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Long term settlement of foundations made of 195 x 147 m slabs built on a layer of fluvial sediment

Affaissements à long terme d'une fondation en dalles de 195 x 147 m sur une nappe de sédiments

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ABSTRACT
A waste water treatment plant was built on an open space in the North of Spain located on top of recent alluvial deposits ranging in thickness from 10 to 20 m. For the past 40 years blast furnace slag has been depositing on this open space forming a layer which, prior to the start of construction of the treatment plant and precisely coinciding with its siting, was as high as 15 m and this caused consolidation of the alluvial deposits beneath, allowing part of the installations to be built using direct foundations, having taken the precaution of not exceeding the preconsolidation load.
The biodigestor tanks occupy two 62 x 195 m rectangles which when filled can take a maximum depth of 8.8 m of water. These two rectangles are separated by a 23-m wide corridor containing a fill conveying a similar pressure on the ground to that of the tanks under operation, whereby the area of 147 x 195 m can be taken to be under a uniform load. The tanks each consist of three equal deposits built on foundations of 28 concrete slabs, 14 for each of the two rectangles. Before they were built, some 5 m of fill were removed to guarantee that the working loads of the two tanks would remain below the ground's preconsolidation pressure. This article analyses the evolution of the settlement recorded over the 2.5-year period following the filling of the tanks and also reports on the way the structure has behaved.

RÉSUMÉ
Les dépôts digesteurs occupent deux rectangles de 62x195 m où, lorsqu'ils sont pleins, l'eau atteint une hauteur de 8,8 m. Ces deux rectangles sont séparés par un couloir de 23 m de large sur lequel a été placé un remblai qui transmet une pression sur le terrain semblable à celle transmise par les dépôts quand ceux-ci sont en fonctionnement, ce qui permet de la considérer comme une zone uniformément chargée de 147x195 m. Ces dépôts sont constitués de six cavités égales, trois dans chaque rectangle, cimentées sur 28 dalles de béton armé, 14 sur chacun des rectangles. Préalablement à sa construction, il a été retiré de la terre sur une hauteur de 5 m afin de garantir que les charges de travail des dépôts soient maintenues au-dessous de la pression d'avant consolidation. Cette communication permet d'analyser l'évolution des affaissements enregistrés pendant 2 ans et demi après avoir rempli les dépôts, ainsi que le comportement de la structure

1 INTRODUCTION

The Galindo Waste Water Treatment Plant was built on clayey silt colluvial deposits ranging in thickness from 10 to 20 m, which for over 20 years had been preconsolidated by a layer of blast furnace slag that was 15 m deep in some places.

Taking advantage of the overconsolidation provided by this fill, the treatment plant was built, removing enough of the slag layer to maintain the working load of the foundations below the consolidation pressure to which the site had been subjected.

As part of the treatment plant, the set of Phase 2 biodigestor tanks consists of six deposits taking up two 62 x 195 m rectangular strips (Fig. 1) each one containing three sequenced deposits, separated by a 23-m strip of fill.

The foundation for each of these strips consists of reinforced concrete slabs, numbered 1 to 14 in Figure 1, on top of which the six deposits were built. The clayey silt in this area was 15 m thick.

The reinforced concrete perimeter deposit walls are 10 m high and 50 cm thick, conferring longitudinal rigidity to the structure.

In addition, the deposits are separated by the same type of wall only running perpendicular to the perimeter walls and are divided even further by another set of similarly transverse walls inside each individual deposit, as illustrated in Figure 1.

Figure 1 also shows the points where settlement monitoring is taking place and gives the deposit filling dates, taken to be the starting date for the settlement, which range from 27 March, 2001 to 15 May, 2002.

The excavation work carried out to build the biodigestor tanks went from elevation +6 to +1.20 m and involved removing an 0.96 kg/cm^2 load from these rectangular deposits, causing the bottom to heave to a greater extent in the centre areas of the site than in the perimeter.

Subsequently, construction of the concrete slabs and walls of the deposits and the pressure of the water during normal operation created an increased load of 1.1 kg/cm^2, giving rise to a net load increase of 0.14 kg/cm^2 as compared to the load over recent years, yet remaining below the site's initial preconsolidation pressure.

