Studia Geotechnica et Mechanica, Vol. XXX, No. 1–2, 2008

LONG-TERM SETTLEMENT OF DOMESTIC WASTE IN LANDFILL: ISPM METHOD

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Abstract: In the context of the continuing rationalization of the management of domestic and biodegradable waste of class II, the control and the prediction of settlement of waste become very technical with whole share of the follow-up of the modern Municipal Solid Waste (MSW). Until recently, the most widely followed method for the determination of long-term settlement for a column of waste is that of Sowers. While ISPM (Incremental Settlement Prediction Model) proposed by the LTHE-Lirigm, which has been calibrated over a dozen of landfill sites in France and abroad, is compared here with the Sowers Model. It is noteworthy that this method proves to be much more effective than that of Sowers.

1. IMPORTANCE OF SETTLEMENT MONITORING

The understanding of the mechanisms governing municipal solid waste settlement (w) and the development of means to accurately predict the rate and magnitude of settlement have become essential elements in the design and operation of landfills. The performance of any structure built on a landfill will depend, to a great extent, on the ability to predict the anticipated settlement. Moreover, a prediction of settlement contributes to the determination of the useful lifespan of the landfill and assists in the design of its components, such as cover and liner systems. The occurrence of differential settlements is even more critical than total settlement and is inevitable, primarily due to the non-homogeneity of solid wastes. Differential settlements eventually result in the problems such as water ponding on the cover system and accumulation of water on the drainage layer, hence increasing the rate of water infiltration into the waste and leachate formation. The implementation of a landfill consists in setting waste layer by layer (figure 1 corresponds to a pile of n layers with an individual thickness h_i) following specific sequence of construction. When the landfill is full, the waste mass is confined by a cap cover of the thickness h_c (clay or geosynthetic).

Three main stages of settlement have been identified, namely, initial settlement, primary settlement, and secondary settlement. In literature, initial settlement and primary settlement are sometimes considered different phenomena, but in the framework of the present study we will consider an overall primary settlement.

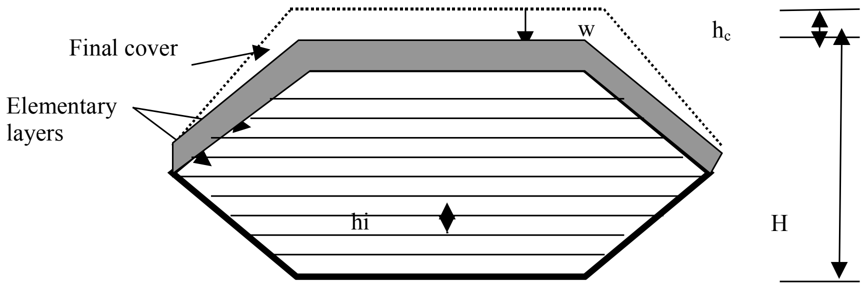

Fig. 1. Typical landfill scheme, implementation of waste layer by layer

Primary settlement is mainly due to compression under load of upper waste. Consolidation due to the dissipation of pore water is not considered here, since the waste is not in saturated state.

Secondary settlement is due to creep of the refuse skeleton and biological decay. In general, secondary settlement occurs over many years.

BUISMAN [1] highlighted that the settlement of clays and peats increased linearly with the logarithm of time under constant conditions of effective stress and proposed the following law for secondary settlement:

$$\frac{\Delta h_s}{h_1} = C_{\alpha\varepsilon}.\log\frac{t}{t_1}\,, \tag{1}$$

where h_1 is the thickness of the soil layer at the time t_1 corresponding to the end of the primary settlement and $C_{\alpha\varepsilon}$ is the coefficient of secondary settlement. $C_{\alpha\varepsilon}$ is regarded as an intrinsic parameter (independent of the load applied).

