Tank bottom plate movements due to freeze and thaw of foundation soils

Etude des mouvements de la base d'un réservoir de gaz liquéfié provoqués par le gel et le dégel du sol

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SYNOPSIS The foundation movements of a liquid gas storage tank are examined and compared with predictions. Due to inoperative foundation heaters soil freezing occurred below the tank with resulting heave of the bottom plate. In 1981 the tank contents were changed from liquid propane (-42°C) to liquid butane (-12°C) with the resulting thawback of the foundation soils and corresponding thaw consolidation. Geotechnical and thermal analyses were carried out to predict movement of the freezefront and bottom plate movements. In 1982 the tank was emptied to permit complete thaw of the foundation. Additional geotechnical analyses were performed to evaluate foundation conditions prior to putting the tank back in service. Finally, a water load test was carried out to confirm the results of a field and laboratory investigation.

INTRODUCTION

The construction of a 250000 barrel liquid gas storage tank was completed in late 1971 on the island terminal of La Salina, located on the eastern shore of lake Maracaibo in Venezuela. The tank was put into service in 1972 for storage of liquid propane at -42°C. After several months in service, the heating system in the tank foundation became inoperational. Freezing of the soils was suspected and proved by horizontal boring during a study carried out in 1976. In 1980, the effect of the frozen soils on the tank foundation became apparent when, after emptying the tank for maintenance purposes, heave of the bottom plate was measured during an internal survey. Based on these findings, an investigation programme was carried out to determine the position of the freezefront and to provide data for thermal and geotechnical analyses regarding future behaviour. In addition, it was planned to change the tank contents from liquid propane (-42°C) to liquid isobutane (-12°C) with the result that the advancing freezefront would begin to thawback to the equilibrium position for butane storage conditions. From April 1981, after putting the tank into butane service, diametral measurements of bottom plate elevation were made using an hydraulic balancing system to monitor thawback in terms of thaw-consolidation settlements. Temperature measurements were also taken using horizontal and vertical thermistor strings installed below the tank.

In 1983, the tank was again taken out of service for maintenance. At this time, it was decided to maintain the tank empty to allow complete thawback of the foundation soils. During this period, a further geotechnical and structural study was performed to analyse tank behaviour under future conditions.

The object of the paper is to consider the measured bottom plate movements and compare them with predictions made using results obtained from laboratory tests. The soil conditions on complete thaw of the foundation, and corrective measures required before putting the tank into service will be briefly discussed.

FOUNDATION CONDITIONS

The liquid propane storage tank is situated on the south side of La Salina island terminal, which was constructed in the mid-fifties by placement of hydraulic fill within an area bounded by a continuous concrete sheet-pile wall. The fill was suction-dredged from Lake Maracaibo and comprised, in general, large balls of stiff clay in a matrix of reworked sand, silt and clay. However, in the area of tank 250130, where an overflow spillway was located for control of the filling process, soil conditions vary and resedimented clays, silts and sands form the foundation soils, with almost total absence of the stiff clay balls that predominate in other areas. These conditions have been observed in the various soil investigation programmes which have been carried out in the vicinity of the tank. Details of the fill process are given by Whitman (1970).

Before construction of the tank, the area was preloaded using a soil surcharge imposing a load of 107 kPa in the centre of the tank; this being equal to the operational load of the tank. In addition, groundwater lowering was carried out using wellpoints to further increase the effective stress levels within the hydraulic fill. However, no details of the preload programme were available, so its effect on the foundation soils could not be assessed.

After completion of the preloading and removal of the soil surcharge, a circular trench approximately 5 m deep, located below the proposed tank ringwall, was excavated and backfilled with a medium plasticity clay compacted to at least 95% modified AASHTO dry density. Beneath the remaining area of the tank a 0,3 m layer of similarly compacted material was also placed.

