Field Survey of Compressibility of Municipal Solid Waste

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Abstract. This paper presents a study on the compressibility of municipal solid waste (MSW) by means of a field survey in Valdemingomez Landfill in Madrid, Spain. Organic matter content was 59%, there was no waste segregation and field compaction, nor internal drainage systems for gas and leachate. Solid waste management changed significantly since then in Madrid, but former characteristics of this landfill are similar to those of present inadequate MSW disposal sites in more than 60% Brazilian municipalities. Initially a geotechnical exploration of the landfill was carried out by mechanically drilled boreholes with Standard Penetration Tests, determination of in-situ density and moisture content, and geophysical methods. Subsequently, vertical and horizontal displacements caused by a surcharge load applied by a trial soil embankment were measured, as well as settlements due to biodegradation of the organic materials, for 19 months. Displacements were monitored by topographical references, inclinometer, continuous lines of settlement, and a sliding micrometer. Young’s modulus was estimated 1900 kN/m². Shear modulus increased from 7 to 31 MPa with depth according to results of spectral analysis of surface waves. The auscultation campaign indicated that primary settlements occurred during approximately 100 days and that accumulated secondary settlements amounted to 0.600 m, representing 55% of the total settlements.

Keywords: landfill, compressibility, solid waste, settlements, field test.

1. Introduction

Land disposal is the usual destination for municipal solid waste (MSW) in developing countries. This disposal alternative tends to decrease in importance with time due to the lack of available areas near large urban centres and to the development of new technologies. Nevertheless, sanitary landfills are still considered safe and relatively low cost, and have reached heights of more than 100 metres, indicating the need to study compressibility of the waste mass as well as of the foundation in order to guarantee slope stability.

Study of MSW settlements is important to predict the increase of landfill storage capacity along time. Landfill compression is also relevant for post-closure projects such as parks, access ways, streets, secondary roads, airports, streets and new urbanizations, as geotechnical problems related to long term settlements are likely to occur in urban development over recovered sanitary landfills.

Design of waste landfills is based on geotechnical concepts and methods, although mechanical behaviour of MSW is remarkably different from soil, mainly as a consequence of biological decomposition of the putrescible organic matter, which transforms part of the solid constituents into gases and leachate. Furthermore, MSW is a complex material with components of different nature, its characteristics and properties change with time, and its mechanical behaviour is influenced by the topography of the disposal area, the compaction method and the landfill operation.

This paper presents a study of MSW compression based on in situ monitoring of a disposal area for fresh waste within one of the largest sanitary landfills in Europe, the Valdemingómez landfill in Madrid, during a period of approximately two years.

Spain changed the paradigm from the disposal of MSW in dumps and controlled landfills (MSW landfills with a few elements and procedures for sanitary protection such as daily soil cover and waste compaction, however insufficient for proper environmental protection) towards sanitary landfills (MSW landfills with complete sanitary and environmental protection) in the time span of 10 years.

This development has also started in Brazil, initially in large cities, where sanitary landfills are already centers of waste treatment with biogas collection for energy generation. Deactivation and recovery of inadequate disposal in small towns and medium-sized cities are being stimulated by the National Politics for Solid Waste, a federal law sanctioned in 2010. There is presently a great demand for a better understanding of the geo-mechanical behavior of controlled landfills and dump sites with the view to recovering and reinserting these areas in the urban context.

Field data presented in this paper aims to meet this demand, for the Valdemingómez landfill has great similarities with other controlled landfills in Latin America: high organic matter and water contents; presence of voluminous waste; lack of material segregation, field compaction, internal drainage systems for gas and leachate; all important factors for the compression behaviour of sanitary landfills.

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2. The Valdemingómez Landfill and Characteristics of MSW from the Community of Madrid

The Valdemingómez controlled landfill occupies an area of 110 ha distant 20 km from Madrid’s city center (Spain). This landfill served Madrid and two small neighbor municipalities from 1978 to 2000, with an average daily production of 3,000 tons of waste. Presently there is biogas extraction and energy production, generating 75% of the annual electricity necessary for Madrid’s street lighting.

Municipal solid waste, composed of domestic, commercial and public waste, was discarded at the Valdemingómez landfill, whereas hazardous and hospital waste was treated by an incinerator located within the landfill area. Figure 1 depicts the composition of the domestic waste of the Community of Madrid, while commercial and public wastes were composed, respectively, of 34% and 32% of organic materials.

While this study was being developed, a plan for solid waste management was implemented to radically change collection and final disposal of waste from the Community of Madrid.