1.1. THE MODEL OF SOWERS [4]

SOWERS [4] was one of the first to propose a transposition of mechanical behaviour relationships of the compressible soils to the waste. This transposition was limited to the oedometric conditions which corresponded to the conditions of deposit in column (with negligible lateral strain) of a waste sufficiently far from the edges of the cell. The method of prediction of SOWERS [4] is simple with a small number of parameters to be introduced. Moreover, its coefficients can be deduced from the observation of a column of waste for one period reduced with an objective of a longer-term prediction. Indeed, this model allowed correct calibrations in a certain number of simple cases.

Secondary settlement results in the following relation:

$$\frac{w_s(t)}{H_{\text{ref}}} = C_{\alpha\varepsilon}\log\frac{t}{t_{\text{ref}}}\,. \tag{2}$$

The presentation of this model in the literature is vague with regard to the definition of the parameters of time (t_{ref}) and the heights of waste (H_{ref}).

Nevertheless this model suffers from three handicaps of certain importance:

• The absence of standardization of its parameters of time, which makes any comparative approach difficult.

• Not very satisfactory calibration in the case of columns of waste of complex history (rest period, late expansion), even impossible in the event of delayed topographic follow-up.

• Parameter of non-intrinsic compression $C_{\alpha\varepsilon}$ since secondary settlement is considered generally only starting with the end of exploitation of the cell, even if secondary settlement is usually starting for every layer at the end of its primary settlement.

A rewriting of the model following the notations used in the model proposed by LTHE-Lirigm is utilized hereafter which comprises the advantage of clarifying each parameter of the model:

• primary settlement

$$\varepsilon_p = \frac{w_p}{H(t_c)} = C_R \log \frac{\sigma_0' + \Delta\sigma'}{\sigma_0'}, \tag{3}$$

• secondary settlement

$$\varepsilon_s(t) = \frac{w_s(t)}{H(t_c)} = C_{\alpha\varepsilon} \log \frac{t - t_0}{t_1 - t_0}, \tag{4}$$

where $H(t_c)$ represents the height of the column of waste at the end of the construction with the time t_c elapsed for overall construction of the landfill, t_0 – the origin of time and t_1 – the origin of secondary settlement, both these terms (t_0, t_1) are taken equal to (t_c, $t_c + x$ month).

1.2. INCREMENTAL SETTLEMENT PREDICTION MODEL (ISPM)

In general, settlements are measured on the cap cover (figure 2) in reference to the column height at the end of construction $H(t_c)$, and the models of prediction are applied conventionally to waste column, without considering the history of exploitation. This is in particular the case of Sowers method as it corresponds to a coarse simplification since the thickness in reference is the global thickness of column whose influence has never been quantified. Buisman's model is normally strictly applicable to a limited layer, so it appeared significant to us to show what this lack of rigour in extrapolation of models (for the majority drawn from the soil mechanics and consequently applicable to elementary layers) for columns of waste involves the settlement derived from the coefficients of compressibility.

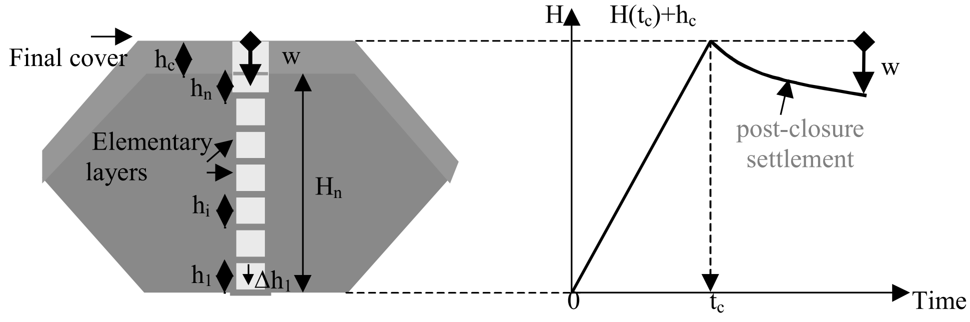

Fig. 2. Illustration of the accreditation of a rack of landfill in elementary layer

