VALIDATION OF THE ASAOKA AND BAGUELIN METHODS FOR ANTON LANDFILL. MULTICRITERIA QUALIFICATION OF PAST SETTLEMENT DATA TO PROJECT FUTURE SETTLEMENT

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SUMMARY: The purpose of the present paper is to suggest a set of criteria allowing one to qualify a series of measured settlements for the reliable application of Asaoka's method or its Baguelin variation. The suggested qualification criteria are presented after reviewing the Anton Landfill measurements database and the problems it raises towards the application of both observational methods. Using a combination of a consistency condition on the projected final settlement as well as a minimization of prediction errors on the tail end of the data series, the authors identify an optimal number of data points to verify the relevance of the suggested criteria. It is shown that, within the Anton Landifill, qualified settlement markers produce a series of measurements fit for Asaoka and Baguelin's methods, while others, which do not satisfy the suggested criteria, continue to settle without enabling a reliable application of Asaoka or Baguelin's method. That differentiated behaviour highlights the potential three-dimensional nature of the vertically conducted observations on a given landfill.

1. DESCRIPTION OF THE SITE

Filled with 1 million m^3 of domestic waste between June 1983 and May 1985, the Anton landfill is situated in an old limestone quarry bordering the Meuse, in Andenne, Belgium. (Figure 1). Subsequent to pollution detection in 1991, the SPAQuE ("Société Publique d'Aide à la Qualité de l'Environnement", i.e. Public Company for assisting the quality of the environment) ordered qualification studies to be carried out, with, in particular, the monitoring of movements (vertical and horizontal) in the waste. (Figure 2).
These markers are still being monitored at present.

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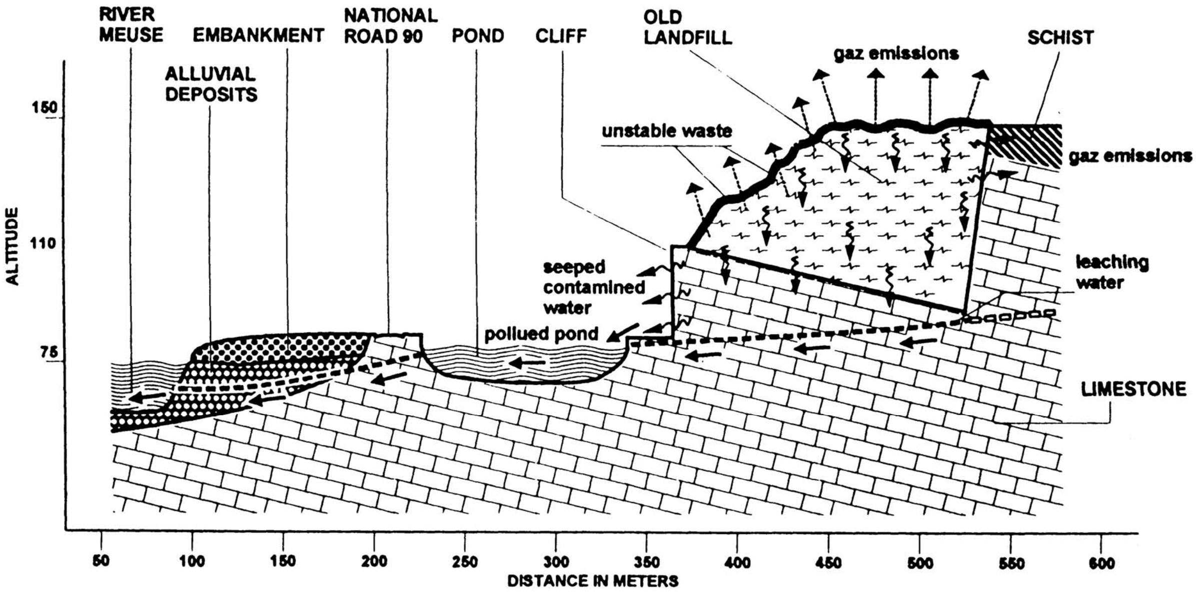