3. Methodology

Initially a survey of the physical properties of the MSW landfill was carried out (inspection phase) by means of SPT tests, samples recovery for visual inspection, geophysical tests with spectral analysis of surface waves, electromagnetic sounding, in situ density tests and water content determination.

Five boreholes were constructed using a mechanical rotary drilling rig. Samples were recovered for visual analysis and determination of waste composition, and SPT tests were executed at intervals of 2 and 3 m. The boreholes were lined with casing to prevent collapse of the inside walls and to permit continuous sample recovery; casing was installed with the aid of water, although drilling was dry. The initial plan was to drill down to the natural substrate; however, due to difficulties arisen during the execution of the first borehole, *i.e.* solid waste obstacles and emanation of gas and leachate, a 20-m depth was established for the remaining boreholes.

The survey also comprised 5 electromagnetic tests along a longitudinal profile located in the NW/SE direction, at 50-m intervals, carried out with a Transient Electromagnetic (TEM) equipment. The apparatus has two antennas: one transmits an electric current in the form of pulses of alternate signal, generating a primary magnetic field according to Ampère’s Law and, consequently, diffusive currents in the interior of the waste mass according to Faraday’s Law. Decrease in the diffusive currents generates a secondary magnetic field of low amplitude and rapid decrease, captured by the second antenna (receiver). Decrease in the intensity of the secondary field depends on conductive characteristics of the subsoil.

Two tests of Spectral Analysis of Surface Waves (SASW) were carried out in the landfill. SASW constitutes a non-destructive method to obtain surface wave velocity. Its rapid execution offers advantages when compared to other techniques which require borehole drilling, such as cross-hole and down-hole.

After the inspection phase, instruments were installed inside the waste mass and a trial soil embankment was built over the MSW landfill surface to perform as a test load (Fig. 2). The site selected for the load test was an area of approximately 2 ha and a thickness of 33 m of waste with a maximum age of 4 years. Most of the waste had been deposited and spread without mechanical compaction, and part of the waste had been deposited in the form of compressed blocks. Before starting the load test, the area was sealed with a 0.80 m-thick soil layer and surrounded by a 0.80 m-high soil dike. The trial soil embankment was built with a height of 4 m, a width of 20 m and a length of 40 m, equivalent to a vertical surcharge of 64 kN/m².

Exploration tests were performed over the entire area; however, auscultation equipments were installed only...
where the waste had been operated as usual, i.e. discharge and spread. The second (auscultation) phase, which took place for 19 months, consisted of a campaign of sounding tests comprising 18 reference points, a fixed reference in order to generate absolute values for the topographical reference points, a sliding micrometer, 2 continuous settlement lines, 1 inclinometer and 1 thermistance line, located according to Fig. 3.

The position immediately after the construction of the soil embankment was assumed as the zero reference, con-

Figure 3 - Layout of the embankment and equipments for the auscultation phase.
considering that previous stresses and compression in the waste mass during the disposal operations were much lower than those induced by the test load.

The continuous settlements lines (LCA in Fig. 3) allowed measurement of displacements at several depths below the surcharge load and of settlement evolution at two parallel cross sections located near the bisector of the largest sides of the trial embankment. Measurements from the continuous lines and the reference points located near the embankment were applied to evaluate immediate and primary displacements.

A Sliding Micrometer to measure secondary displacements was installed at a 15-m horizontal distance from the embankment, outside the influence area of the load test, in order to guarantee that immediate and primary settlements due to waste self-weight had already occurred during the landfill operation and before the construction of the soil embankment for the load test. Time zero was considered as that corresponding to the end of waste disposal. This apparatus was developed by the Zurich Federal Institute of Technology (Switzerland) and measures axial displacement along depth.

4. Inspection Tests in the Landfill Area

4.1. SPT tests

Results in Fig. 4 show a great dispersion due to the presence of obstacles of voluminous waste. If the pair of abnormal results is disregarded, N-value would be in the range 5-15 and resistance would show an increase with depth as described by Marbri (1977), Carvalho & Villar (1998) and Jucá et al. (2000).

4.2. Unit weight

The bulk unit weight of MSW landfills is difficult to evaluate because of the heterogeneous composition of the material, the variety in size of the components and the presence of soil cover layers. The bulk unit weight of the waste was determined in situ, excavating a trench 1.5 m long, 1.0 m wide and 0.5 m high in the waste mass after removal of a 0.80-m thick soil cover. The obtained density of 5.0 kN/m³ is consistent with fresh and loose (not compacted) waste.

4.3. Water content

The water content within the waste mass is influenced by initial composition, climatic conditions, construction method, presence of internal drainage system for leachate (non-existent in this case), landfill cover, moisture generated by biological processes, and amount of water eliminated by the gases generated in the landfill.

