the most direct data. An Encardio-rite model EAN-20 inclinometer system is the primary tool, supplemented with surface deformation monitoring by surveying methods. However, measurement of pore water pressure often gives a first indication of failure conditions developing than can be derived from deformation data. To be certain of having measurements in the zones of initial yielding, a relatively large number of piezometers may be required.

3 CASE STUDY

1.7 Consolidation of open stacking ground (OSG) behind jetty at Kandla sea port

With increasing shipping load, new ports are being constructed and additional berths are being added to several existing ports. At the Kandla port in Gujarat, seven berths are already in operation. Construction work on the eighth berth is now nearing completion. Two more berths have been planned for the near future



Encardio-rite instrumented the eighth berth at Kandla port. The instruments were supplied through the civil engineering firm of 'Afcons Infrastructure Limited' and were found to be very useful in optimizing the pre-loading operations for consolidating the OSG area. Some of the important data monitored by the geotechnical instruments manufactured and installed by Encardio-rite at Kandla during 1998-99 has been highlighted in this application note. The instruments included 20 piezometers, inclinometer system at 8 locations and 5 vertical settlement gages. In addition to this, Afcons themselves installed 29 settlement platforms at the OSG to monitor the soil consolidation with the help of a theodolite. Instrumentation data was collected and monitored for the final 4 m of surcharging from El 7.0 m to El 11.0 m above sea level.

At the Kandla port, the cargo is off-loaded from the ship to one of the seven concrete jetties, built on pile foundations. The cargo is immediately transferred for storage to the OSG next to the jetty. The OSG has to be stable enough to take up the weight of cargo which may accumulate over long periods of time. For this reason, the soft clayey soil of the OSG has to be stabilized by pre-loading it with layers of soil. This was done in the case of the OSGs adjacent to the first seven jetties. The OSG next to the eight jetty is presently being consolidated. The existing soil, being close to the sea, is loose and is saturated with pore water. During and after the pre-loading process, the pore water is dissipated through vertical band drains installed for the purpose. The vertical band drains are in turn terminated in horizontal sand filled trenches. During pre-loading, the pore water pressure in the soft soil under the OSG increases. The band drains accelerate the consolidation process by fast dissipation of the pore water pressure.

During the pre-loading process, critical geotechnical parameters at the OSG area were continuously monitored to assess the behavior of soil during consolidation and thus decide the optimum pre-loading conditions.

1.8 Piezometers

Encardio-rite model EPP-31V electron beam welded vibrating wire type piezometers (stainless steel construction) having a range of 0-5 kg/cm^2 were installed to monitor pore water pressure (refer to data sheet no. 1087-97w for complete specifications). The piezometers were installed at elevations of +2 m (Pz 1,3,18 & 20), -2 m (Pz 5,7,14 & 16), -5 m (Pz 9,10,11 & 12), -9 m (Pz 6,8,13 & 15, and -13m (2,4,17 & 19) at twenty different locations on the OSG (0 m being the sea level). The OSG was pre-loaded gradually with soil and the behavior of pore water pressure, during and after the gradual pre-loading process was continuously monitored with the help of piezometers. Actual data on settlement and pore pressure, along with the theoretically expected trend, for the first 32 weeks from three of the piezometers is reproduced in § 3.2.1, § 3.2.2 and § 3.2.3.