The final stage of the foundation treatment programme consisted of a water load test to 1,25 times the full product load. No details of this hydrotest were available. However, details of previous and later hydrotesting, suggested that the surcharge period used, was sufficiently long enough for 90 to 95% of primary consolidation settlement to have occurred.

The tank itself is 54 m in diameter and 18 m high, with the tank shell supported on a reinforced concrete ringwall. The tank bottom plate is 7 mm thick welded steel plate over a 50 mm layer of bitumen, which covers a 150 mm layer of foamglass. Below the foamglass lies a 300 mm sand layer which incorporates the 18 mm diameter heating conduits, which were installed on 300 mm centres. A PVC membrane separates the sand layer from the foundation soils.

Groundwater is located approximately 1,5 m below the tank bottom plate.

PREDICTED FREEZEFRONT MOVEMENTS

In early 1976, it was discovered that the electrical heating elements, installed in the tank foundation to prevent soil freezing, had not been in use for approximately 4,5 years. Consequently, freezing of the soil beneath the tank had ocurred, which had caused heave of the bottom plate; the maximum amount of heave predictably occurring in the centre of the tank. Based on thermal computer analyses, a frost front advance of 3,96 m in the 4,5 year period was predicted with an equilibrium depth of 13,72 m obtainable after a further period of 25 years (Exxon, 1977).

To confirm the above analyses, a horizontal borehole was drilled 1,22 m beneath the tank ringwall. Good correlation with predicted results was obtained. On completion of the borehole, a horizontal thermistor string was installed in the hole to enable temperature measurements to be taken. Frost heave tests on retrieved samples were also performed, the results of which, will be discussed later.

In October 1980, a further site investigation was carried out by Woodward-Clyde Consultants (1981) by means of two vertical borings through the base of the tank and one outside the tank, adjacent to the shell. The operating company had decided to change the tank contents to isobutane at -12°C with the result that significant thanback of frozen soil was expected. The purpose of the investigation was to obtain data for analysis of future tank behaviour due to the change in conditions. Visual observations made at the time of the investigation indicated that the central area of the tank had heaved between 300 mm and 450 mm with a relatively symmetrical deformation pattern. After completion of drilling and sampling, a vertical thermistor string was installed in the borehole located in the centre of the tank.
Finite element analyses were carried out using a computer program capable of solving both linear and non-linear axisymmetric heat conduction problems for steady-state and transient condition, to enable the following:

- to estimate the position of the existing freezefront, i.e. the 0°C isotherm, under propane storage conditions
- to estimate freezefront position at the time of change in tank contents
- to estimate the steady-state position of the freezefront under butane storage conditions
- to estimate the rate of thawback of the foundation from existing conditions to the final steady-state condition in butane service.

The results obtained from finite element analyses were compared with those previously obtained from one-dimensional hand calculations with a correlation applied to account for three-dimensional conditions (WWC, 1981). The results of the analyses are shown in Fig. 1. The following points are of interest:

- reasonable agreement was obtained between the two types of analyses, considering the more rigorous nature of the computer solution.
- the predicted freezefront depth obtained from the computer solution as of October 1980 agreed extremely