In this context, Incremental Settlement Prediction Model (ISPM) was introduced by GOURC et al. [2] before being developed by THOMAS (2000) and OLIVIER [3]. Based on the stacking of elementary layers of waste leading to the formation of total height of the deposit (column), this algorithm integrates behaviour in primary and secondary settlement of each elementary layer constituting the column. In each layer, the intrinsic parameters of the behaviour are affected and the behaviour of each layer is studied individually according to the evolution of the overload and time (figure 2).

1.3. GENERAL FORMULATION OF MODEL ISPM: EXPRESSION OF THE SECONDARY SETTLEMENT OF A WASTE COLUMN

The modelling of settlement prediction starts from this part of the former version of ISPM as developed by OLIVIER [3] to the newer one as ISPM 1.1. The fundamental equations of primary and secondary settlement are the same;

$$\frac{\Delta h_i^p}{h_0} = C_R^*.\log\frac{\sigma_i}{\sigma_c} \quad \text{in normally consolidated phase } (\sigma_i > \sigma_c), \tag{5}$$

$$\frac{\Delta h_i^s}{h_0} = C_{\alpha\varepsilon}^*.\log\frac{\tau}{\tau_c}. \tag{6}$$

In the present case, construction rate is assumed to be constant (the same time for the installation of each waste layer). Absolute time (t) originates from the time of the beginning of construction, the operating times (τ_j) and of the rest periods (τ_{rj}) of each one of the sub-layers, τ_{rj} corresponds to one period of rest lasting between the installation of the layers j and $j + 1$ ($\tau_{rj} \neq 0$ only in the event of rest between two successive layers). τ_c is the time at which secondary settlement of a layer is started (1 month).

The expression for the primary settlement is as follows:

$$w_n^p = \sum_{i=1}^{i_c-1} \Delta h_i^p = h_0 C_R^* X \quad \text{with} \quad X = \log \frac{\prod_{i=1}^{i_c-1}((n-i)\gamma_0 h_0 + q)}{(\sigma_c)^{i_c-1}}. \tag{7}$$

But for the secondary settlement to simplify the equation we make the assumption of constant thickness (h_0) for every layer. $W_n^s(t)$ is the secondary settlement at the time of measurement.

For $\tau_j = \tau_p$ and $\tau_{rj} = \tau_r$ and $t_n = n\tau_p + (n-1)\tau_r$.

$$W_n^s(t) = h_0.C_{\alpha\varepsilon}^* \log\left(\frac{\prod_{i=1}^{n}\left(t - \sum_{j=1}^{i-1}\tau_j - \sum_{j=1}^{i-1}\tau_{rj} - \frac{\tau_i}{2} \right)}{(\tau_c)^n} \right). \tag{8}$$

We modified the calculation methodology of secondary settlement for taking into account the construction phases. On the basis of Buisman's relationship, $C_{\alpha\varepsilon}^*$ in the ISPM model could be considered as an intrinsic parameter for the waste and consequently independent of the compression history.

2. COMPARISON OF THE ISPM MODEL WITH THE SOWERS MODEL

In the settlement model of SOWERS [4], the evolution of secondary settlement according to time depends on the secondary coefficient of compression $C_{\alpha\varepsilon}$ known as 'global'; it generally starts from the measurements of settlement of surface in the period of post-exploitation ($t = tc + x$ months, refer § 1.2). By comparing this model with the ISPM model, we compare the post-exploitation deformation $\varepsilon_{\text{Sowers}}$ with $\varepsilon_{\text{ISPM}}$, as well as the 'global' secondary coefficient of compression $C_{\alpha\varepsilon}$ with the 'intrinsic' coefficient $C_{\alpha\varepsilon}^*$ from the ISPM model.