The effect of the preloading on the settlement caused by primary consolidation was studied by a series of authors including Johnson, 1970, Mitchell, 1981, Stamatopoulos & Kotzias, 1983, and on the secondary consolidation by Jamiolkowski et al 1983, Magnan, 1984, Kousotfas et al 1987, Yu & Frizzi, 1992 and more recently by Alonso, Gens & Lloret, 2000 and 2001, and Alonso, 2004.

The particular site under analysis produces a peculiar type of preloading as it remained at 2 kg/cm^2 for over 20 years thereby affecting the primary consolidation process, but also in the settlement caused by the secondary consolidation. This behaviour pattern however was modified by the drop in the preloading pressure by as much as 0.96 kg/cm^2 which took place over the past five-year period.

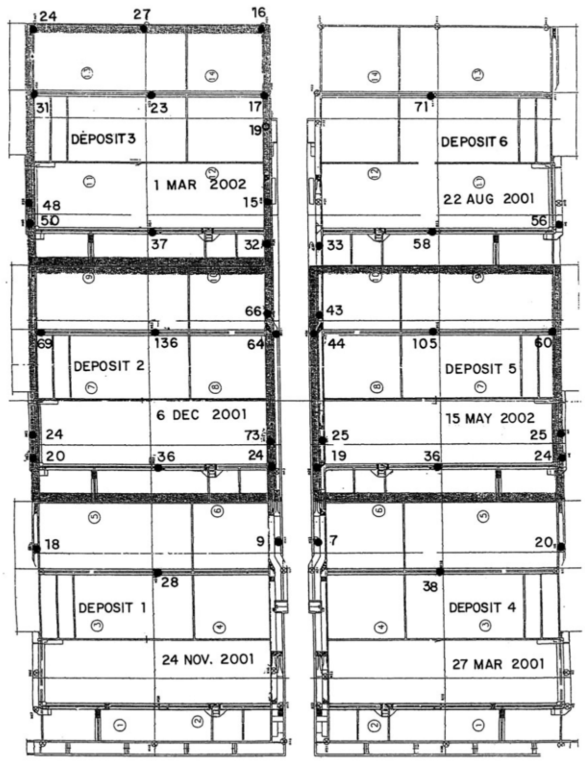

Figure 1. Ground plan distribution of the biodigestor deposits, the date each was filled and the magnitude of the settlement as recorded on 9 November, 2004.

2 SETTLEMENT MEASURING

Although a short consolidation period was initially planned, as a result of the overloading to which the ground was subjected for over ten years and the loading tests applying an 8-m high fill, considering the ground to be stabilised after one year, the actual fact is that over three and a half years later the stabilisation process is still ongoing.

Another aspect to be highlighted is the importance of the ground-structure interaction on the settlement measuring. Measurements were taken at points located at the top of the walls at spots where the high rigidity of the concrete walls forming the perimeter of the tanks and thereby standardising the settlement must be taken into account.

Water table variation is another factor influencing settlement measurements as the tank foundation level stands at +1.20 m while the water table stands above +2.50 m, with annual fluctuations in the range of 50 cm, causing movements to slow down at such times.

The settlement measured up to 9 November, 2004 is given in Figure 1.

As a general rule and in accordance with the load distribution, the settlement measured in the centre area of each deposit proved greater than that recorded in the perimeter.

Deposits 1 and 4, located in the South of the site and appearing at the bottom of Figure 1, were the first to fill up and yet record lower settlement. This ranges from 9 to 38 mm, indicating low compressibility of the clayey silt layer, similar to the behaviour seen in Phase 1.

This lower settlement was also recorded in the South of Deposits 2 and 5, the foundations of which share slabs with Deposits 1 and 4. Settlement in this area also ranges from 19 to 36 mm.

The highest settlement was recorded in the centre of Deposits 2 and 5 and corresponds to Slabs 7 and 8 belonging to Deposit 2 and the slabs also numbered 7 and 8 belonging to Deposit 5. Settlement in this area goes from 24 to 136 mm.

Deposit 6, appearing at the top of Figure 1, recorded an intermediate settlement value at its centre, lower than that of Deposits 2 and 5.

Deposit 3 was kept empty for long periods of time during which heave took place and has remained empty since the month of July, 2004, as a result of which the measurements recorded do not reflect the behaviour under load being analysed here, even though the measurements are accurate.

