Settlement velocity measured over ten years in major-scale shallow foundations on a preloaded 20-m thick silty alluvial layer

Velocité des affaissements mesurés sur dix ans, sur une foundation superficielle de grandes dimensions, sur une couche alluviale limoneuse de 20 m d'épaisseur préchargée

Dapena E.
Geotechnics Laboratory, CEDEX, Madrid Polytechnical University, Spain
Román F.
Confederation Hidrográfica del Norte, Ministry for the Environment, Spain
Pardo de Santayana F., Cuéllar V.
Geotechnics Laboratory, CEDEX, Madrid, Spain

ABSTRACT: 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 biodigester 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. 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, ten years after construction, three different areas can be seen at the site of these biodigester tanks: the area corresponding to Deposits 1 and 4, which has low compressibility, where the maximum settlement recorded was 32 and 40 mm; the area corresponding to Deposits 3 and 6, with average compressibility and maximum settlement recorded at 114 and 108 mm and that of Deposits 2 and 5, located in the intermediate area, with high compressibility and maximum settlement recorded at 217 and 156 mm. One obtains the settlement velocity distribution and analyzes them for each of the four deposits that have significant movement, comparing the average velocity corresponding to the period between 0.5 and 9 years, and the average velocity for the period between 8 and 10.3 years.

RÉSUMÉ : le site de la Station de traitement des eaux usées de GALINDO repose sur une couche de dépôts alluviaux de 15 à 20 m d'épaisseur qui a fait l'objet d'une surcharge moyenne de 2 Kg/cm^2 pendant plus de 20 ans. Les réservoirs du digesteur anaérobie de la Phase 2 utilisent deux rectangles de 62 x 195 m, séparés par un couloir central de 23 m de large dans lequel la couche des sédiments alluviaux mesure 15 m d'épaisseur. La construction des dalles et des parois des dépôts et le chargement de l'eau pendant le fonctionnement normal de la station entraînent un chargement supplémentaire de 1,1 Kg/cm^2, ce qui donne lieu à une augmentation nette du chargement de 0,14 Kg/cm^2, si nous le comparons à ceux des cinq années précédentes, tandis qu'il reste au-dessous de la pression de préconsolidation présente depuis le début. Conformément aux mesures de tassement enregistrées, dix ans après la construction, trois zones différentes peuvent être observées à l'endroit de ces réservoirs du digesteur anaérobie : la zone correspondant aux Dépôts 1 et 4 qui présente une faible compressibilité, où les tassements maximums enregistrés étaient de 32 et 40 mm ; la zone correspondant aux Dépôts 3 et 6 présentant une compressibilité moyenne et un tassement maximum enregistrés de 114 et 108 mm et ceux des Dépôts 2 et 5 qui se trouvent dans la zone intermédiaire, présentant une compressibilité élevée et un tassement maximum enregistré de 217 et 156 mm. Nous obtenons la distribution de la vitesse de tassement et nous l'analysons pour chacun des quatre dépôts qui présentent un mouvement significatif. Nous comparons la vitesse moyenne correspondant à une période de 0,5 à 9 ans et la vitesse moyenne sur une période de 8 à 10,3 ans.

KEYWORDS: settlement, alluvial sediments, waste-water treatment plant, blast furnace slag

1 INTRODUCTION

The foundations of the phase 2 biodigester tanks at the Galindo Waste Water Treatment Plant are located on top of a layer of dark gray silty clay alluvial sediments between 15 and 20 m thick. See Fig. 1. Beneath that is a compact layer of clay with gravel between 1 and 2 m thick, which extends down to solid rock.

This soil was preloaded for over 20 years with a layer of blast furnace slag, which transferred an average preload of 2 kg/cm^2. However, the distribution of the preload on the site of the phase 2 biodigesters was not known for certain, and this may explain the different behavior of the pools in response to settlement.