Water content ranged from 13 to 70% (Fig. 5). The peak value of 70% measured at 16 m depth, confirmed by electromagnetic tests, was associated to a leachate pocket. Leachate pockets generally occur inside the waste mass in the absence of an internal drainage system. This also explains the large amount of leachate expelled when the first borehole reached the depth of 16 m.

4.4. Spectral analysis of surface waves

Figure 6 shows results obtained with Spectral Analysis of Surface Waves. Tangential wave velocity varied from 210 m/s to 100 m/s within the top layer (0 to 1-m depth), and increased from 100 m/s up to 250 m/s with depth. At a depth of 33 m the natural subsoil surface was reached, where wave velocity reached 800 m/s. Rigidity is higher in the superficial layer because it is constituted of a soil cover. A velocity of 210 m/s was measured in the upper 0.20 m of this layer, which could be the effect of compression by trucks or of desiccation (Cuéllar & Valerio, 2000).

Results for the depths between 1 m and 33 m are within the variation range of 50-350 m/s indicated by Singh & Murphy (1990), Sharma et al. (1990), Kavazanjian et al. (1994) and Del Greco et al. (2007).

Tangential wave velocity varies with depth and age of solid waste (Kavazanjian & Matasovic, 1995; Matasovic & Kavazanjian, 1998). Haker et al. (1997) add type of waste, density, confinement, disposal method and soil content as influential factors, while advertting that it is difficult to ascertain the separate influence of each factor. The authors
measured wave velocities at three landfills with a variation range of 122 m/s to 365 m/s.

Shear modulus ($G$) was calculated by:

$$G = \frac{\rho V_s^2}{c_{114}}$$

where $G$ = shear modulus (MPa), $V_s$ = tangential wave velocity (m/s), $\rho$ = bulk unit weight (= 500 kg/m$^3$).

$G$ values depend significantly on the bulk unit weight. Fasset et al. (1994), Kavazanjian et al. (1995) and Jessberger (1996) suggest that MSW bulk unit weight increases with depth as a result of compression under self-weight, loads, machinery activities and soil covers. However, $G$ was calculated considering a constant bulk unit weight equal to the value obtained by trench excavation due to the operational difficulty of repeating this test at greater depths.

Excluding the soil cover, the shear modulus $G$ increases with depth from 7.2 MPa to 31 MPa (Fig. 7) at a bulk unit weight of 5 kN/m$^3$ (500 kF/m$^3$). $G$ obtained by cross-hole tests for the Richmond landfill in California, USA, was 30 MPa for a bulk unit weight of 7.3 kN/m$^3$ (Sharma et al., 1990), and 8.0 MPa for the Bandeirantes landfill in Sao Paulo, Brazil, at a bulk unit weight of 8.0 kN/m$^3$ (Carvalho, 1999).

4.5. Electromagnetic tests

Figure 8 summarizes results of five electromagnetic tests performed in a longitudinal profile in the investigation area and includes the original geometry of the terrain surface. Four distinct layers can be observed:

- The superficial or top layer, extending until a depth of 7-12 m, where two zones can be differentiated: compressed waste blocks with a resistance of 60-80 ohm-m and loose waste with a resistance of 200-500 ohm-m.
- The second layer, not continuous and showing a lower resistance, between 20 and 30 ohm-m, possibly due to a partial contamination by leachate.
- The third layer, homogeneous and very conductive (resistance of 0.6 ohm-m) due to saturation by leachate, behaving as a piezometric level.
- Finally, the soil substrate upon which the MSW landfill is founded, displaying a resistance of 100 ohm-m. The bedrock was identified (900 ohm-m) at a spot located 5 m below the subsoil surface.

5. Auscultation Phase

The auscultation phase begun with the installation of equipments to measure vertical and horizontal displacements as a function of time and surcharge load, and temperature variation as a function of depth. A trial soil embankment was built to act as load test, and the area was monitored for 19 months.

Significant settlements started 7 days after the construction of the experimental embankment was finalized. Readings were taken every 10 days during the first month and thereafter at intervals of 30 and 60 days.

5.1. Reference points

In order to measure vertical displacements caused by the surcharge, 18 reference points were installed at the northern and southern sides of the embankment (Fig. 3). Displacements are referred to a fixed point especially installed for this purpose.

Figures 9 and 10 show the evolution of settlements with time obtained, respectively, in the northern and southern sides of the landfill. Settlements are greater in the southern than in the northern side, what could be explained by the significant heterogeneity of the waste mass.