Figure 1. Geologic Cross-section of the Anton Landfill 1

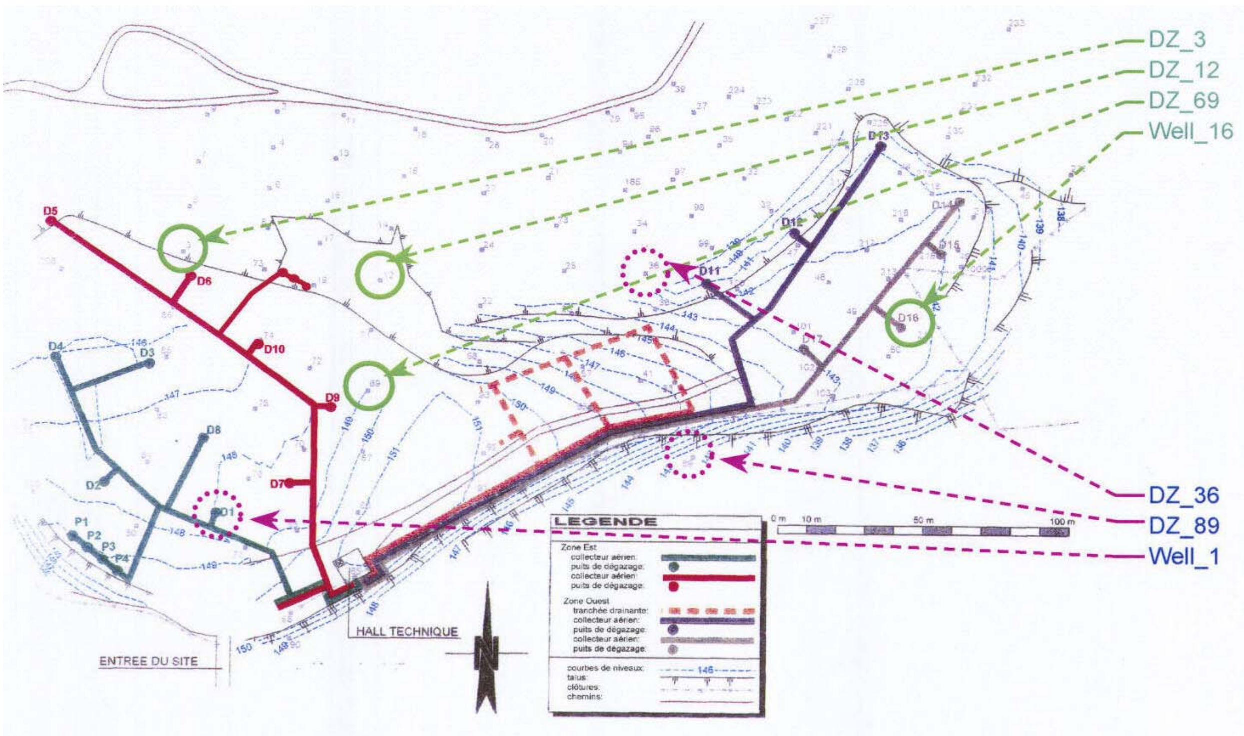

Figure 2. Site Plan of the Anton Landfill

In 1996, the restoration work that had been decided on, was carried out. This work basically consisted of the erection of a semi-permeable cover, the installation of a gas removal system and a plant for treatment of the recovered leachate.

2. MOTIVATION OF THE STUDY

Predicting the final settlement of a landfill is important. Not only does it permit to estimate of the total volume of waste to be placed in order to achieve a given profile, but it also establishes the likely duration of the post-management period. So it is still necessary to be in a position to make this prediction although often the information is missing.

Traditional methods of estimating the settlement of waste such as, for example, Sowers method (1968), require knowledge of parameters such as the void ratio, the depth of the waste, as well as the secondary compression index linked to the organic matter content. This information does not exist for the Anton landfill site. What is available at most is a rough estimate of the filling depth (the bottom not being very well known) on the basis of CPTs and degassing Wells.

The Asaoka method (1978) only requires the recording of settlements at relatively regular intervals of time. The Baguelin method (1999), inspired by the Asaoka method, allows one to get away from regular time intervals. These methods do not require knowing the filling conditions or characteristics of the waste. Consequently they should be of interest to this site where such information is missing. These two methods rely on the following laws of settlement according to the estimated final settlement :

$$S(t) = S_\infty (1 - e^{(-\lambda t)}) \qquad [1]$$

with : $S(t)$ = settlement at time t ;
S_∞ = final settlement according to Asaoka ;

$$\lambda = - \ln \beta_1 / \Delta t \qquad [2]$$

with
Δt = interval of time between 2 measurements (constant for the Asaoka method) ;
β_1 = slope of the regression line $S(t+ \Delta t)$ vs. $S(t)$ following Asaoka's procedure.