Post-exploitation secondary settlements for the two models are expressed by:

$$\varepsilon_{\text{ISPM}} = \frac{w(t)}{H_n(t_c)} = \frac{w_n^s(t) - w_n^s(t_c)}{nh_0 - w_n^p - w_n^s(t_c)}, \quad \varepsilon_{\text{Sowers}} = \frac{w(t)}{H(t_c)} = C_{\alpha\varepsilon}.\log\left(\frac{t-t_0}{t_1-t_0}\right). \tag{9}$$

The conventions adopted below for the model of Sowers's are as follows:

- the origin of time $t = 0$: the beginning of the construction of the column of waste (the same for ISPM);
- $t_0 = t_c$ (the time of construction), though for certain authors, the definition of t_0 is different;

• the origin of the secondary settlement $\Rightarrow t_1 = t_c + x$ (months), with x variable from one author to another. In the present report, we use $x = 1$ month.

2.1. ASSESSMENT OF THE SECONDARY COEFFICIENT OF COMPRESSION $(C_{\alpha\varepsilon})_{\text{SOWERS}}$ FOR $(C^*_{\alpha\varepsilon})_{\text{ISPM}}$ AS CONSTANT

$C^*_{\alpha\varepsilon}$ of ISPM model is considered as constant with the elapsed time. We look for the value of equivalent $(C_{\alpha\varepsilon})_{\text{Sowers}}$ which gives at the same time (t) the same value of settlement. Equating the above expressions for the time t, we obtain:

$$\varepsilon_{\text{ISPM}} = \frac{C^*_{\alpha\varepsilon}.[Y(t) - Y(t_c)]}{n - C^*_R X - C^*_{\alpha\varepsilon} Y(t_c)} = \varepsilon_{\text{Sowers}} = C_{\alpha\varepsilon}.\log\left(\frac{t - t_0}{t_1 - t_0}\right) \qquad (10)$$

with $X = \log \dfrac{\prod_{i=1}^{i_c - 1}((n-i)\gamma_0 h_0 + q)}{(\sigma_c)^{i_c - 1}}$ and $Y(t) = \log\left\{\dfrac{\prod_{i=1}^{n}\left(t - \sum_{j=1}^{i}\tau_j - \sum_{j=1}^{i}\tau_j - \dfrac{\tau_i}{2}\right)}{\tau_c^n}\right\}$.

To facilitate the demonstration, we will consider an example, namely Cases A1 &A2. For A1, t_c = 12 months and for A2, t_c = 24 months. The column characteristics are as follows: $\tau_i = \tau = t_n/n$, $\tau_{ri} = 0$ and $t_c = t_n$. The following parameters are fixed: $C^*_R = 0.20$, $C^*_{\alpha\varepsilon} = 0.08$, initial unit weight of waste $\gamma_0 = 8$ kN/m^3; cover layer overload $q = \gamma_c h_c = 18$ kPa.

2.2. INFLUENCE OF TIME OF CONSTRUCTION (t_c)

Figure 3 shows the evolution of the waste settlement (cases A1 & A2) corresponding to two different construction times t_c with a constant value of $(C^*_{\alpha\varepsilon})_{\text{ISPM}}$. In addition, the mean value of $(C_{\alpha\varepsilon})_{\text{Sowers}}$ is significantly different from the value of $(C^*_{\alpha\varepsilon})_{\text{ISPM}} = 0.08$. For every value of $(t - t_c)$ it is possible to evaluate a different $(C_{\alpha\varepsilon})_{\text{Sowers}}$ which we can observe in figure 3 (b).

It is demonstrated in figure 3 that unlike $(C^*_{\alpha\varepsilon})$, $(C_{\alpha\varepsilon})_{\text{Sowers}}$ is not constant during the settlement process. It is worth noticing that the coefficient of the secondary settlement by Sowers, $C_{\alpha\varepsilon}$, is wrongly considered as a geo-mechanical characteristic of the waste material by all the users of this model of settlement prediction. In the following application we display the variation of $(C_{\alpha\varepsilon})_{\text{Sowers}}$ due to the variation of the parameters above.

