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1. Defra Project code
   WR0301

2. Project title
   LANDFILL SETTLEMENT:
   ESTIMATING TIME TO COMPLETION

3. Contractor organisation(s)
   Golder Associates (UK) Ltd
   Napier University
   Loughborough University

4. Total Defra project costs (agreed fixed price)
   £ 76,450

5. Project:
   start date ............... 13 September 2006
   end date ............... 31 May 2008
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Executive Summary

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Waste settlement analysis and prediction are crucial to understanding and managing the lifecycle of a landfill. Settlement determines the pre and post-settlement contours of the completed landfill and the planned filling volumes, it influences the progress of hydraulic and biodegradation processes, affects the performance of the landfill engineering and is part of the designation of when landfill sites have stabilised to the point that all management can be removed.

Landfill settlement predictions are typically carried out using time-dependant methods, based on mathematical functions matched to previously recorded waste settlements. Despite the refinement of existing methods of settlement prediction over many years, they have serious shortcomings in handling the organic fraction and the many factors that control its decomposition, and they are unable to account for changing landfill conditions, such as waste types and interruptions in the filling phase. They are, therefore, difficult to use in a predictive manner and require recalibration for changing waste streams. The Hydro-Biological-Mechanical (HBM) model is a settlement prediction tool which considers the actual processes occurring within the body of the waste that cause settlement. The HBM model is unique in that it provides a coupling between the, hydraulic, biodegradation and mechanical components of waste behaviour.

The principal objective of this research project has been firstly the assessment and validation of the HBM model using settlement and associated data from actual landfills; and secondly the preparation of an accompanying settlement prediction protocol to collect the necessary data and to analyse, interpret and predict the magnitude and time to completion of long-term landfill settlements of landfills in relation to site conditions, waste factors and site operations.
The project has focused on the acquisition of landfill settlement measurements, and site-specific and waste-specific data which influence future settlements of the waste, and then on the application of these data in the HBM model which has been developed by Napier University over several years.

In order to validate the performance of the HBM model, data on landfill geometry, filling history and waste characteristics have been collated from landfill operators in the UK, USA, Australia and Hong Kong. The types of information requested from operators for use in the model comprised data normally gathered either for the operational purposes of the companies or for compliance with permit conditions. Acquisition of adequately complete data sets proved to be challenging, and the quality, extent and format of acquired data sets varied significantly.

Comparisons were made between results computed by the model and measured landfill settlement data, and it has been shown that the model can be used to reproduce measured settlement traces for a number of landfills with markedly different waste and site characteristics, and waste disposal histories.

The model is complex in its formulation and despite an effective graphical interface, it remains a relatively complex tool to implement. As with all finite element software, particularly bespoke codes such as this, it cannot be treated as a “black box”, and a sound understanding of the theory is required in order to implement the code. In its present form, it is considered to be an extremely useful research tool. However, users with the requisite experience and theoretical understanding can currently apply the model with relatively little effort to real cases and obtain settlement predictions with a sounder technical basis than the presently used time-dependant methods. Sensitivity and parameter analyses can be readily incorporated in the analyses.

With the aim of advancing landfill settlement data collection and settlement prediction, a landfill settlement protocol has been produced including a hierarchy of settlement prediction techniques.

Conclusions are drawn on the benefits to stakeholders (landfill operators, planning authorities and environmental regulators) of a consistent, industry-wide settlement monitoring and operational data collection protocol; the increased frequency of certain data measurements, especially of settlement; settlement prediction based on actual settlement processes; and on the present lack of guidance on settlement prediction methods which causes a wide variety of procedures to be submitted with planning applications, which can cause difficulties to planning authorities in the assessment of applications.

From the findings of the project, future work of considerable benefit to stakeholders has been identified. The development of guidance is recommended on landfill monitoring procedures to meet the legal monitoring requirements in a thorough and consistent format. The preparation of guidance is also recommended on the settlement prediction process to assist in the preparation of reliable estimates of future landfill settlements, and their consideration by the planning authorities and regulatory bodies. Several aspects of the HBM model have been identified for further development to enable improvements in the operation of the model to be achieved, and research on key parameters (the decomposition induced void change parameter, digestibility and solid degradable fraction) are recommended. In addition, further validation of the gas generation function and the HBM model would be beneficial, together with assessing the potential to link the model with the GasSim2 model.
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SUMMARY REPORT ON

LANDFILL SETTLEMENT:
ESTIMATING TIME TO COMPLETION

Submitted to:

DEFRA
17 Smith Square
London
SW1P 3JR

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1 copy  -  Golder Associates (UK) Ltd

June 2008 06529217.503/A.0
**REPORT ISSUE FORM**

<table>
<thead>
<tr>
<th>Version Code</th>
<th>Issue Date</th>
<th>30 June 2008</th>
</tr>
</thead>
</table>

**Document Title**  
Landfill Settlement: Estimating Time to Completion  
06529217.503

**Comments**  
Formatted by njt

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(Printed version signed)

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(Printed version signed)

**Report Distribution**  
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1.0 INTRODUCTION

This is a summary of the final report of the Defra Research Project “Landfill settlement: controlling the time to completion”. The project has the DEFRA reference number WR0301 (previously WRT381). The project has been undertaken by Golder Associates (UK) Limited (Golder) and Napier University, Edinburgh, with review by Loughborough University.

Waste settlement analysis and prediction are crucial to understanding and managing the lifecycle of a landfill. Settlement determines the pre- and post-settlement contours of the completed landfill and the planned filling volumes, it influences the progress of hydraulic and biodegradation processes, affects the performance of the landfill engineering, and is part of the designation of when landfill sites have stabilised to the point that all management can be removed. Despite the refinement of existing methods of settlement prediction, they have serious shortcomings in handling the organic fraction and the many factors that control its decomposition, and they are unable to account for changing landfill conditions, such as waste types and interruptions in the filling phase. They are, therefore, difficult to use in a predictive manner and require recalibration for changing waste streams. An alternative, more fundamental approach to the estimation of landfill settlement has been developed based on combining individually proven models of hydraulic, biodegradation and mechanical (HBM) behaviour to give an integrated interpretation of landfill behaviour.

This project has focused on the acquisition of landfill settlement measurements and of site-specific and waste-specific data which influence future settlements of the waste, and then on the application of these data in the hydraulic-biodegradation-mechanical (HBM) model developed by Napier University. The HBM model and graphical user interface is freely available at http://www.sbe.napier.ac.uk/HBM/.

The study commenced with a search for field-scale settlement records and the landfill data that influence settlement from UK operators and other research-led field scale projects overseas. In the second phase, the settlement data were analysed using simple time dependent methods. This was done firstly to assess the nature and scale of the landfill settlement interpretation problem today and secondly to identify data sets suitable for further analysis using the HBM model. In the final phase, performance of the HBM model was assessed and evaluated. A Workshop was held on 29 April 2008 in Birmingham following issue of the draft final report, attended by representatives from landfill operators, planning authorities, the Environment Agency, Defra and the project team. Presentations on landfill settlement issues and on the project were each followed by discussion sessions.

The HBM model of waste degradation has been under development for several years to simulate the actual processes involved in the settlement of landfill wastes. This model has theoretical advantages over the currently-used simplified settlement prediction methods, in that the actual processes of waste settlement and decomposition are considered with coupled hydraulic, biodegradation and mechanical modelling. This model provides a more fundamental, and hence more comprehensive, prediction of short-term and long-term settlements and time to completion. This report provides an assessment of the operational and
quantitative performance of the HBM model against actual settlement data. In the context of this assessment, “operation” refers to the ease of use and stability of the model and graphical user interface (GUI), while “quantitative” performance refers to the resulting fit between model output and the actual settlement data.

The acquisition of actual landfill data under normal operating conditions, rather than data from laboratory or larger scale test facilities, has enabled full-scale testing and validation of the model to be undertaken for a variety of landfill cases. An early finding of the project was that acquisition of complete data sets of information from the records that landfill operators have normally collected was challenging. The process of collection, recording and storing settlement records and other relevant data by operators is carried out in a variety of ways and for different purposes. This project has examined these procedures and provides recommendations for improvements to facilitate the use of these data in settlement calculations. The benefits to landfill operators of settlement prediction are important for operational and commercial reasons but are not necessarily widely accepted at present.

The time-dependent approach to landfill settlement analysis as currently used throughout the industry is compared with the more fundamental approach examined in this project. It is not a simple comparison because this latter approach (HBM model) is part of a wider interpretation of landfill behaviour and offers more than just an analysis of post-closure settlement. Of particular relevance are the additional data and skills requirements of the more fundamental approach, although these enable the benefits of the fundamental approach to be realised. Time-dependent predictions would also benefit from the availability of the additional data.