3. ANTON LANDFILL SETTLEMENT DATABASE

The first stage of the evaluation consisted in determining the applicability of both these methods in relation to the settlement data available. Figure 3 shows the evolution of the settlements recorded at 16 settlement markers, spanning more than 12 years of the landfill life. It can be noted that time intervals separating measurements are generally rather uniform, in spite of a denser set at the beginning of the monitoring period (i.e. during 1991-1994) and of three data gaps exceeding 300 days.

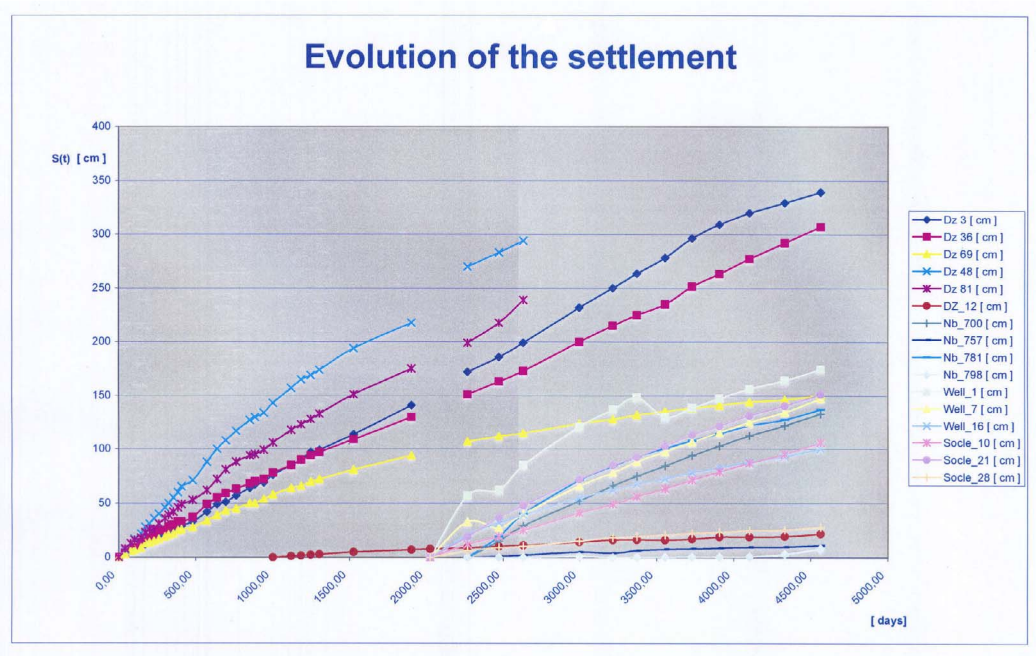

Figure 3. Settlements records versus time at Anton Landfill

Four markers were selected which were deemed to represent- typical conditions encountered on the site. These are the markers Dz_3, Dz_12, Dz_69 and Well_16, respectively, as shown on the location map of Figure 2.

An initial analysis of the settlement readings shows that the settlement trend exhibited by certain markers is still relatively linear (e.g.: markers Dz_36, Dz_89, Well_1) after more than 13 years of measurements on more than 19 years old waste.

Figure 4 represents the average rate of settlement v = dS / dt, calculated by linear regression over 7 settlement measurement points. That graph shows a clear tendency towards decrease for markers Dz_69 and Well_16. Conversely, we do not find this decrease for markers Dz_3 and Dz_12.

The observed decrease translates the tendency towards a reduction in the rate of settlement: if the external conditions do not change (no drying out of the waste, for example), this means that the waste is approaching stabilisation. This is the case of markers Dz_69 and Well _16. Application of regression methods of the Asaoka (A) and Baguelin (B) type is possible.

The marker Dz_3 does not yet show clear-cut stabilisation. It might be expected that application of the A and B prediction methods will lead to a wide scatter of results depending on the series of data taken into account.

The marker Dz_12 shows that settlement is probably in its final phase (2.8 cm over almost 2 years). However the A and B prediction methods are becoming too sensitive to the quality of the measurements as differences between successive measurements become too small. What is more, the impact of horizontal movements, given the configuration of the landfill, makes the interpretation the results difficult.

