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Performance of LPG Storage Tanks on Ground Improved by Stone Columns

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SYNOPSIS: This paper describes the construction of four large tanks on poor soil conditions consisting of hydraulic fill placed over estuarine silt in Dublin port. The limited differential settlement that could be tolerated by the tanks required that they could not be placed on the existing ground. The optimum solution was found to be ground treatment using vibro-replacement with the formation of stone columns and compaction of the fill. The paper describes the design method used and the control tests. The predicted settlements are compared with settlement readings of the tanks following construction. These show that the chosen solution has performed well and satisfied the design requirements.

INTRODUCTION

The storage capacity of a Liquid Petroleum Gas (LPG) depot 2 km from of the city centre of Dublin, Ireland was to be expanded. Aesthetics and space considerations precluded the use of overground storge tanks. Other storage methods were investigated, including deep underground caverns. The site was on land reclaimed from the estuary of the River Liffey and because of this the soil conditions were relatively poor. A cost analysis of the various storage options indicated that the optimum solution comprised the construction of cylindrical steel tanks placed on the surface of the existing ground with their longitudinal axes horizontal and covered with earth. The manufacturers of the tanks laid down very strict tolerances for the allowable differential settlement of these tanks. Various methods of support for these tanks such as piles and preloading were considered before it was decided that ground treatment by vibro-replacement offered the optimum solution.

This paper sets out the methods used to estimate the short and long term settlements and the site control tests carried out during the work. These estimates are compared with the settlement readings taken on the tanks since their construction.

DETAILS OF STRUCTURE

The proposed structure comprised four LPG "bullet" storage tanks. These were 50m long by 5.5m diameter, placed on a 1m thick granular bed and covered with granular fill to give 0.5m cover to the tanks. The area covered by the tanks and fill was about 45m by 60m. Details of the arrangement are shown in Figure 1. A further four tanks may be placed adjacent to these tanks at a later date. The approximate average bearing pressure on the surface of the existing ground with the tanks full of LPG is 110kN/m2.

The tanks were designed to withstand a 50mm differential deflection over half their length (25m) and were to be water tested prior to filling with LPG.

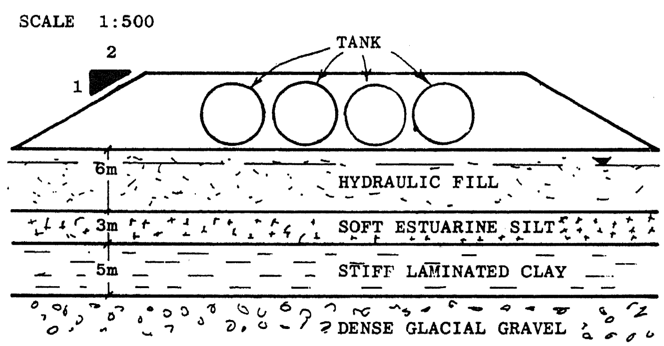

FIG 1 TANK ARRANGEMENT AND STRATIFICATION

GROUND CONDITIONS

The subsoil comprised about 6m of hydraulically placed fill over 3m of loose estuarine silt over 3m of gravel, over 5m of stiff laminated clay over dense glacial gravels. This stratification is indicated in Figure 1. The hydraulic fill and the soft estuarine silts had the greatest potential for settlement and are discussed in further detail below.

The hydraulic fill was essentially a loose silty sand with pockets of very silty material at the lower levels. A plot of the N-values versus depth are shown in Figure 2 and typical grading curves are given in Figure 3. It can be seen that the N-values dropped to zero in the silt pockets but were generally within the range 5 to 15.