1.8.1 Most of the piezometers followed the expected trend

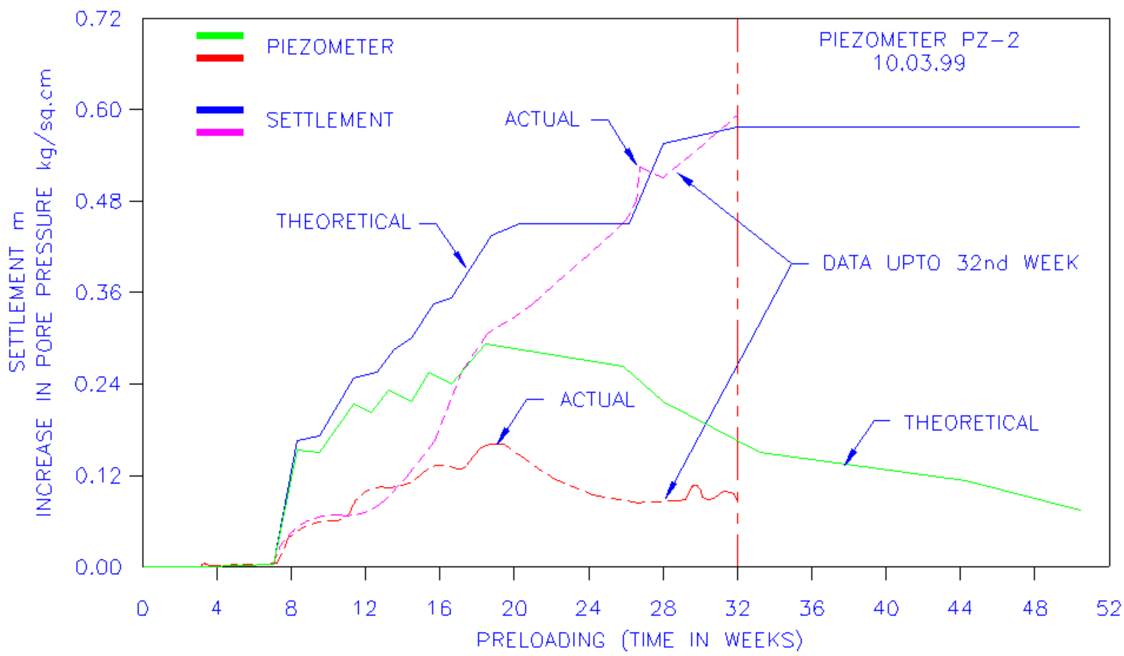


Figure 3.2: Readings of piezometer Pz-2 following expected trend

There was an increasing trend in piezometer readings (figure 3.2 above) during the pre-loading stage. After some time, the piezometer reading showed a slowly decreasing trend indicating water dissipation from that area. As can be noticed, 0.6 m of settlement has taken place by the end of 32 weeks.