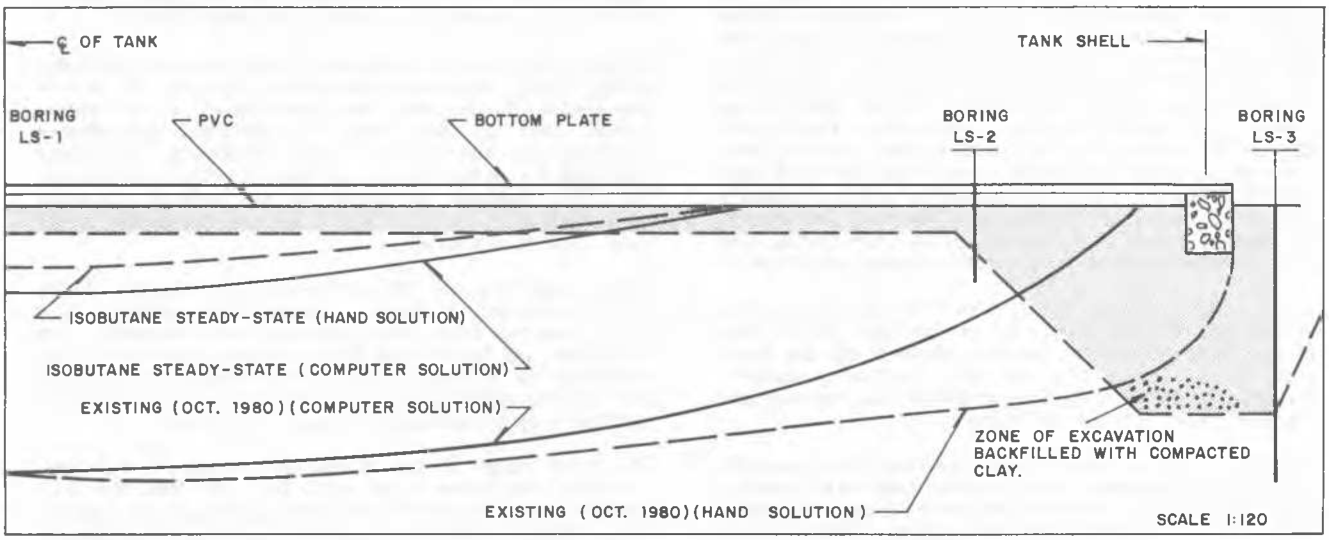


Fig. 1 Predicted Locations of Freezefront for Existing and Isobutane Conditions (WCC, 1981).

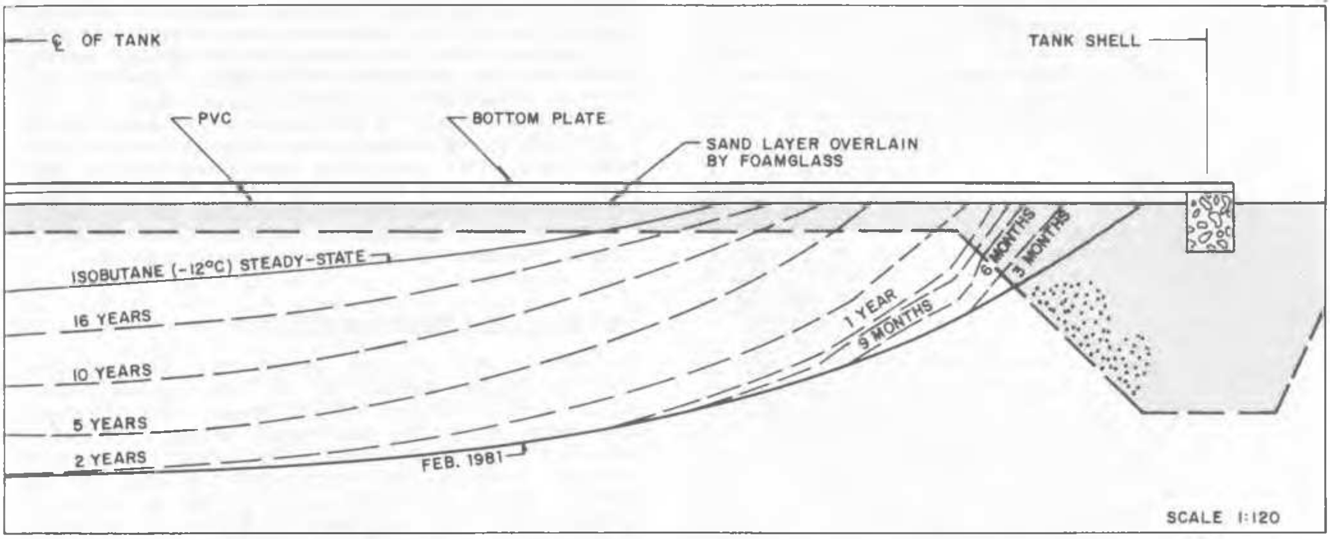


Fig. 2 Regression of the Freezefront Position for Change to Isobutane Storage (WCC, 1981).

well with depths obtained from the two borings.
- the steady-state freezefront depth at the centre of the tank under butane conditions was predicted to be approximately 2,5 m, implying a thawback of 4 m of soil below the tank.
- the time to achieve steady-state conditions in butane service would be in excess of 15 years.