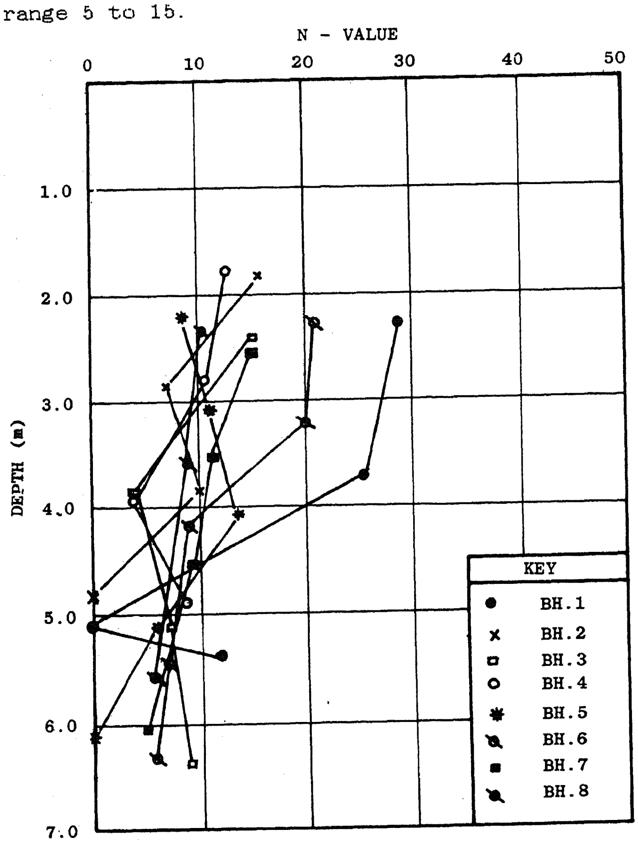

FIG. 2. **N VALUE versus DEPTH**

The estuarine silt was loose or soft and slightly organic. The undrained shear strength measured by in situ vanes tests and quick undrained triaxial tests on 38mm and 100mm diameter specimen from piston samples recorded c_u values of between 15kN/m2 and 30kN/m2 with a sensitivity of 1 to 2. Laboratory consolidation tests indicated that the appropriate m_v value was between 0.19m2/MN and 0.75m2/MN, the low values being associated with the sandy zones. The preconsolidation pressure for these soils obtained from the e-log p curves using the Casagrande method agreed with the existing overburden pressure. The silt layer was therefore essentially normally consolidated. The silt had a liquid limit of between 34% and 60% with a plasticity index of about 16% to 30%. This material generally plotted as an inorganic clay of medium plasticity on the plasticity chart. A typical grading is shown on Figure 3. Although the index tests classified this soil as a clay, its grading and visual behaviour was more that of a silt. Because of this the term silt is used to describe this soil. Laboratory consolidation tests gave c_v values of between 1m2/yr and 15 m2/yr whilst in situ permeability tests carried out in piezometers inserted into the silt gave permeability values which indicated c_v values of about 40 m2/yr.

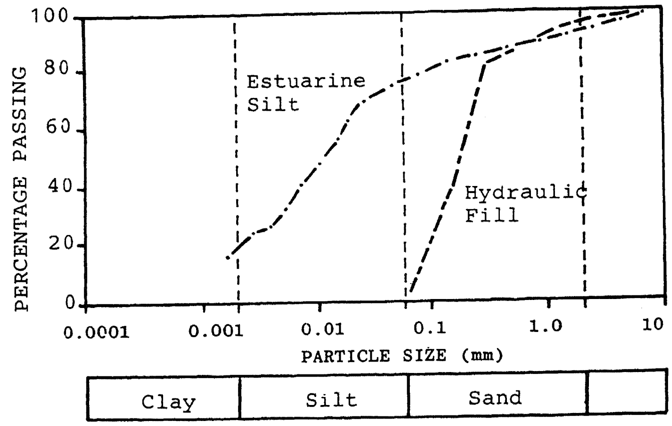

FIG. 3 GRADING CURVES FOR SILT AND FILL

The water level in the hydraulic fill varied with the tide. The minimum recorded level was 1.55m below ground level at the time of the investigation.

GROUND IMPROVEMENT METHOD

Using a conventional analysis it was estimated that the settlement of the existing fill and the estuarine silt due to the loading of 110kN/m2 from the tanks and the earth embankment would be about 175mm. About 80% of this settlement, 140mm, is due to consolidation of the silt layer. Settlements of this order were unacceptable for the LPG tanks and therefore it was necessary to find some method to reduce these settlements.