3 SETTLEMENT ANALYSIS

Taking into account the particular circumstances of Deposit 3, which can affect the way Deposit 2 behaves, the analysis of the evolution of the maximum settlement centred on Deposit 5.

Figures 2 show the settlement recorded, S in mm, as a function of $\sqrt{t}$, where t is the time in minutes. The evolution of the settlement occurring over these 2.5 years approaches a linear relationship, which for Deposit 5 is as follows:

$$Y_{26} = \frac{13}{1000}\sqrt{t} + 6 = 9{,}4\sqrt{t_a} + 6$$

$$Y_{17} = \frac{14}{1000}\sqrt{t} + 20 = 10{,}1\sqrt{t_a} + 20$$

$$Y_{6} = \frac{14}{1000}\sqrt{t} + 10 = 10{,}1\sqrt{t_a} + 10$$

$$Y_{27} = \frac{24}{1000}\sqrt{t} + 10 = 17{,}4\sqrt{t_a} + 10$$

$$Y_{28} = \frac{30}{1000}\sqrt{t} + 10 = 21{,}7\sqrt{t_a} + 10$$

$$Y_{16} = \frac{55}{1000}\sqrt{t} + 45 = 40\sqrt{t_a} + 45$$

$$Y_{8} = \frac{38}{1000}\sqrt{t} + 18 = 27{,}5\sqrt{t_a} + 18$$

$$Y_{29} = \frac{39}{1000}\sqrt{t} + 15 = 28{,}3\sqrt{t_a} + 15$$

t_a = time in years; t = time in minutes.

It can be deduced from this linear relationship that the initial settlement in perimeter areas is low, ranging from 6 to 18 mm, whereas it is higher in centre areas, ranging from 20 to 45 mm.

The speed of settlement is related to the coefficient $\sqrt{t}$ corresponding to the highest values, between 17.4 and 40 at the points measured in Slabs 7-5 and 8-5 forming the foundation for the centre area of this deposit. In the meantime the smallest settlement speeds appear in the southern area, next to Deposit 4, over Slabs 6-5 and 5-5, and do not go higher than a value of 10, despite the fact that part of them are under Deposit 5 (filling date 15 May,