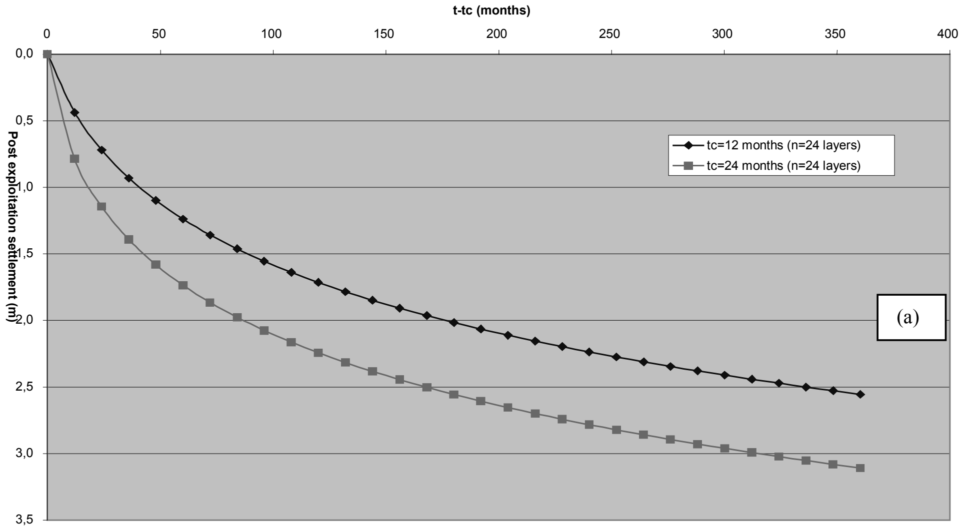

Fig. 3(a). Evolution of settlement as the function of time (ISPM 1.1)

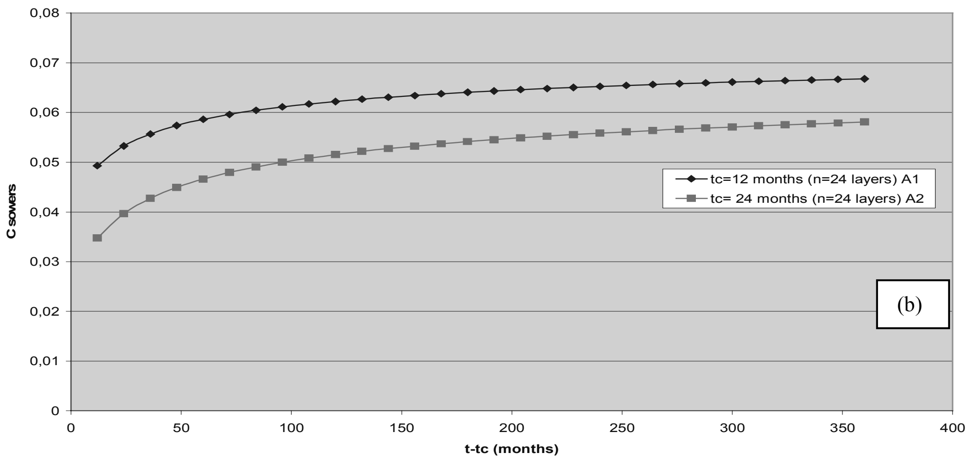

Fig. 3(b). The coefficient of the secondary compression (the method of Sowers')
during the secondary settlement for $C^*_{\alpha\varepsilon} = 0.08$

2.3. VERSATILITY OF INCREMENTAL ISPM MODEL FOR AN EVALUATION OF C^*_R AND $C^*_{\alpha\varepsilon}$ (CONSTRUCTION IN 2 PHASES)

This example is presented in order to demonstrate the flexibility of ISPM model. This application is related to a construction of a landfill in two phases. The topographic follow-up includes exclusively the measurement of secondary settlement (figure 4). Nevertheless, a reactivation of primary settlement is induced in the case of extensions of cells or in the case of rehabilitation of old landfills including the construction of various works (earth fills, light constructions, roads, etc). Terrain survey for this objective was undertaken by LTHE-Lirigm on Chatuzange by means of internal instrumentations.