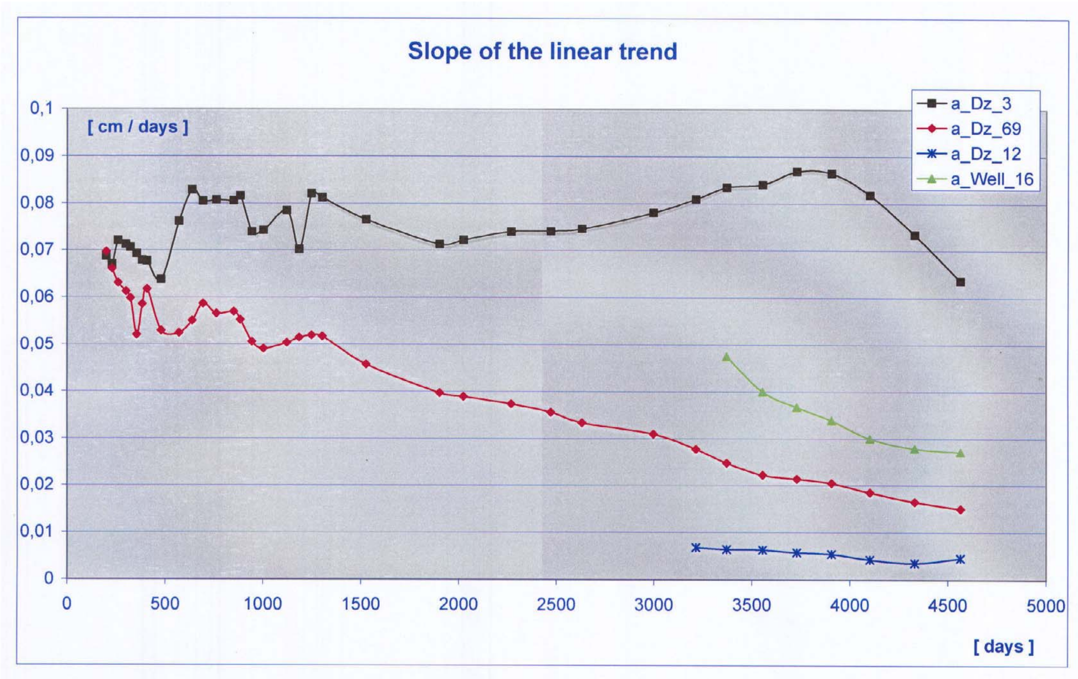

Figure 4. Rate of settlement [cm/day] for selected markers

4. SUGGESTED QUALIFYING CRITERIA

Showing the settlement speeds in relation to the estimated depth of the waste in graph form (Figure 5) confirms the previous analysis and leads us to formulate the following qualification criterion : the Asaoka prediction method and its Baguelin variant become applicable and stable from the moment the following three conditions are met :

a) the settlement speed graph deduced from the measurements is correct,
   [3a] i.e. $\Delta v/|v|<0.1$ between neighbouring points
b) the settlement speed graph deduced from the measurements is decreasing,
   [3b]i.e. $\Delta v<0$
c) the average unitary speed of the compression of the column of waste of depth H_R is becoming less than 12 10^{-6} days $^{-1}$,
   [3c] i.e.$(dS / dt) /H_R < 12$ µstr/day

This value is to be considered with some caution, given the lack of knowledge concerning the level of the bottom of the landfill. It must probably be adapted according to the characteristics of the site being studied.