The position of the freezefront at various times after product changeover is shown in Fig. 2.

BOTTOM PLATE MOVEMENTS

Measurement Systems

Two methods of measurement were used to monitor bottom plate movements:

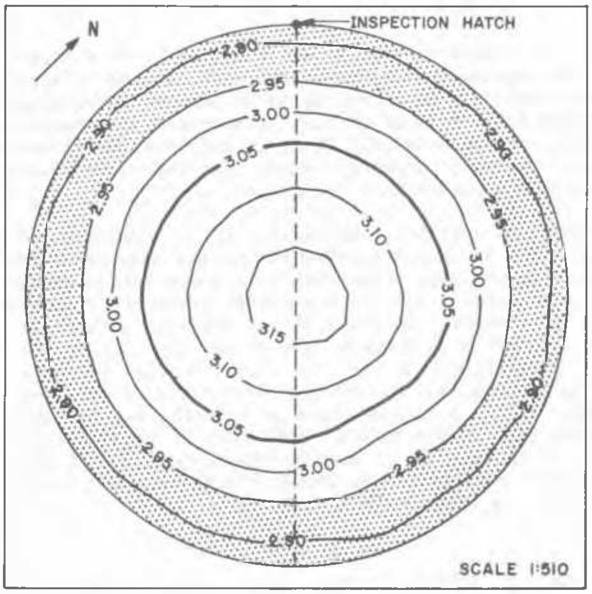
- internal theodolite survey after the tank had been emptied.
- measurement of relative change in level in one of the heating conduits using a petur-gauge system.

The results of the petur-gauge measurements, however, could only be used qualitatively since a significant range in values at any one point was obtained due to movement of the sensor in the conduit, temperature effects and the high compressibility of the system.

Maximum Heave of Bottom Plate

The maximum heave was recorded in October 1980, just prior to changing the tank contents to isobutane. Results of an internal survey, comparing the difference in elevation between the centre of the tank and twelve equally-spaced points on the inside edge of the shell, gave average, maximum and minimum heave values of 0,405 m, 0,456 m and 0,375 m, respectively.

The contours of the tank base plate after being put in service, as inferred from available construction drawings, are shown in Fig. 3, while Fig. 4 shows the effect of frost heave at is maximum condition. The shown contours are in metres.



— — POSITION OF CONDUIT LATER USED FOR PETUR GAUGE MEASUREMENTS

Fig. 3 Contours of Tank Base according to Construction Drawing (INTEVEP, 1984a)

Comparison of both figures indicates that the deformation was essentially symmetrical with only slight elongation on a N - S axis. Differences in the contour positions indicate an outward movement of 13,91 m for the 3,14 m contour, reducing to 2,91 for the 2,95 m contour. At this time pratically all of the tank foundation is above the 2,94 m level, compared to a corresponding 2,98 m level for the as-built structure. As the freezefront does not extend right to the edge of the tank foundation-a minimum distance of 1,5 m was predicted - it is unlikely that the increase in level at the shell is due to frost heave. A possible explanation is that formation of the rigid wedge of frozen soil had caused a certain degree of ground squeezing and subsequent heave in the area of the tank ringwall.