1.8.2 Piezometers at two locations showed almost constant data

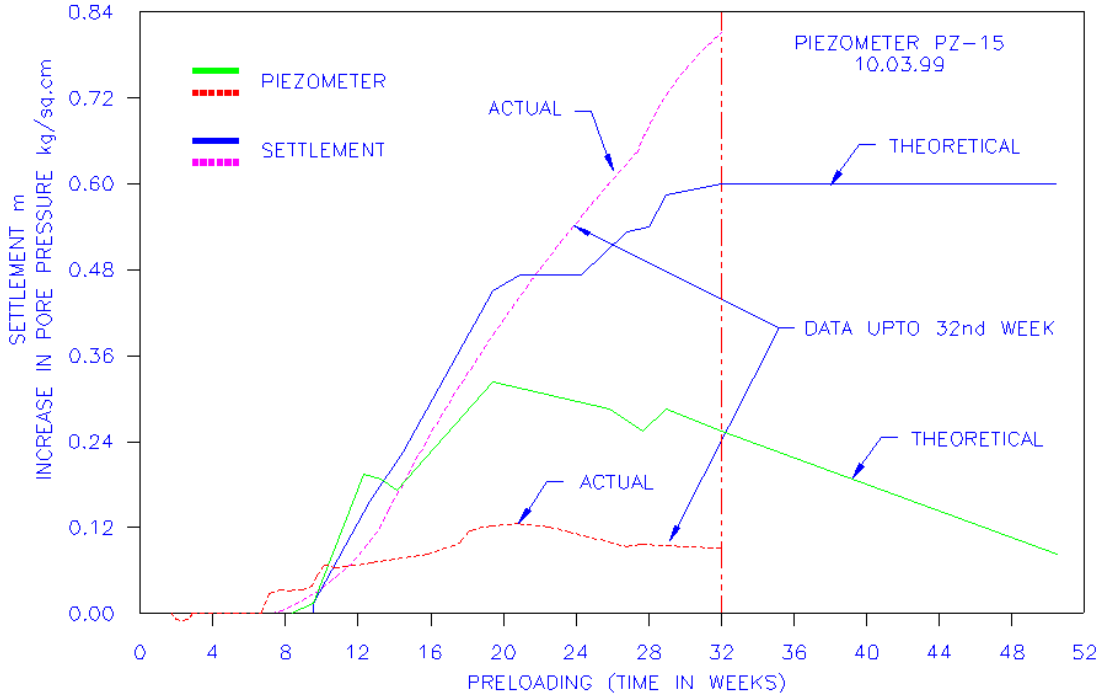


Figure 3.3: Readings of piezometer Pz-15 showing constant output

At the location at which the piezometer PZ-15 was installed, the rate of increase of pore water pressure because of pre-loading and the rate of dissipation of water is nearly equal. The amount of pore pressure rise is immediately nullified by quick dissipation of water through the band drains. See figure 3.3 on previous page. Also notice that the settlement is greater than the theoretically estimated value.