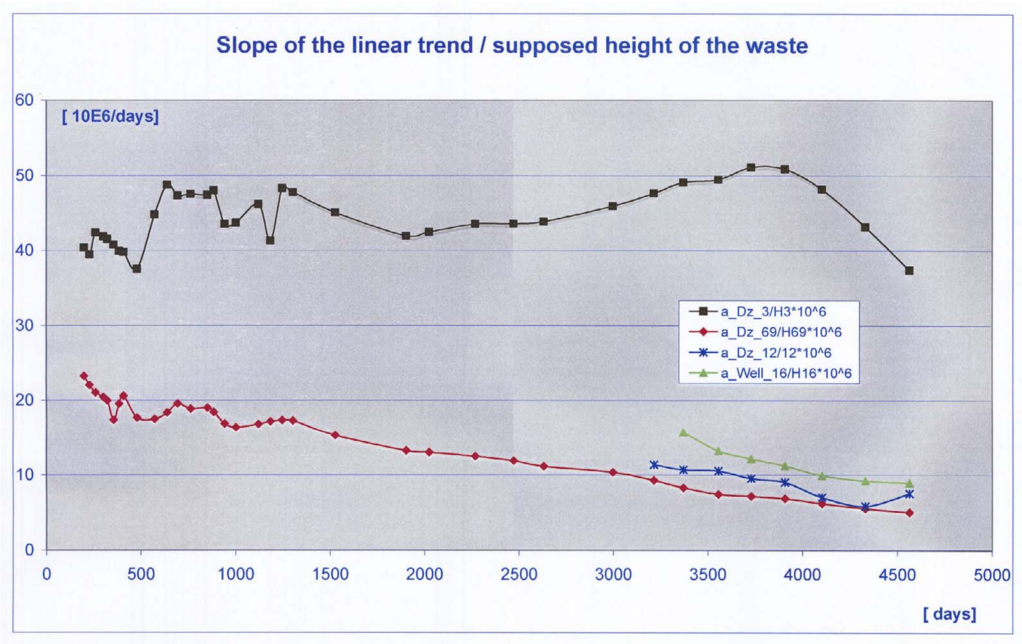

Figure 5. Unit compression rate [μstr/day] at selected markers

5. CONSISTENCY OF FINAL SETTLEMENT PROJECTED BY ASAOKA AND BAGUELIN METHODS

This section focuses on markers Dz_3 (the marker for which the previous analysis shows that that the data is not sufficiently “stable”) and Dz_69.

Table I summarizes the scatter affecting predictions of the final settlement obtained by the Asaoka and Baguelin methods based on a variable number N of measurements taken into account (progressive reduction of the complete series of data from the beginning until only the last 7 measurements remain). This analysis demonstrates that the scatter of the results is wider the greater the variability in the rate of settlement.

It appears that, even if the settlement measurements meet the proposed applicability criteria per eqs. 3a, b and c, the prediction varies with the amount of data considered. Figures 6 and 7 show the settlement curves predicted by, respectively the A an B methods, for different values of the number N of data points used to coin the regressions). The Baguelin method has the advantage over the Asaoka method to be free from the necessary condition of a constant time interval between the measurements. This has particular merit as it is rare to benefit from regularly spaced settlement readings.

Table 1. Summary of scatter affecting the prediction of the final settlement

	Prediction Asaoka		Prediction Baguelin	
	Minimum [cm]	Maximum [cm]	Minimum [cm]	Maximum [cm]
Dz_69	174	196,8	170,7	182,7
Dz_3	411,8	986,9	387,7	4580,7

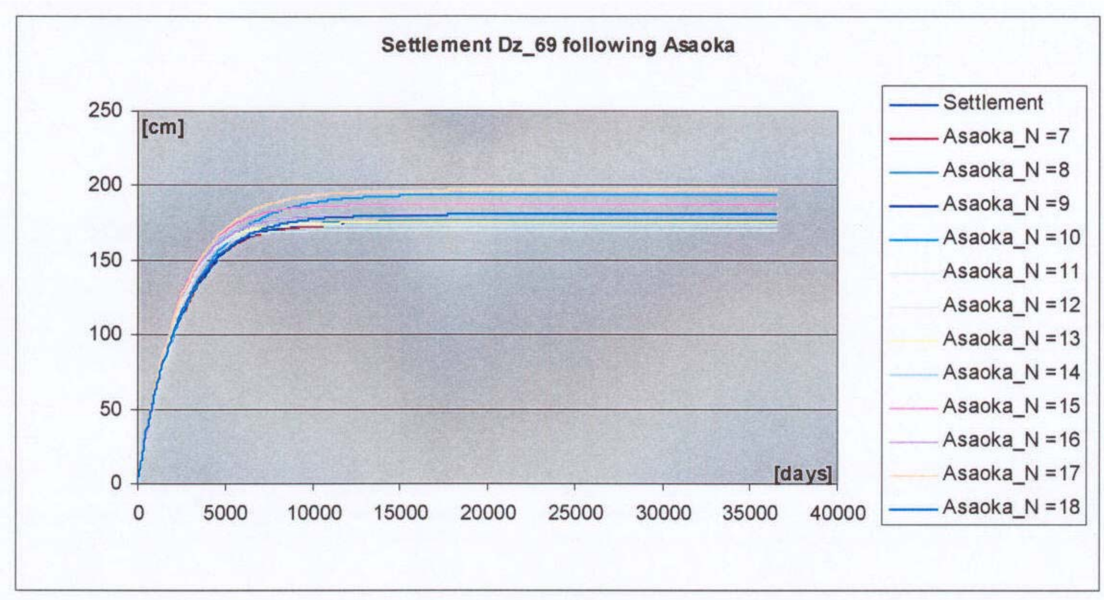

Figure 6. Measured settlements and Asaoka's extrapolations of settlement curve for different numbers N of data points used for Marker Dz_69 series

In order to determine the most suitable prediction method, the authors suggest a reliability index placing the emphasis on the last settlement measurements recorded. In fact, it seems justifiable to believe, under unchanged external conditions, that the most recent settlement measurements (i.e. the tail end of the data series) are more representative of future settlements than the initial ones.