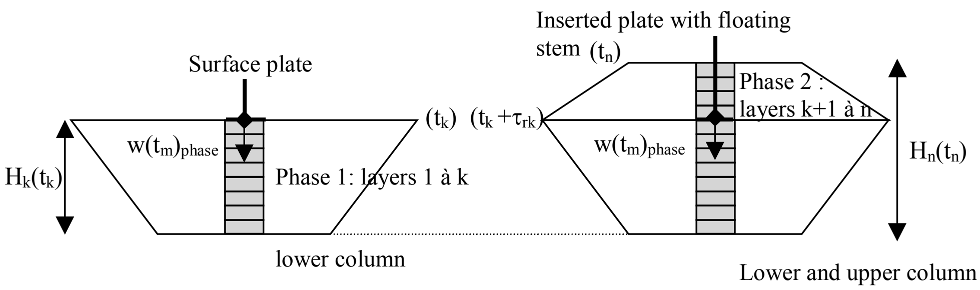

Fig. 4. Exploitation in 2 phases separated by one period of rest

The secondary settlement coefficient $C^*_{\alpha\varepsilon}$ is deduced from the monitored settlement, which is reported from the measurements of a buried plate located at the top of the first-phase waste body. An original application relates to the storage of waste in 2 distinct phases (phase 1: installation of layers from 1 to k; phase 2: installation of layers from $k + 1$ to n) separated by one rest period of τ_{rk} duration. ISPM is presently

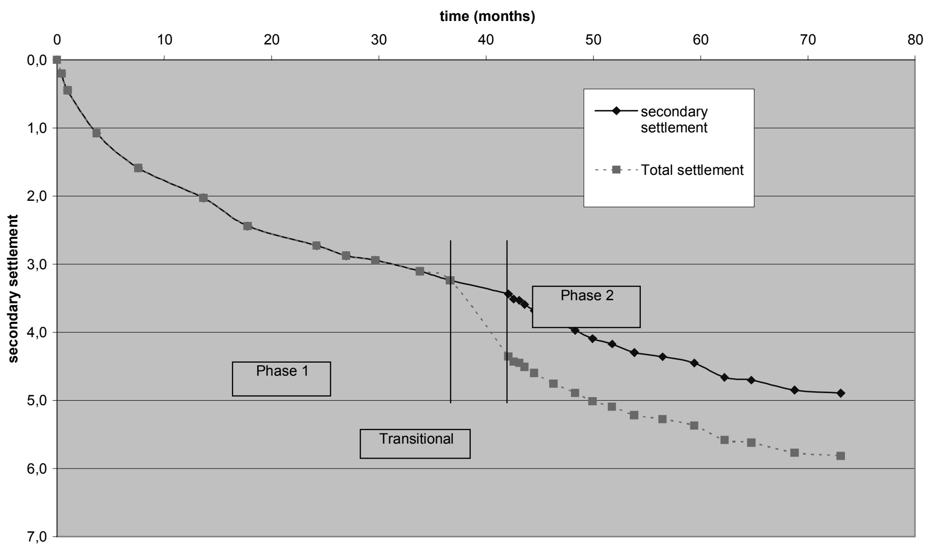

Fig. 5. Influence of overloading on secondary settlement of the lower column, C_R (0.13)

used with a back analysis approach for each time. The values of $(C^*_{\alpha\varepsilon})_{\text{Phase 2}}$ can be compared with the values of $(C^*_{\alpha\varepsilon})_{\text{Phase 1}}$ with the aim of checking the assumption of the independence of $C^*_{\alpha\varepsilon}$ with respect to the overload. The primary coefficient of compression C^*_R is estimated also by back analysis during the transitional period of the overloading of phase 1.