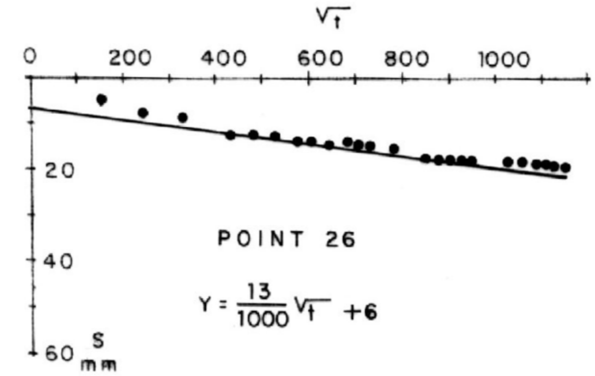

Figure 2a

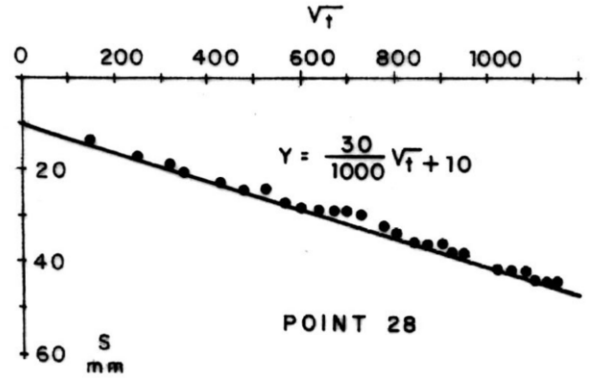

Figure 2e

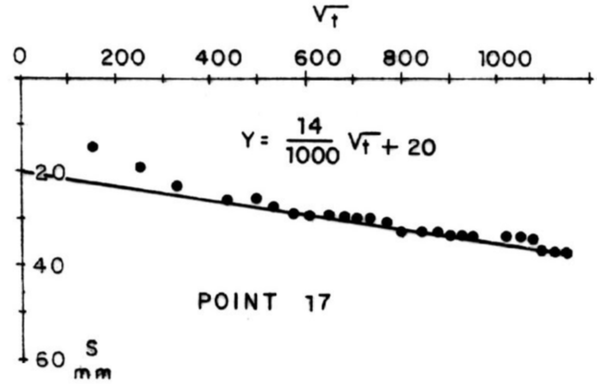

Figure 2b

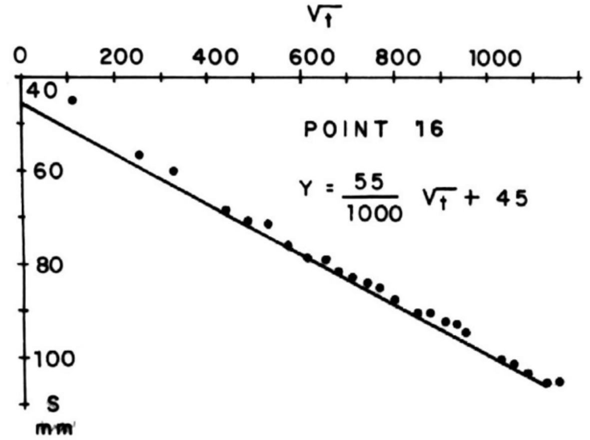

Figure 2f

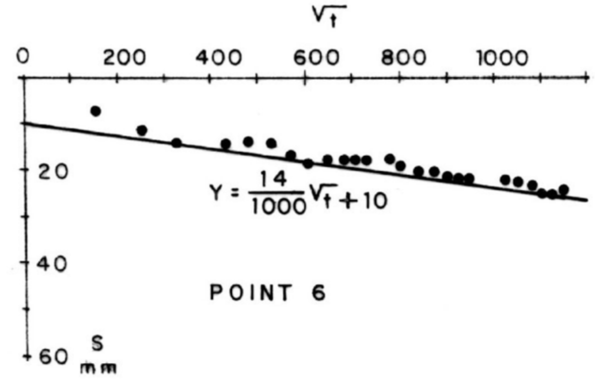

Figure 2c

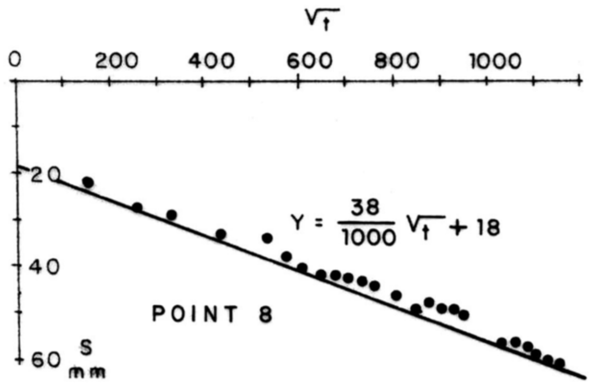

Figure 2g

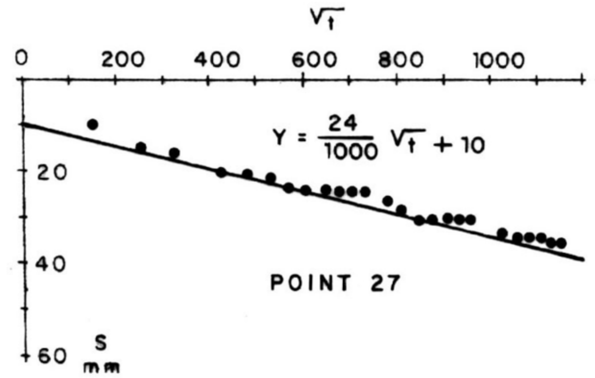

Figure 2d

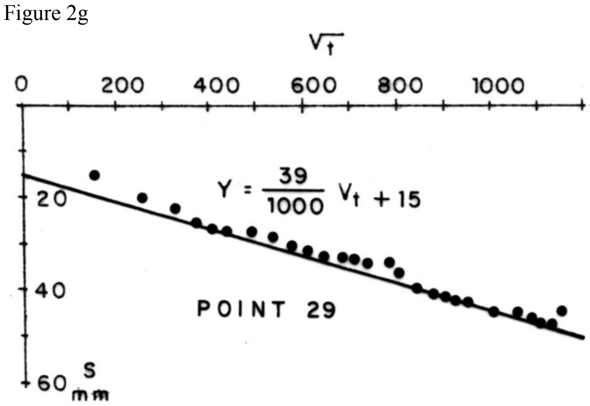

Figure 2h

Figure 2. Settlement S (mm) as a function of $\sqrt{t}$ (t time in minutes), at different points in Deposit 5.