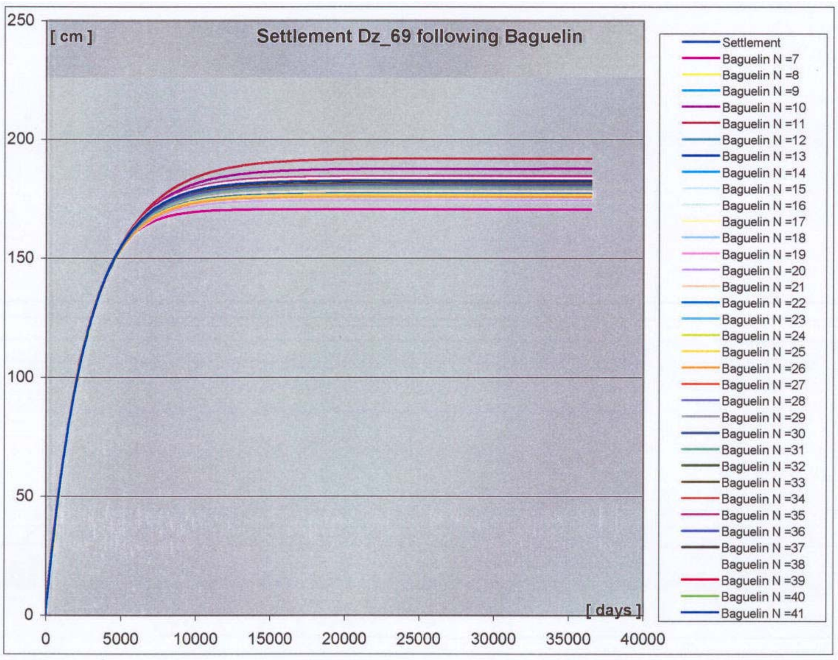

Figure 7. Measured settlements and Baguelin's extrapolations of settlement curve for different numbers N (from 7 to 41) of data points used from Marker Dz_69 series

The proposed reliability index consists of minimising the following time-weighted Error Function :

$$E(N,n) = \Sigma[(t_i^2 \times (S^*(t_i) - S(t_i))^2] \text{ for } i = N-n+1 \text{ up to } N \quad [4]$$

with :

N = the number of measurements used for the prediction
n = the number of points selected for the reliability index
t_i = the time of the measurement i
$S^*(t_i)$ = settlement measured at time t_i
$S(t_i)$ = settlement estimated (according to Asaoka or Baguelin) at time t_i

This criterion expressed in [cm.day²] emphasizes the weight of the last measurements by multiplying them by the square of the time, putting a heavier penalty on errors made towards the tail end of the data series. In the present study, the number n of points selected to assess the reliability index was chosen as 4.

The application of this reliability index leads one to select the Asaoka model built on the last 7 records (N_A = 7, Figure 8) and the Baguelin model built on the last 13 records (N_B = 13 Figure 9) with an estimated final settlement of 174 cm and 191 cm respectively. The Baguelin method improves on the bias introduced with the Asaoka method as a result of irregular time intervals.

It is the authors' opinion that the results according to the Baguelin method therefore seem to be closer to the truth.