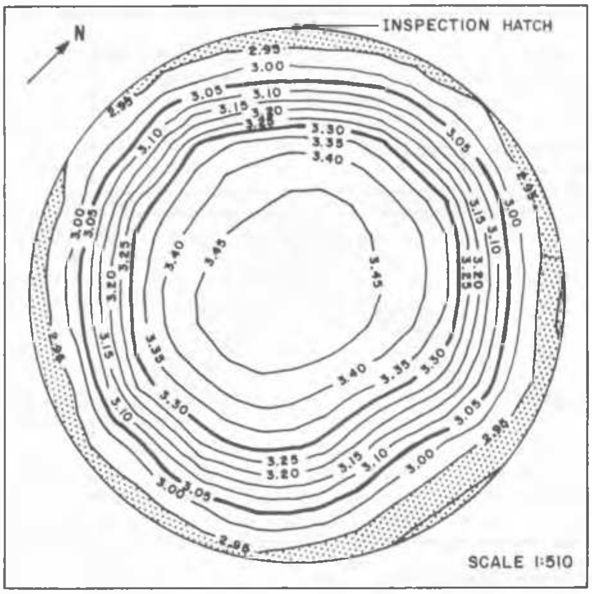


Fig. 4 Contours of Tank Base at Time of Maximum Frost Heave (INTEVEP, 1984a).

Since the freezefront depth was found to be at a depth of 6,86 m below the centre of the tank, the percentage heave which had occurred can be estimated as between 5,6% and 6,8%. A value of 5,9% is obtained at a radial distance of approximately 21 m, at the location of the second internal borehole, where the freezefront was encountered at a depth of 1,61 m.

As mentioned earlier, during the 1977 investigation frost heave tests were carried out on two samples taken from the upper soil strata which is present to a depth of 2,1 m. Using a 3,4 kPa overburden pressure, a frost heave of between 2,5% and 2,8% was obtained with heave rates between of 0,36 mm to 0,42 mm per day, giving the soils a negligible to very low classification in terms of frost susceptibility for the first cycle of freezing (EXXON, 1977). A second cycle of freezing was carried out for one of the samples resulting in an increased heave of 25,7% with an average heave rate of 2,3 mm/day. These results can be compared with recorded field data which is summarized in Table I.

TABLE I Summary of Heave Data to October 1980

Date	Depth of Freezefront (m)	Average Percent Heave	Heave Rate (mm/day)	Freezefront Penetration Rate (mm/day)
1976	3,96	6,3*	0,17	2,71
1980	6,40	6,3	0,14(0,10)	2,19 (1,63)

* assumed value
( ) value for period 1976-1980

It is apparent that the percentage heave obtained in the field is 2,5 times that obtained from laboratory tests, even though a larger overburden pressure was in existence. The reverse is true, however, in terms of heave rate, where field values are approximately 3 times smaller than laboratory ones. This can be explained by comparing the average rates of freezefront penetration. In the laboratory test it was controlled at 12 mm/day, while field rates ranged from 2,71 mm/day (1972-1976) to 1,63 mm/day (1972-1980), the difference being a factor of 6. Consequently, at least for the upper clayey layer, the increase in frost heave can be attributed to the slower rate of penetration of the freezefront; this permitting more extensive ice lens formation than would be the case for a faster penetrating condition. It would also appear that the soil below 3,96 m is less susceptible to heave which probably results from the increase in overburden pressure.

Thawback Under Isobutane Conditions

In February 1981, the tank was put into isobutane service and gradual thawback of the frozen ground began. For the period February 1981 to January 1983, readings were taken using the petur-gauge system, originally installed by Woodward-Clyde Consultants, to measure vertical foundation movements when the tank was in service. Using an average value of the variation in obtained readings, a settlement of 0,07 m at the centre of the tank can be estimated for this 2-year period. Average settlements in the foundation of 0,11 m were measured at a radial distance of 15 m, with less settlement (0,055 m) being recorded at distances greater than 20m**.

The results of the third internal survey of the tank bottom plate, carried out in January 1983, are shown in Fig. 5, which indicate that significant movement of the bottom plate had occurred.