2002) and part of them under Deposit 4 (filling date 27 March, 2001).

The greatest settlement difference within a single foundation slab (Fig. 1) occurs in Slab 8-5 and is 80 mm, with no irregularity detected in the behaviour of the deposit.

Settlement was calculated in Deposit 5 at five years and at ten, applying the above linear relationship, and the results are shown in Table 1.

The maximum settlement predictable in the period of time between the 2.5 years and the 5 years, calculated on the theory that settlement will not ease off until that time, will occur in the centre of Deposit 5 and will be 29 mm.

In the South, next to Deposit 4, the maximum settlement increase predictable will be 8 mm, after five years, and the total settlement will be less than the amount calculated based on the results of the 53-mm load test.

Table 1. Deposit 5. Settlement measured after 2.5 years and calculated for 5 and 10 years.

Point	2.5 years mm	5 years mm	10 years mm
26	19	27	36
17	36	42	52
6	25	32	42
27	36	49	65
28	44	59	79
16	105	134	171
8	60	80	105
29	47	78	104

4 SUMMARY AND CONCLUSIONS

The site of the Galindo Waste Water Treatment Plant stands on a layer of alluvial deposits between 15 and 20 m thick, which has been subjected to an average preloading of 2 kg/cm^2 for over 20 years.

The Phase 2 biodigestor tanks take up two 62 x 195 m rectangles, separated by a 23-m wide central corridor in which the layer of alluvial sediment is 15 m thick.

For five years prior to construction of the biodigestor tanks, the height of the fill was reduced to an elevation of +6, implying a preloading of 4.80 m from the height of the slag fill. Without taking into account the water table, this fill height is designed to maintain a preloading pressure of 0.96 kg/cm^2 in respect of the foundation plane for the deposits.

Construction of the slabs and walls of the deposits and the load of the water during normal operation of the plant bring about an increased load of 1.1 kg/cm^2, giving rise to a net increase in load, as compared to that of the previous five years, of **0.14** kg/cm^2, while still remaining below the preconsolidation pressure present from the beginning.

According to the settlement measurements recorded, three different areas can be seen at the site of these biodigestor tanks. The area corresponding to Deposits 1 and 4, which has low compressibility, where the maximum settlement recorded was 28 and 39 mm. The area corresponding to Deposits 3 and 6, with average compressibility and maximum settlement recorded at 71 and 58 mm and that of Deposits 2 and 5, located in the intermediate area, with high compressibility and maximum settlement recorded at 136 and 105 mm.

All the maximum settlement values occur in the centre of each of the three sequenced deposits, in line with the construction process used: reduction of the fill, construction of the deposit and restitution of the load with the filling up of the deposits once they were put into operation.

Bearing in mind that, for operating reasons, Deposit 3 is kept empty for long periods of time, the detailed analysis of maximum settlement centred on Deposit 5.

In this Deposit 5, two and a half years after its filling process the settlement occurring described a linear relationship with $\sqrt{t_a}$ (t_a = time in years). From this linear relationship it can be deduced that the initial settlement in the perimeter zone ranges from 6 to 18 mm, whereas in the centre it goes from 20 to 45 mm.

The highest $\sqrt{t_a}$ coefficients, involving values ranging from 17.4 to 40, appear at the points measured in Slabs 7-5 and 8-5, forming the foundation for the centre area of this deposit, whereas the smallest values, in the range of 10, appear in the southern area next to Deposit 4, on Slabs 6-5 and 5-5, part of which belong to Deposit 5 and part to Deposit 4.

The greatest settlement difference within a single foundation slab occurs in Slab 8-5 and amounts to 80 mm, without any irregularity being detected in the way the deposit is behaving.

The maximum predictable increase of settlement over the period of time between 2.5 and 5 years, based on the theory that the settlement will not ease off until that time, will occur in the centre area and will be 29 mm.

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