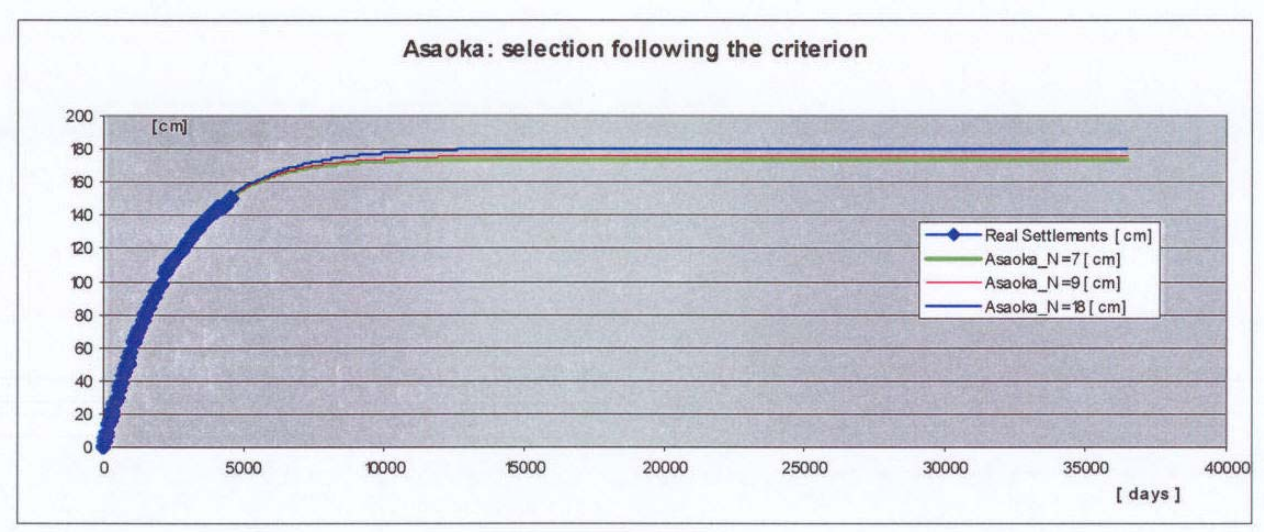

Figure 8. Measured settlements and Asaoka's extrapolations of settlement curve for different numbers N (7, 9 and 10) of data points used from Marker Dz_69 series

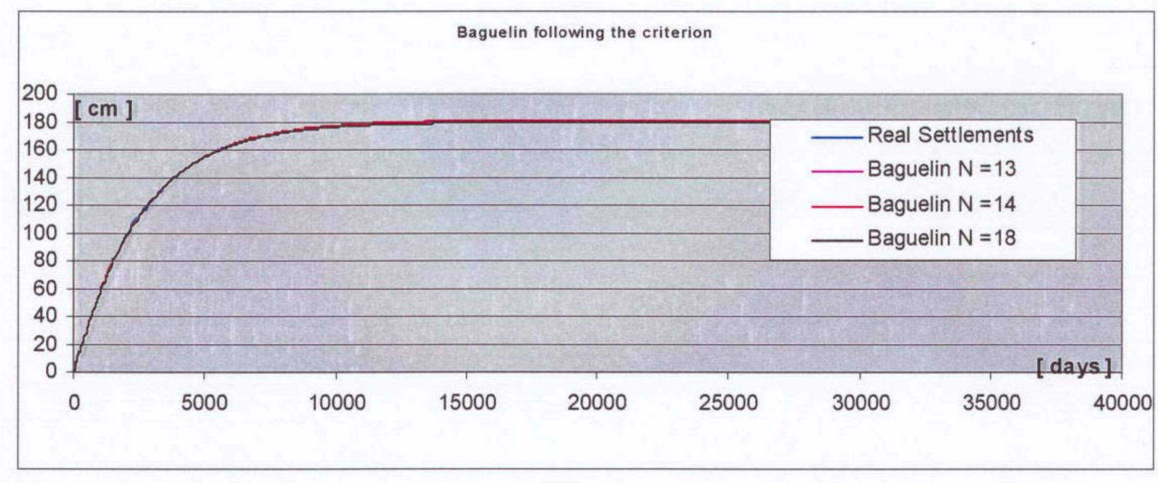

Figure 9. Measured settlements and Baguelin's extrapolations of settlement curve for different numbers N (13, 14 & 18) of data points used from Marker Dz_69 series

The graph shown in Figure 10 demonstrates a certain stability in the estimates of the final settlement as a function of N_B according to the Baguelin method. This estimation is to be put into perspective with the initial analysis of the data. The variation in the settlement predictions as a function of N_B is lower the closer we get to the criteria described in point 4. In fact $N_B = 13$ corresponds to taking into account a series of data *ending* in $t_{NB=13} = 2997$ days and a unitary speed of compression calculated over the interval of time running from $t_{NB=13-7} = 1527$ days until $t_{NB=13} = 2997$ days (figure 6). In this particular case this value is situated below the validation criteria, since it is estimated at $10.3\ 10^{-6}$ day $^{-1}$.