In addition, for the 6 years prior to construction of the phase 2 biodigesters, there was a uniform preload throughout the entire area on a scale equal to that which would be transferred by the biodigesters. However, when they were built, the initial design was modified and the load transferred was 0.14 kg/cm^2 greater than the load of the soil removed.

In Figure 1, it is possible to see that in the middle section of the site, precisely where pools 2 and 5 are located, the level of alluvial sediments is high, at the height of the support level for the foundation slab of pools 2 and 5. However, at the sites of pools 3 and 6, the surface of these deposits is 2.5 m below the foundation height, and the alluvial deposits are at an average depth of 3.5 m at pools 1 and 4.

The influence of preloading on settlement due to primary consolidation has been studied by Johnson (1970), Mitchell (1981), and Statmatopoulos and Kotzias (1983), among others. Secondary consolidation has been studied by Jamiolkowski, et al. (1983), Magnan (1984), Kousotfas, et al. (1987), Yu and Frizzi (1992), Alonso, Gens and Lloret (2000 and 2001), and Alonso (2004).

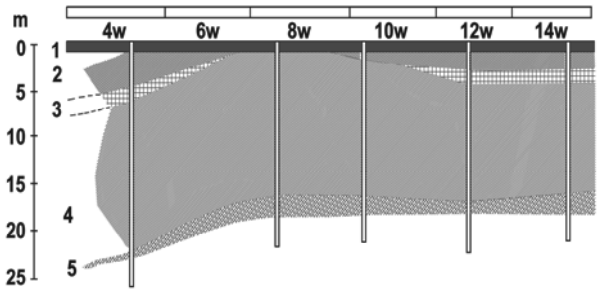

Figure 1. Stratigraphic profile of the soil under the biodigester foundation slabs. 1. Concrete. 2. Slag. 3 and 4. Silty clay. 5. Clay with gravel.

This paper discusses the amount of settlement recorded over the first 10 years since the biodigesters were put into operation and how it has developed over time. It also identifies how the pools have behaved differently, delimiting the areas with settlement and with similar settlement rates

2 SETTLEMENT RECORDED OVER THE 10 YEARS OF OPERATION

Figure 2 shows the total settlement recorded 10 years after the phase 2 biodigesters were constructed and filled. There are also lines connecting points with the same amount of settlement for the following values: 50, 60, 70, 100, 150 and 200 mm. The 50 mm settlement line includes pools 2, 3, 5 and 6. Pools 1 and 4 have settlement of less than 50 mm. Figure 2. The areas with the most settlement are in the center of pool 2, where it reaches 218 mm, and the middle of pool 5, where settlement reaches the level of 158 mm. Despite this significant settlement, no problems with the operation of the pools have become apparent

3 SETTLEMENT MODELS

Settlement development over the 10 years since the phase 2 biodigesters were constructed resembles the model $s = a_m \sqrt{tm} + b = a \sqrt{ta} + b$, where tm is the time since the biodigesters were first filled expressed in minutes, and ta is this time expressed in years.

This model was determined by adjusting the settlement values collected after 2.5 years, as contained in Dapena, et al. (2005). A least squares adjustment has now been applied to the settlement values collected for the period between 0.5 and 9 years after the pools were filled, using the computer program.

The corresponding a and b values at each point have thus been determined, as shown in Table 1.

The graph of how settlement developed at point 53 of pool 2, where the greatest settlement value was obtained, is shown in Figure 3, together with the corresponding model.

$$S_{53} = 0.0812 \sqrt{tm} + 37.4 = 58.9 \sqrt{ta} + 37.4;\ R^2 = 0.99$$

Because a decrease in the settlement rate was noted after 8 years, the model has also been adjusted for the settlement values measured between 8 and 10 years, obtaining the value $a_{8\text{-}10}$. Table 1.