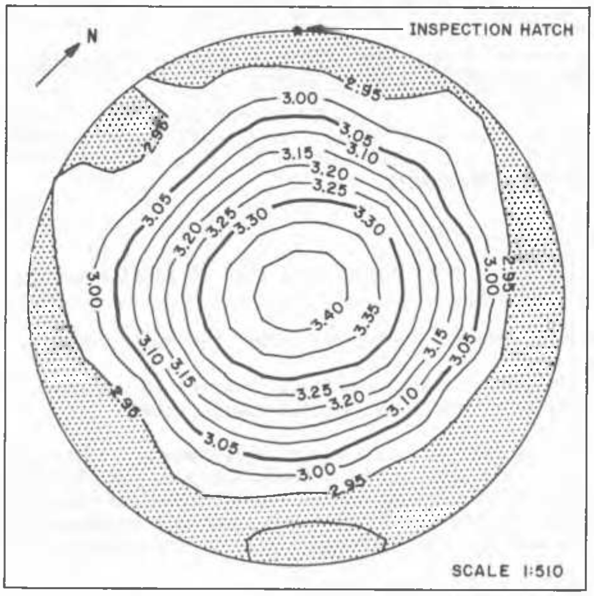


Fig. 5 Internal Survey after a 2 year Period of Thawback (INTEVEP, 1984a)

Comparison of Figs. 4 and 5 indicates a central settlement of 25 mm, with a maximum settlement of 90 mm at a radial distance of 15 m.

Inspection of the bottom plate in January 1983 also revealed that at various locations inside the tank,

** Settlements at radial distances were only evaluated for the east side of the tank since unacceptably large scatter in the data was obtained on the west side.

especially in the annular region adjacent to the tank shell, the bottom plate was not directly in contact with the underlying foamglass. A gap width of up to 3 cm was measured. Rippling of the bottom plate was also visible. The subsequent settlement distribution, hence became of greater importance due to the possible effect of high localised stresses caused by creasing of the bottom plate and welds.

In January 1983, a water load test using 10 m of water was carried out. The tank was loaded in a period of 16 days, and left to consolidate for a further sixteen. Unloading was completed in 25 days. The maximum settlement recorded was 0,016 m and the foundation behavior was essentially elastic with the frozen soil acting as a rigid inclusion in the foundation.

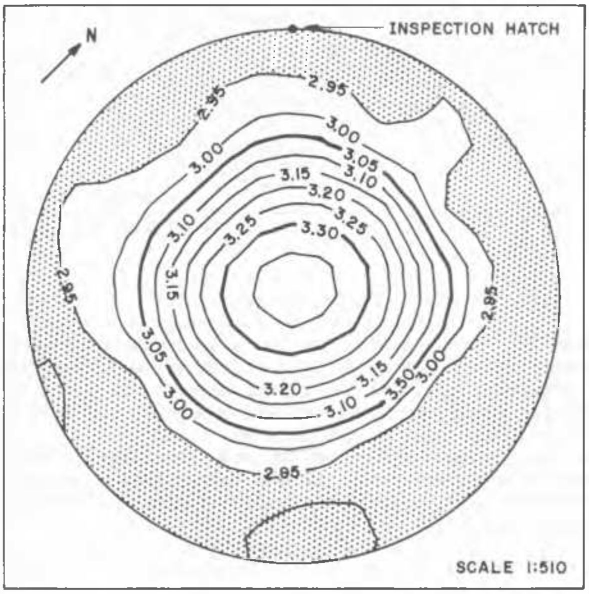


Fig. 6 Internal Survey for April 1983 (INTEVEP 1984a).