The immediate settlement was considered as that developed during the first 7 days after the completion of the trial embankment. The average immediate settlement was 0.066 m on the northern side and 0.061 m on the southern side.

After 100 days average settlements were approximately 0.40 m at both sides of the embankment. In the end of the monitoring period, 19 months, average settlements were 1.23 m on the southern side and 1.06 m on the north-
The two continuous settlement lines showed similar settlements during the entire monitoring period (Figs. 11 and 12). Initial settlements measured seven days after the construction were approximately 0.50 m in the embankment centre (point 12 of each line) and 0.15 m in the extremities. Long term settlement was approximately 2.0 m in the centre and 1.4 m in the extremities of the embankment. Settlements measured in the extremities of the lines are very close to those obtained through the reference points.

Immediate settlement was used to calculate Young’s modulus based on the hypothesis of a flexible plate resting on a semi-infinite space (Eq. 2):

Figure 8 - Profile obtained from electromagnetic tests.

Figure 9 - Vertical displacements - Northern side.

Figure 10 - Vertical Displacements - Southern side.
\[ E = \frac{Kq b (1 - \nu^2)}{S_i} \]

where \( E \) = Young’s or elastic modulus (kN/m\(^2\)),
\( K \) = coefficient (\( n = 40/20 = 2 \)),
\( q \) = surcharge (64 kN/m\(^2\)),
\( b \) = rectangle side (20 m),
\( \nu \) = Poisson coefficient (0.3),
\( S_i \) = immediate settlement (0.50 m).

The calculated elastic modulus is 1864 kN/m\(^2\), consistent with the values for domestic waste of 1000-2000 kN/m\(^2\) appointed by Charles (1984) and 1000-4000 kN/m\(^2\) by Campi (2011).

Figure 13 shows that settlement velocity obtained from the continuous settlement lines decreases with time, more significantly in the first 100 days and apparently asymptotically for longer times. Initial higher velocities are related to immediate and primary settlements. The variation amplitude is considerable: for the two continuous settlement lines, average velocity decreases from 64.0 mm/day to 3.6 mm/day in 19 months. The decrease of settlement velocity with time is a consensus for the great majority of authors in the specialized literature (Sowers, 1973; Frantzis, 1991; König & Jessberg, 1997; Carvalho, 1999; Abreu, 2000).

5.3. Sliding micrometer

Figure 14 shows measured differential settlement as a function of depth and time. Considering each time, measured settlements are very variable with depth; however, results are consistent: layers that show smaller or larger settlements at distinct dates are the same during the entire monitoring period. The variation can be explained by the presence of soil, which is less deformable, between waste layers; by the heterogeneity of the soil mass, with zones of more deformable materials; by different densities; and by variations in water content. A higher settlement is observed at depth 2-3 m, consistent with a water content of 43% at
the depth of 2.5 m; while the lowest water content, 13%, occurred at a depth that developed low settlements. Likewise, a water content of 70% was registered at a depth of 16.5 m, while from depth 16-17 m deformation was considerably larger than at 15 m, where the water content was 25%.

It should be noted that excessive differential settlements can lead to fissures or cracks in the internal drainage systems for leachate and gases, as well as in the landfill cover. Fig. 15 shows accumulated secondary settlements as a function of time and depth.

Accumulated secondary settlements amounted to 0.60 m after 19 months of monitoring at the depth of 18 m. Secondary settlements are caused by two processes: creep, which occurs under constant stress and water content conditions, and decomposition of organic matter. The first process is influenced by landfill height and compaction degree (Charles, 1984), and the second process, by environmental conditions, such as water content, temperature, pH and waste composition.

5.4. Inclinometer

The inclinometer was installed inside borehole S2. For each inclinometer, the bottom extremity was considered as a reference point with zero horizontal movement.

Due to the occurrence of settlements that resulted in the accommodation of the inclinometer tube, it was not possible to measure horizontal displacements along the entire depth and to calculate accumulated horizontal displacements.

Figures 16 and 17 present horizontal displacements as a function of depth for directions AB and CD. It can be noticed that measured horizontal displacements are small. The influence of the surcharge load from the trial embankment is much more significant on vertical than on horizontal displacements. The influence of the surcharge load is superficial and reaches just about the depth of 2.5 m (Fig. 16), causing a maximum horizontal displacement of 0.030 m. At a depth of 4 m a maximum displacement of 0.009 m was measured, and displacements tend to zero with increasing depth. The oscillations of positive and negative horizontal displacements below a depth of 4 m can result from the presence of soil layers inside the waste mass.