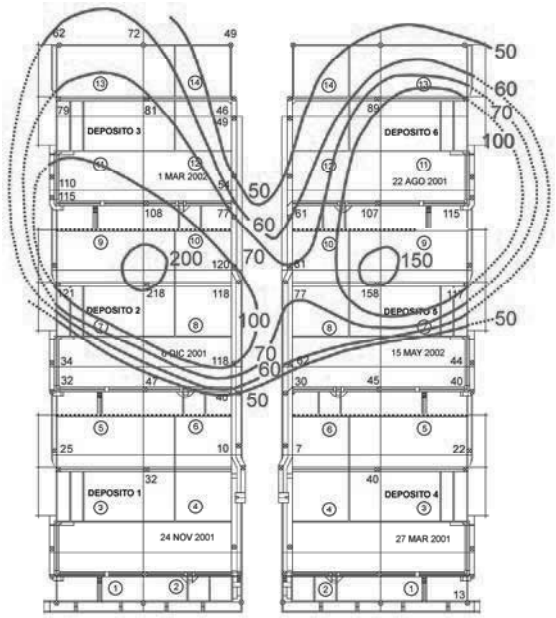

Figure 2. Contour lines for settlement at the biodigesters in mm. Settlement measured on March 12, 2012.

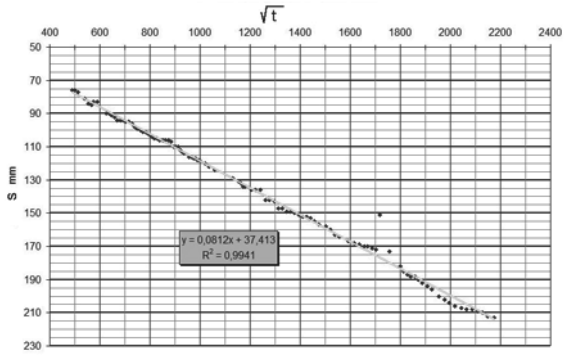

Figure 3. Settlement at point 53 of pool 2 based on the root of t (t= time in minutes) between 0.5 and 9 years and adjustment of the model.

4 DISTRIBUTION OF THE COEFFICIENT $\sqrt{ta}$

The increase in settlement over time is related to coefficient "a" of $\sqrt{ta}$ in the model used. The greater this coefficient is, the greater is the increase in settlement which will occur over a certain period of time.

The distribution of the $a_{0.5\text{-}9}$ coefficient for the biodigesters is shown in Figure 4. The lines connect points with the same value for this coefficient, separating different areas based on this value. The area of pools 1 and 4, where there was the least settlement, also has $a_{0.5\text{-}9}$ coefficients with lower values, less than $a_{0.5\text{-}9}$=5, whereas the center of pool 2 and pool 5, where the greatest settlement was recorded, have higher values for the coefficient: $a_{0.5\text{-}9}$=58.9 and $a_{0.5\text{-}9}$=37.5, respectively.

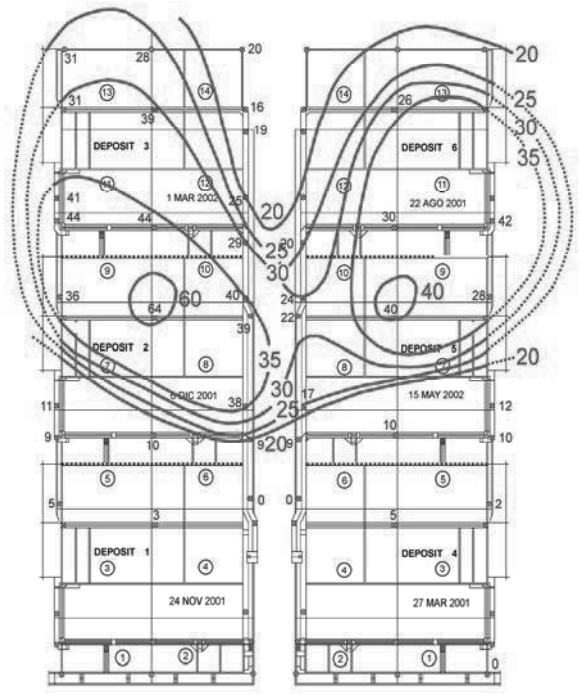

Figure 4. Distribution of values for the coefficient a.