Various options were considered including preloading, piled foundations and vibro-replacement. Preloading was ruled out because of the extreme time constraints imposed on the project. Piling was more expensive than ground treatment and was considered to be less compatible with the flexible type of structure proposed. Ground compaction-replacement with water flush was considered to be the most appropriate method. The ground treatment was taken through the hydraulic fill and the estuarine silt layers onto the underlying gravels. The average depth of treatment was 10m. This process essentially formed stone columns for the entire depth and also compacted the permeable hydraulic fill. Thus a stiff upper layer was formed under the tanks.

In line with normal construction practice in this country for this type of specialist work, specialist contractors were required to submit their design/construct proposals for the ground treatment and to indemnify the client against non-performance. The specification set out the settlement criterion, the type of gravel or stone to be used in the columns, the environmental conditions relating to the disposal of outwash water and the number and type of site control tests to be carried out. The proposals submitted by the contractors were assessed by E G Pettit and Co. The joint proposal submitted by Irish Geotechnical Consulting Services Ltd and Cementation Co (Ire) Ltd was accepted for the work. This proposal provided for stone columns at 2.3m centres on a triangular grid pattern with a minimum diameter of 700mm and a maximum diameter of 1000mm. The vibroflot was 300mm diameter. The design proposal included extra columns at the outer edges to prevent lateral squeezing out of the soil by plastic yielding.

The work commenced on 28 January 1985 and was completed on 4th March of the same year. A total of 637 No. stone columns were formed. The volume of gravel used far exceeded the initial estimates. This was considered to be due to erosion of the estuarine silt layer by the water flush.

SETTLEMENT PREDICTION

The settlement of the tanks on the improved ground was estimated principally by using the reduction factors proposed by Priebe (1976). These showed that, for the triangular pattern of probe points adopted and assuming a O' = 45 for the angular stone used in the columns, the settlements in the estuarine silt layer would be half those determined from the conventional analysis for the untreated ground under the same load. This implies that the consolidation settlement would be about 70mm. The settlement due to compression of the hydraulic fill would be of the order of 10mm. The total settlement was therefore estimated to be about 80mm with an estimated differential settlement of 40mm. This was within the design tolerence.

Because of the high values of the coefficient of consolidation, the consolidation settlements were estimated to take about 6 months.

CONTROL TESTS

It was appreciated that it would be difficult to carry out a site test capable of applying a reasonable load to the section of the stone column in the estuarine silt. The effectiveness of the ground treatment was assessed using three different types of load test, each designed to test different volumes of soil. These comprised 0.6m diameter circular plate tests, a 2.5m by 2.5m pad test located centrally over a column with a load of up to 140 tonnes and a water test of the tanks themselves.

The plate loading tests were carried out both on top of the columns and in between, the latter to see if the hydraulic fill itself was compacted. The results of these tests demonstrated that the vibro-flot successfully compacted the hydraulic fill. The estimated Young's modulus (E) values at both locations assuming a Poisson's ratio of 0.2, were 95 MN/m2 and 78 MN/m2, respectively. These values were confirmed by the pad test which gave an approximate E value for the hydraulic fill of 70MN/m2.

The water test of each of the tanks applied a pressure of about 120 kN/m2 over a relatively large area. The earth surround was not at full height for these tests and each tank was tested separately. The settlements under these tests were less than 25mm.

MEASURED SETTLEMENTS

Since completion of construction, the settlement of all four tanks has been monitored by recording regularly the levels at four points on the top of each tank. These readings were first taken after the tanks had been constructed and covered with soil . They have been filled with LPG for most of the time since the readings began. As mentioned previously, the consolidation settlements were estimated to take about 6 months. The tanks have been in place for over 3 yrs, consequently movement would be expected to have essentially ceased.