In the direction parallel to the embankment axis (Fig. 17), the maximum displacement is 0.005 m at a depth of 2 m. In this direction displacements are less pronounced than in the perpendicular direction.

These results are consistent with observations of Coducto & Huitric (1990) and Siegel et al. (1990): higher displacements occur near the landfill surface, while displacements tend to zero at increasing depths; and displacements mainly occur in the direction perpendicular to the embankment axis, while no significant movements were measured in the direction parallel to the embankment.
Velocity of the horizontal displacements is apparently not correlated to rain periods, since seasons changed along the monitoring period whereas no variation in the velocity was observed.

The ratio between horizontal and vertical displacements due to the surcharge load of the trial embankment is very low (less than 1-2%) and shows that there is an unimportant lateral transmission of the load influence. This can be reported to the low bearing capacity of waste, which behaves as a loose soil and leads to a puncture or indentation of the embankment into the waste material, with very moderate lateral effects (low equivalent Poisson coefficient) compared to the remarkably large vertical displacements.

5.5. Thermistance line

Temperature profiles were obtained from 21 temperature sensors installed inside the boreholes (Fig. 18) in order to investigate a relation of temperature to processes of biochemical decomposition inside the waste mass.

Temperature varies between 30 °C and 55 °C in the superficial layer (0 to 5 m), and rises progressively with depth until 63 °C to 70 °C at a depth of 20 m.

The high temperature values, associated to available water content (Fig. 5) and high organic matter content (Fig. 1), indicate that the waste mass undergoes a very active decomposition process, as expected for fresh waste, and suggest a significant methane production.

Figure 19 highlights temperatures registered in July and December 1998, corresponding to summer and winter seasons in Spain. It is interesting to observe that temperature fluctuation is only reflected down to a depth of 12 m; at greater depths temperatures measured during winter are equal or even higher than those measured during summer. These data confirm results obtained by Rees (1982), Coumoulous et al. (1995) and Junqueira & Palmeira (1999).

6. Conclusions

Visual inspection revealed that the waste was in an advanced stage of decomposition, despite the maximum age of 4 years. In situ investigation indicated water contents of 13% to 70% and occurrence of leachate pockets. Electromagnetic scans divided the landfill in zones with different resistances depending on leachate content. Saturation by leachate in the bottom layers was detected by results of electromagnetic tests and mechanical drilling. SPT results showed a significant dispersion (N values between 6 and 63), probably because of obstacles of voluminous waste. Estimated Young’s modulus is approximately 1900 kN/m². Spectral analysis of surface waves indicated that rigidity of the waste mass increases with depth (shear modulus increases from 7 to 31 MPa with depth), as a result of compression by self-weight.

The auscultation campaign after the construction of the soil embankment as a trial test load exposed that the settlement velocity decreased from 64.0 mm/day after the construction of the embankment to an asymptotic value of 3.6 mm/day in 19 months. In the embankment extremities, immediate settlements were measured as 0.06-0.15 m and settlements after 19 months, as 1.0-1.4 m. In the embankment centre, immediate settlements were 0.50 m and settlements after 19 months, 1.5 m. Accumulated secondary settlements amounted to 0.600 m after 19 months of monitoring. The ratio of horizontal to vertical displacements due to the load test is very low, of 1-2%, characterizing the behavior of a loose material.

Settlements developed along this study, caused both by surcharge and biodegradation, were of great magnitude and therefore characterize the landfill material as highly deformable. Furthermore, results indicate that secondary compression represents 55% of the total settlements; this percentage will increase with time, since settlements induced by surcharge load take place in a short time, while secondary settlements continue to develop over the years.

The analysis of settlement velocity as a function of time curves suggests that primary settlements occurred during approximately 100 days. This period of time is higher than that proposed by Sowers (1973), but is in accordance with the observed trends.
Secondary settlements during the investigation amounted to 3% of the landfill height. The occurrence of secondary settlements can be related to the high temperatures measured inside the landfill, up to 70 °C at a depth of 20 m, which indicate the existence of intensive biochemical activity. Furthermore, these high temperatures are unrelated to seasonal variations.

The sliding micrometer tests indicated the existence of layers with different deformability, consistent with the water content profile and also explained by the heterogeneity of the waste mass and the presence of soil cover layers.

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References


**List of Symbols**

- $G$: shear modulus
- $V_s$: tangential wave velocity
- $\gamma$: bulk unit weight
- $E$: Young’s or elastic modulus
- $K$: Schleicher coefficient
- $q$: surcharge
- $b$: rectangle side
- $\nu$: Poisson coefficient
- $w$: water content
- $S_i$: immediate settlement
- $N$: SPT result