In this specific case, it is possible to plot the settlement of the lower column for the phase 1 and for phase 2 (figure 6), the settlement during the phase 1 is exclusively secondary settlement. The settlement during the transitional phase, corresponding to the implementation of the secondary column of waste, is the combination of a primary settlement and a secondary settlement in continuation of the phase 1.

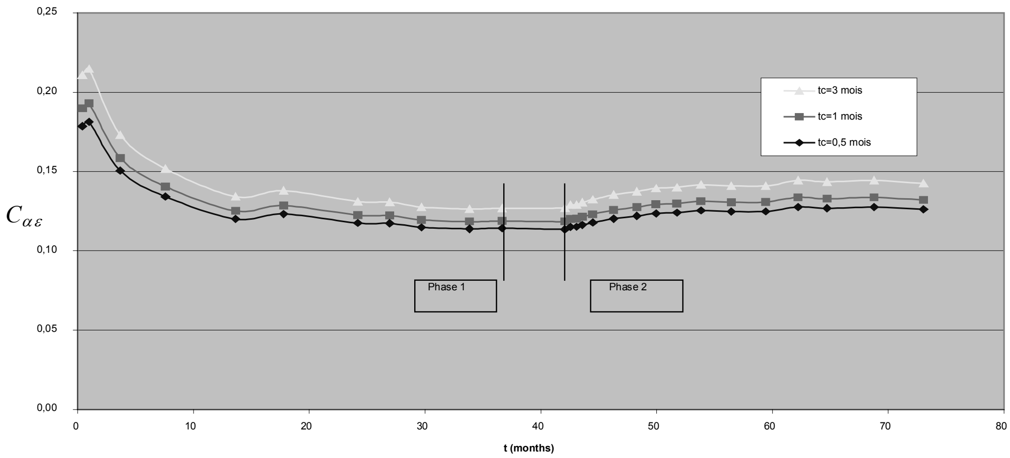

Fig. 6. Influence of τ_c on $C_{\alpha\varepsilon}$ for C_R (0.13), Chatuzange

The part of the settlement due to overloading can be subtracted and the value of C^*_R deduced. A C^*_R value equal to 0.13 is determined from figure 5 corresponding to the transitional period. It is specifically worth noticing that the value of $C^*_{\alpha\varepsilon}$ is becoming constant independently of the overloading. It is a key point since it is demonstrated that the parameter $C^*_{\alpha\varepsilon}$ can be considered an intrinsic characteristic of the waste independent of the waste column construction sequence.

3. CONCLUSION

Unlike the Sowers model, usually applied in the prediction of long-term settlement, the ISPM model takes into account all the history of waste installation in the landfill. In the case of a cell at the stage of the preliminary draft or in post-exploitation, the ISPM model may initially be used for the determination of the secondary coefficient of compression $C^*_{\alpha\varepsilon}$ which can be carried out according to one of the two approaches:

• By direct analysis: on the basis of pre-gauged or supposed coefficient of compression (only approach applicable to the stage of the preliminary draft or the case of non-instrumented racks). New progress is needed for research of the assumed value of the coefficient of compressibility $C^*_{\alpha\varepsilon}$ which depends on the type of waste.

• By back analysis: after calibration of $C^*_{\alpha\varepsilon}$ from a topographic campaign starting from one year to a few years (approach privileged for the modern MSW). The systematic use of the ISPM model for case histories would allow us to find a correlation between the type of waste and the value of $C^*_{\alpha\varepsilon}$.

The point of interest is that by back analysis it is possible to determine a secondary compression coefficient $C^*_{\alpha\varepsilon}$ for waste which seems of intrinsic value to the material.

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