1.8.3 Piezometers at three locations stopped giving proper output

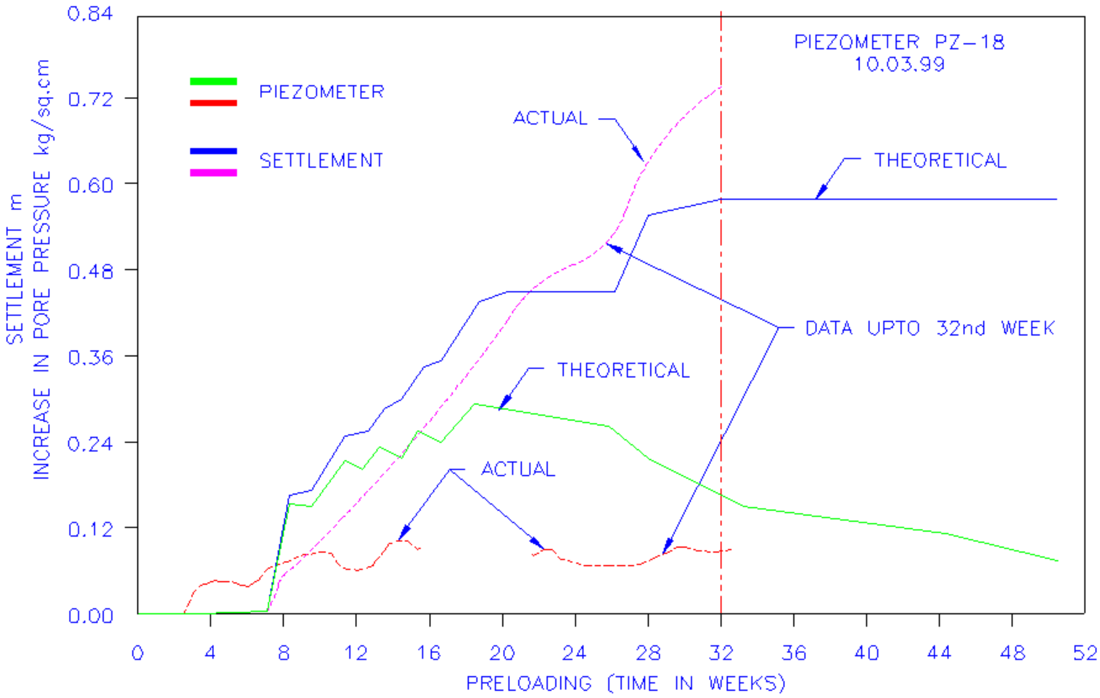


Figure 3.4: Readings of piezometer Pz- 18 before and after replacement

Three of the piezometers got damaged in the 15th week due to saline corrosion, even though they were of stainless steel construction. Stainless steels are normally passive, but when exposed to corrosive solutions whose oxygenating power is low, these steels become active. Oxygenating agents must be present and replenished constantly to maintain passivity. Otherwise localized corrosion frequently results in pitting at the surface. It should be remembered that in case sea water in the vicinity of the piezometer is flowing, the pitting will be less than when it is stationary, as is in our application.

The piezometers were replaced with new piezometers in the 21st week. The new piezometers were provided with ample protection against sea water corrosion. For details of protection provided, refer to § 6.2 of instruction manual # WI 6002.19 - model EPP-30/34V. In short, the stainless steel diaphragm of the piezometer was protected with a thin layer of GE silicone compound TSE 399 and the outer surface of the piezometer was protected by wrapping a saline resistant tape like '33 super PVC 3M tape'.

The newly installed piezometers are now giving satisfactory data. Data from one of these piezometers up to the 32nd week along with the settlement data is reproduced above in figure 3.4.

1.9 Vertical settlement devices

Encardio-rite magnetic probe extensometer model EDS-91 along with its casing and telescopic coupling (refer to data sheet no. 1098-98w for complete specifications) were installed to monitor and measure the subsurface vertical settlement of the soil. The extensometer casing was installed up to a depth of 16.5 m below the sea level at five locations in the OSG area. The OSG was 7 m above the sea level at the time of installation of the casing. Holes of 75 mm ϕ were drilled to a depth of around 25 m to install the casing and the ring type spider magnets. After completion of the drilling, the holes were treated by pumping a thick solution of bentonite for about one hour to prevent the bored holes from collapsing. Spider magnets were arranged at approximately 3 m spacing along the length of the casing. On advice of the consultants, the space around the casing was filled with a solution consisting of 20 % cement and 80 % local clay.

Settlement readings were taken with a properly encapsulated water proof reed switch probe firmly attached to a flat graduated cable made of high tensile virtually non-expandable, non stretch polyethylene coated tape.

The data on vertical soil movement matched with the settlement shown by the 29 number of platform type settlement gages provided and installed by AFCONS themselves at the site.

1.10 Inclinometer system

At Kandla port, the OSG has the eighth berth to its east, in the direction of the Arabian Sea. The OSG of the seventh berth is to its north (see figure 3.1). All the existing seven berths and the new eighth berth are parallel to the coast line. There is open land with unconsolidated soil in the west and the south of the OSG of the eight berth.

The usefulness of the inclinometer system lies in the fact that it gives the actual lateral sub-surface ground movement during the soil consolidation process and also later on for long term monitoring. Ground movement towards the newly constructed jetty is dangerous. To ensure safety of the jetty, it was concluded on the basis of theoretical analysis that the movement of the underground soil in the east direction should not be allowed to exceed 300 mm during consolidation or later during operation of the jetty. The inclinometer system therefore forms an important part of the instrumentation scheme, during consolidation of the soil and also for long term monitoring.

The Encardio-rite model EAN-20 inclinometer system (refer to data sheet no. 1064-97w for complete specifications) has been installed to monitor the lateral movement in the subsurface underground soil. 75.5 mm outside diameter PVC inclinometer grooved casing (3 m long) with telescopic couplings was installed up to a depth of 16.5 m below the sea level at seven locations in the OSG. area. Holes of 100 mm ϕ were drilled to a depth of around 25 m from the top of the OSG which at the time of installation was 7 m above the sea level. On the advice of the consultants, the inclinometer casing was installed in these holes using a 1:1.25 cement bentonite mix. During the final 4 m of surcharging from El 7.0 m to El 11.0 m above sea level, the inclinometer casing was extended using 1.5 m long casings and telescopic couplings.