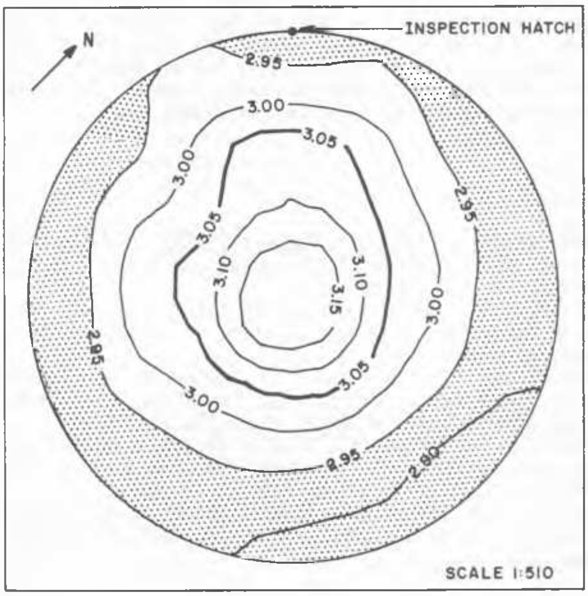


Fig. 7 Internal Survey Results for December 1983 (INTEVEP, 1984a).

At this time the decision was taken by the operating company to maintain the tank empty to allow complete thawback of the foundation soils. The thawback period was estimated to be between 12 and 18 months, assuming an average temperature inside the tank of 32°C. Figures 6 and 7 show conntours of the bottom plate obtained during 1983.

Thaw-Consolidation Tests

A total of 8 thaw-consolidation tests were carried out as part of the 1980 investigation. After placing the sample in the cell and applying a load equivalent to in-situ conditions, the sample was then left to thaw for 24 hours. The settlement occurring in this period was denoted as the thaw-consolidation of the sample. The sample was then loaded as in the normal consolidation test. Thaw strains of between 2% and 17,5% were recorded; the lower values being obtained for samples with an initial high dry density (1910 kg/m^3) and the higher strains corresponding to a lower initial dry density (1808 kg/m^3).

Calculated Thaw-Consolidation Settlements

Using the predicted positions of the freezefront during the thawback period shown in Fig. 2, and the results of the thaw-consolidation tests, settlements due to thaw of the frozen ground were calculated. Fig. 8 shows the obtained results for the period June 1981 to October 1983.

The full lines in the figure show settlement estimates made by WCC, obtained from petur-gauge readings. These values geneally correspond to the lower limit of settlement calculated using the thaw-consolidation test results. The dashed lines in the figure are calculated values using thaw-consolidation test data. Comparison of Figs. 4, 5, 6 and 7 show the values to be in reasonable agreement with those measured, i.e. for the period June 1982 to 1983 an additional settlement of 280 m was calculated whereas the measured value was approximately 250 mm.

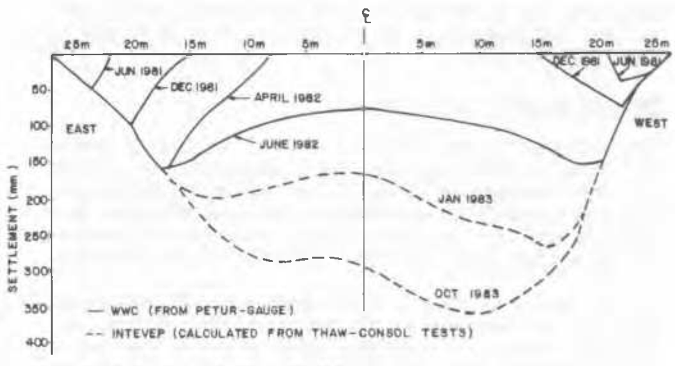


Fig. 8 Calculated Thaw Settlements

The results shown in Fig. 8 must be considered in terms of the following:

- the initial estimates using petur-gauge data for the west side of the tank were obtained from a mid-range assessment of the data scatter. Since at times this approached a value of 120 mm, the estimates may contain significant error. However, the data seem to be in good agreement with the survey carried out in

January 1983.
- due to soil variations between the east and west sides of the tank, the calculated values are more applicable to conditions on the west side. Settlement shown for the east side are 'best-estimates' using available data.
- the average amount of thaw-strain is 4,9%.
- based on measured and calculated settlement, it appears that reasonable values of foundation movement were obtained by use of data from thaw-consolidation tests, even though, at times, selection of the various parameters was somewhat subjective.