5 SETTLEMENT DEVELOPMENT

According to the values for the coefficient a, shown in Table 1, in general, at each point the values for $a_{8\text{-}10}$ are lower than the values for $a_{0.5\text{-}9}$. This would seem to indicate that between 8 and 10 years after the biodigesters were first filled, there was a period of stabilization.

Dapena, et al. (2007) compared the settlement values for pool 5 measured after 4.5 years with the settlement values calculated for 4.5 years, using the model adjusted using the settlement values after 2.5 years. Except for point 8 of pool 5, where real settlement was clearly greater than calculations indicated, settlement at the remaining points of pool 5 matched that calculated using the model. The settlement measured at 10 years for pool 5 is shown in Table 2, together with the calculations. We can see that the real settlement is lower than the calculations, confirming the stabilization process.

6 SUMMARY AND CONCLUSIONS

The phase 2 biodigesters at the Galindo Waste Water Treatment Plant are located on a layer of silty clay between 15 and 20 m thick, which has been subjected to irregular preloading for 20 years, with average preconsolidation pressure of 2 kg/cm^2. However, for the site of the phase 2 biodigesters, the distribution of the preload was not known for certain.

Table 1. Values for coefficient a when the model $s=a\sqrt{ta}+b$ is adjusted using measurements between 0.5 and 9 years ($a_{0.5\text{-}9}$) and measurements between 8 and 10 years ($a_{8\text{-}10}$).

Point	$a_{0.5\text{-}9}$	$a_{8\text{-}10}$	R^2_{8-10}	$b_{0.5\text{-}9}$
Tank 2				
40	38.5	23.7	0.96	2.4
41	38.3	24.7	0.97	-0.1
42	36.3	19.1	0.95	8.9
43	10.8	15.2	0.88	5.3
52	9.5	6.2	0.84	17.1
53	58.9	31.6	0.97	37.4
61	36.2	26.4	0.97	7.9
62	10.8	0	0.87	3.5
63	9.9	0	0.87	2.0
Tank 3				
35	18.1	10.9	0.98	-6.3
36	15.0	3.9	0.92	-0.3
37	13.5	9.6	0.91	+5.6
38	-	13.6	0.92	-
39	23.7	18.0	0.91	+0.9
54	28.9	23.3	0.97	14.5
55	21.0	9.0	0.95	16.1
56	21.8	27	0.92	-1.1
57	22.4	0	0.95	-4.1
58	26.0	11.3	0.97	-1.6
59	34.9	22.7	0.98	1.3
60	36.0	26.7	0.97	1.0
Tank 5				
6	7.7	6.7	0.59	7.1
7	12.7	5.9	0.70	5.8
8	35.2	29.7	0.96	8.1
16	37.5	23.3	0.97	46
17	7.8	4.4	0.08	22.0
26	7.5	2.9	0.52	6.6
27	17.5	13.6	0.92	8.3
28	22.8	15.6	0.96	8.0
29	22.8	12.0	0.96	11.6
Tank 6				
9	38.3	35.8	0.95	-6
14	21.5	16.1	0.89	32.2
15	28.9	28.7	0.94	21.5
30	20.3	18.4	0.95	0.5

Table 2. Tank 5. Settlement measured after 4.5 and 10 years and calculated for 4.5 and 10 years.

Point	4.5 years Measured mm	4.5 years Calculated mm	10 years Measured mm	10 years Calculated mm
26	24	26	30	36
17	41	41	45	52
6	33	31	40	42
27	46	46	62	65
28	57	56	77	79
16	128	128	158	171
8	84	76	117	105
29	61	74	81	104

For the 6 years prior to construction of the phase 2 biodigesters, a uniform preload equal to that which would be transferred by the biodigesters was kept on the entire area. However, when they were constructed, the initial design was modified and the load transferred was 0.14 kg/cm^2 greater than the load of the soil removed.