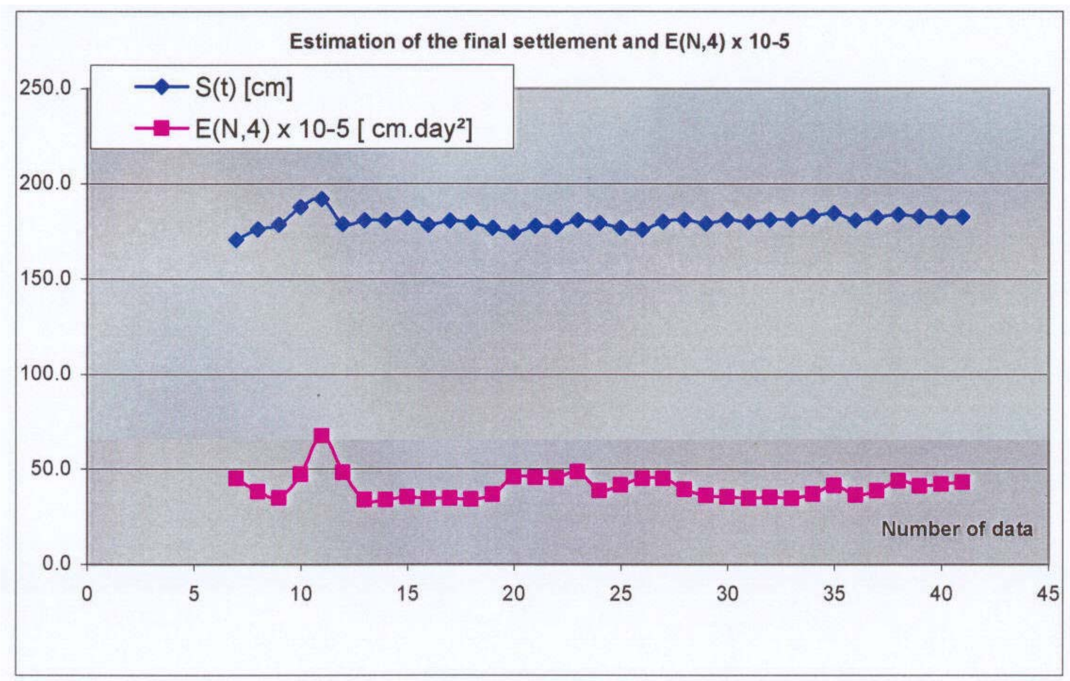

Figure 10. Stability of Baguelin's method in terms of final settlement estimate and time weighted error function, E(N,4) per eq. [4] as functions of N

Table 2. Comparison of estimates and measurements for marker Dz_69

	Real settlement	**Prediction**	**Difference**
[days]	**[cm]**	**[cm]**	**[%]**
4331	146,4	147,1	0,5
4564	150,3	150,0	0,2

6. MEDIUM-TERM VALIDATION OF THE QUALIFYING CRITERIA

To further validate the preference towards Baguelin's model, we have assumed that the last 2 measurements are unknown and we have applied the ***same*** procedure. The results in Table 2 show the difference compared to the measurement for a prediction on the marker Dz_69 starting from a series ending at t = 4103 days, i.e. an 18 month prediction. A difference of less than 0.2% (3 mm !) against the last measurement should be noted!

Therefore the model selected gives satisfaction.

On the other hand, when the unit compression rate is greater than =12 10^{-6} days $^{-1}$, the spread of the estimates is much wider, as sown by Table III relating to the same evaluation carried out on marker Dz_3.

The prediction model therefore becomes less reliable.

7. CONCLUSIONS

Predicting the final settlement of a landfill is important. Not only does it permit estimation of the total volume of waste to be implemented in order to achieve a given profile, but it also establishes the likely duration of the post-management period. So it is still necessary to be in a position to make this prediction although often the information is missing.

The method proposed here is solely based on settlement readings. After analysis of the data, aimed at determining the applicability of a prediction model, the Asaoka and Baguelin methods were used to predict the probable final settlement. The final settlement estimates vary particularly according to the length of the series of data taken into account. The authors propose both a limited value of the unit compression rate and a simple reliability index enabling the model sticking closest to the actual measurements to be selected. This method has been verified for settlement measurements deemed to be unknown and the results of the estimations are very close to the true values.

It is difficult and no doubt risky to draw general conclusions from a single site. This method must certainly be validated on other sites.

Table 3. Comparison of estimates and measurements for marker Dz_3

	Real settlement	**Prediction**	**Difference**
[days]	**[cm]**	**[cm]**	**[%]**
4331	329,3	338,5	2,78
4564	339,3	355,1	4,64

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