The level readings for the four tanks have been plotted in Figure 4. These show that the

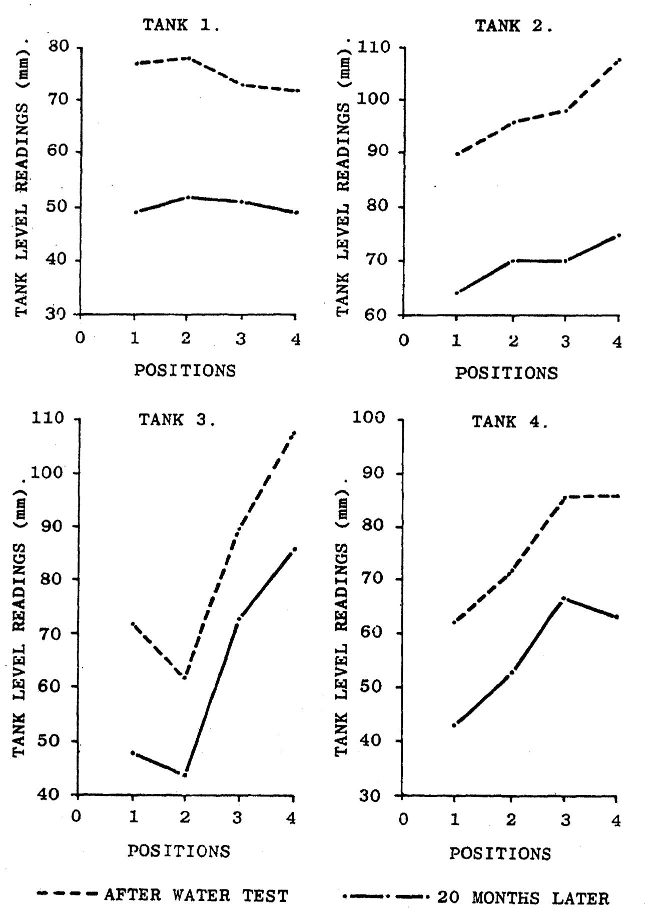

Fig. 4. LEVEL READINGS ON TANKS.

tanks are settling uniformly and that the differential settlement has not increased beyond the initial differential settlement which occurred on the first filling of the tank. The settlement for a point on tank 18 has been plotted against log t in Figure 5. This plot shows that settlement is continuing at a steady rate and is likely to continue. Assuming that this represents secondary consolidation a C_α value of 8x10-3 would be interpreted. This of the order of magnitude to be expected from an organic silt with an initial water content of about 60%. However the total settlement to date is still less than that estimated from the field and laboratory tests and the differential settlement is well within the design tolerances.

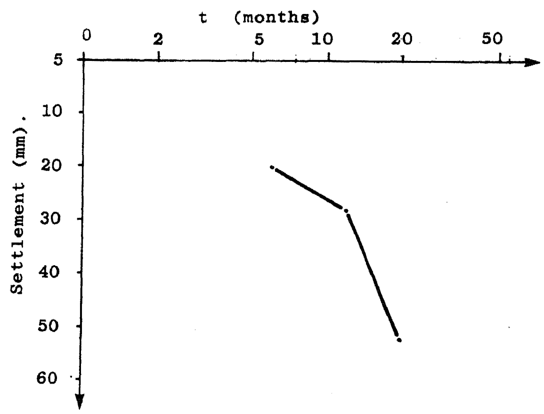

FIG 5 SETTLEMENT versus TIME

CONCLUSIONS

1 Ground treatment by vibrocompaction-replacement with the formation of stone columns and compaction of the fill was used successfully to improve the ground to enable the construction of long 'bullet' LPG storage tanks constructed on loose hydraulic fill over soft estuarine silt.

2 The total and differential settlements are considerably less than those estimated from field and laboratory tests. There is a small but on-going settlement of the tanks which is possibly due to secondary consolidation. However this further movement is occurring uniformly along the length of the tanks and is not giving rise to increased differential settlements.

REFERENCES

Priebe, H. (1976) "Abschätzung des Setzungsverhaltens eines durch Stopfverdichtung verbesserten Baugrundes" Die Bautechnik, 53.5.