10 years after the biodigesters were constructed, tanks 1 and 4 have practically stabilized, as settlement is less than 50 mm in these areas. Tanks 2 and 5 are the areas with the greatest settlement, reaching 218 mm at tank 2 and 158 mm at tank 5, without any problems with the operation of the tanks having been detected. This settlement can be divided into zones, as shown in Figure 2.

The settlement which occurs based on time fits the model S = a $\sqrt{t_a}$ +b, where t_a is the time in years where the tank has been full.

Coefficient "a" is related to the rate of settlement and its distribution is similar to the settlement values as shown in Figure 4. Thus, at tanks 1 and 4, where the least settlement has occurred, the value of "a" is less than or equal to 5, while at the center of tank 2, it is $a_{0.5\text{-}9}$ =58.9, and at the center of tank 5, it is $a_{05\text{-}9}$ = 37.5.

By comparing the "a" values when the model is adjusted for the period of time between 0.5 and 9 years, and the "a" values when this period of time is between 8 and 10 years, it is possible to observe that the settlement is stabilizing, particularly in the areas with greater settlement.

7 REFERENCES

Alonso, E.E., Gens, A. y Lloret, A. (2000). *Precompresión design for secondary settlement reduction*. Geotechnique 50(6), 645-654.

Alonso, E.E., (2004). *Deformabilidad a largo plazo de suelos precargados.* 8º Simposio Nacional de la S.E.M.S.I.G., Valencia, págs 245 a 250.

Alonso, E.S., Lloret, A., Gens, A. y M. Salvadó (2001). *Overconsolidation effects on secondary compresión rates*. Proc. 15th International Conference on Soil Mechanics & Geotechnical Engineering.Istambul, 1:5-8.

Dapena, E., Román, E., San Salvador, J. (2005). Long term settlement of foundations made of 195 x 147 m slabs built on a layer of fluvial sediment. *Proc. 16th Int. Conf. Soil Mech. & Geotech. Engng. 1, 1033-1036.*

Dapena, E., Román, F. (2007). *Differential settlement measured over five years in major-scale shallow foundations on a preloaded 20 m. thick silty alluvial layer.* Proceedings of the 14th European Conference on Soil Mechanics and Geotechnical Engineering. Madrid. Vol. 2 pp.451-456

Jamiolkowsky, M., Lancellota, R. y Wolski, W. (1983). *Precompression and speeding up consolidation.* General Report. Proc. Europ. Conf. Soil Mech. Found. Engng. Helsinki, 3:1201-1226.

Johnson, S.J., (1970). *Precompression for improving foundations soils* J. Soil *Mech*. Found. Div. ASCE, 96(1): 111-114.

Koutsoflas, DC., Foott, R. y Hadleft, L.D. (1987). *Geotechnical investigations offshore Hong Kong*, J. Geotech. Enging. Dic. ASCE, 113(2): 87-105.

Magnan, J.P. (1994). *Methods to reduce the settlement of embankments on soft clay, a review,* In: Vertical and horizontal displacements. ASCE. Geotech. Special Pub. 40(1): 77-91

Mitchell, J.M. (1981). *Soil Improvement.* State of the art report. Proc. 10th *I*nt. Conf. Soil Mech. And Found. Engng. Stockholm. 2:509-565.

Stamatopoulos, A.C. y Kotzias, P.C. (1983). *Settlement-time predictions in preloading*. J. Geotech. Engng. Div. ASCE, 109(6): 802-820.

Yu, K.P. y Frizzi, R.P. (1994). *Preloading organic soils to limit future* settlements. Vertical and horizontal displacements of foundations and embankments, ASCE. Geotech. Special Pub. 40(1): 476-490.