The locations where the tubing is installed are marked in figure 3.1. The inclinometer grooved casing was installed at four locations at the east (near the newly constructed eighth berth), three locations at the south, two locations at the west and one location in the middle of the OSG. No casing was installed at the north side where the OSG of the seventh berth was located as the soil there was already in a consolidated state.

Readings were taken at 0.5 m intervals from the bottom of the borehole. The probe used is an Encardio-rite biaxial servo accelerometer and senses the horizontal deviations in the north-south and east-west directions simultaneously. Data was recorded on a portable battery operated data logger with a storage capacity of 30,000 readings.

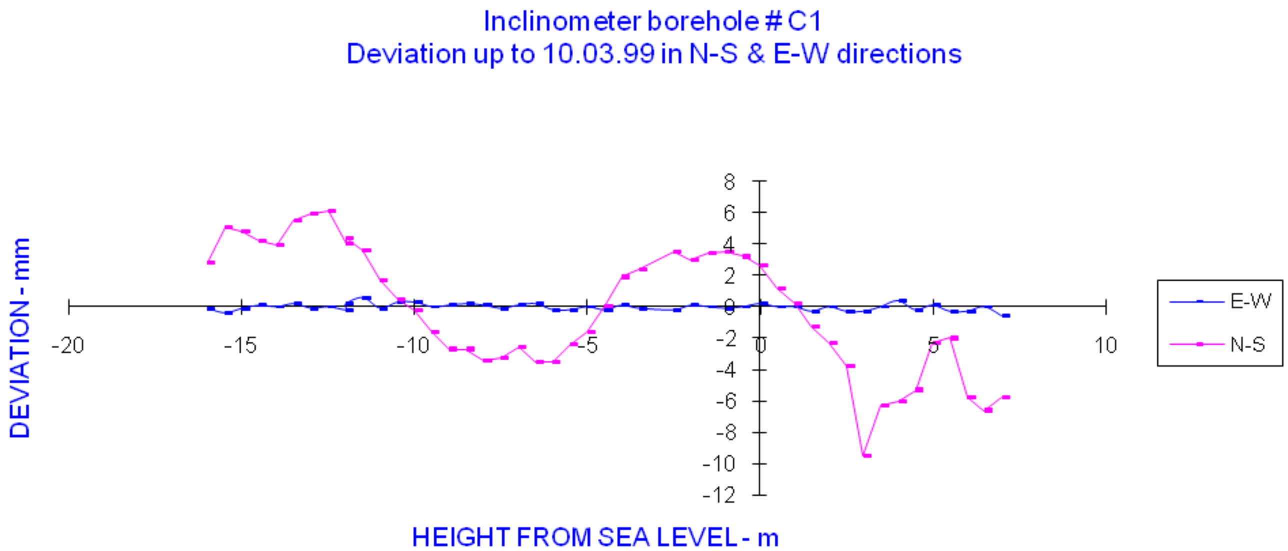


Figure 3.5: Inclinometer readings at bore-hole C1

During the final 4 m of surcharging from El 7.0 m to El 11.0 m above sea level, the maximum deviation observed in borehole C1 (next to the jetty at the north side) was towards the south and was only 9.5 mm. There was hardly any lateral shift in the direction of the jetty. The data is plotted in figure 3.5.

Inference :

- **In the east-west direction, the “on date” curve is coinciding with the “initial” curve, meaning no appreciable change in deviation.**
- **In the north-south direction, the maximum deviation is 9.5 mm towards the south direction.**

Data from the other boreholes is not presented in this application note. However, the maximum subsoil deviation observed in any borehole up to the 32nd week was at location C8. At this location a maximum subsoil lateral movement of 260 mm was registered in the south direction. This was as expected owing to unstable and unconsolidated soil on the south side.

Acknowledgment

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