EVALUATION OF FINAL SOIL CONDITIONS

In September 1983, a further investigation was performed to evalute soil conditions prior to placing the tank in service. Thermistor readings indicated that the majority of the frozen soil had thawed; this thawback had occurred, for the most part, when the tank was empty and there was some doubt as to the condition of the soils in terms of strength and compressibility characteristics. Three vertical borings, two of which were located inside the tank, and three Dutch Cone penetration tests were carried out, followed by laboratory testing of disturbed and undisturbed samples. The results of the investigation can be summarized as follows:

- a 1,5 m thick layer of frozen soil was encountered below the centre of the tank. No frozen soil was found at a radial distance of 20 m.
- consolidation tests indicated that below 8 m depth, the soils were normally consolidated with respect to in-situ stresses for a fully loaded tank. Above 8 m, the soils were found to be underconsolidated, with OCR values between 0,47 and 0,67 (INTEVEP, 1984b)
- at a depth of approximately 7m, a layer of soft soil was encountered, typically with an undrained shear strength of 20 kPa.
- expected settlements for a fully loaded tank were calculated to be 250 mm in the centre, with lesser values at radial distances.

Based on the above results, and to further verify calculated settlements, a water load test was performed to 100% product load.

Results of Water Load Test

The hydrotest of the tank was carried out over a period of 90 days, which included three consolidation periods at water heights of 5 m, 7,5 m and 8 m. During the test, mesurement of settlement, and pore pressure were made in addition to strain gauge readings of stresses in the bottom plate in areas most affected by creasing.

At the centre of tank a total settlement of 145 mm was obtained as compared to 135 mm calculated for the hydrotest. Thermistor readings taken prior to the hydrotest suggested that all previously frozen soil had now thawed. The final state of the tank bottom plate is shown in Fig. 9.

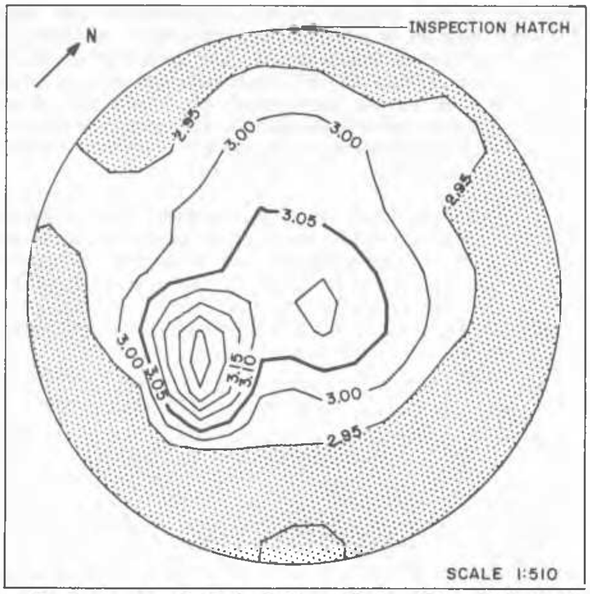


Fig. 9 Contours of Tank Bottom Plate after Hydrotesting.

CONCLUSIONS

Results obtained from oedometer tests suggested that, to a depth of approximately 8 m, the soil below the tank was underconsolidated with respect to the in situ stresses caused by a fully loaded tank. This depth corresponds to a zone 1 m deeper than the recorded extent of frozen soil. Hence, it would appear that, contrary to other studies, the effect of soil freezing on soil properties was such as to cause a reduction in undrained shear strength and an increase in compressibility, once thawing had ocurred.
The ratio between heave due to soil freezing and settlement from thaw-consolidation, was found to be approximately 0,8, which falls within limits obtained in previous studies.

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