A technical paper on the data collection and assembly was presented at the Sardinia waste management conference in 2007 (Needham et al., 2007) and an abstract for a second technical paper for presentation at Waste 2008 has been accepted (Needham et al., 2008).
2.0 AIMS AND OBJECTIVES

The research project had the principal aim of establishing a model and accompanying protocol by which to analyse, interpret and predict the magnitude and time to completion of long-term landfill settlement in relation to (i) fundamental factors, such as moisture content, degradable fraction and degradability, and (ii) site operations such as filling sequence, compactive effort, leachate management and capping. Specific objectives within this principal aim were:

- The assembly and evaluation of long-term settlement data sets and compilation of selected suitable data sets for model validation;
- A critical evaluation of the operation and quantitative performance of the HBM model using actual landfill data sets and refinement of the model as necessary; and
- The development of a landfill settlement protocol on the monitoring and prediction of landfill settlement.

All the project aims and objectives were met. No refinements were found to be necessary to the HBM model although specific areas of improvement, outside the scope of the current project, were identified.

The project comprised three phases:

- Phase 1 covered the assembly and evaluation of available data sets from landfill sites in the UK and overseas. Agreement was reached with five of the main UK landfill operators to provide data sets for the project. In addition, access was gained by the project team to a number of long-term landfill data sets from several countries outside the UK. The data sets were assessed for completeness and suitable sets compiled for use in the HBM model.

- Phase 2 focused on quantitative simulations of the assembled data sets. Model performance with differing waste composition, under different climatic conditions and other operational conditions have been assessed, and the strengths and weaknesses of the HBM model evaluated.

- Phase 3 concentrated on the distillation of the outcomes of Phases 1 and 2 into a landfill settlement protocol. The protocol provides guidance on the recording and compilation of landfill data relevant to settlement prediction and on the analysis of landfill settlement, and establishes benchmark conditions based on the best available landfill data sets for use in the freely available HBM landfill settlement model.
3.0 BACKGROUND

The Landfill Directive is changing the way in which waste is managed. Much more stringent criteria and controls are required for the active management and relinquishment of landfill permits. For current and future sites, the nature of the waste stream will change significantly. Municipal biodegradable waste diversion targets and waste pre-treatment will cause the types of waste that are landfilled to change and will lead to modifications in the way in which landfills are operated. The amount of degradable matter in municipal waste will reduce and the quantities of inert wastes are likely to continue reducing. Sustainable management of past, present and future landfills must ensure that at landfill completion, no significant contamination remains and that the site is mechanically stable.

The term completion here refers to a state in which a landfill site is no longer a threat to the environment and that all active management can cease. Mechanical stability, or settlement, of the waste pile is a key factor in the definition of completion. Whilst en route to completion, waste settlement modifies hydraulic and gas permeabilities, and final load bearing capacity. Ideally, productive re-use of the site should be anticipated, in which case long-term mechanical stability should also be attained. The prediction of long-term mechanical stability in the form of settlement cessation is also required to determine completion of filling (pre-settlement) and post-settlement surface profiles and hence available void space. (Waste Management Paper 26E, 1996).

3.1 Settlement implications to Operators, Planning Authorities and Regulators

The settlement of a landfill during filling and after completion of filling will have many implications to the main stakeholders involved, being the site operators and owners, planning authorities in administering planning policy and guidance, and the environmental regulators.

Planning permissions for landfill developments include the post-settlement levels or contours, and the agreed pre-settlement surface to be attained on completion of filling, with the intent that the surface will settle down to the desired post-settlement levels. Experience has frequently shown that the landfill surface settles below the planned post-settlement levels and forms irregular surfaces. The irregularity is caused by different waste types or filling rates in the different parts of the landfill. This has sometimes led to repeated re-filling at sites to achieve the post-settlement levels, requiring new planning permissions, and causing disruption to restoration, capping and leachate and gas management systems.

A sound understanding of settlement and reliable settlement predictions made during filling enables operators to maximise waste infill quantities, to estimate future void space availability accurately, and to provide necessary information for closure planning.

The substantial settlements that occur at landfills, and the differential settlements between wastes and the adjacent natural ground, impose considerable challenges to the integrity of landfill engineering. Environmental regulators need to be satisfied that the containment
systems, surface water drainage and landfill gas and leachate management systems operate as intended.

3.2 Existing Approaches to Long-Term Landfill Settlement

The factors controlling biodegradation-related long-term landfill settlement are varied, many of which are not part of conventional geotechnical settlement models. Nevertheless, simple time-dependent methods based on soil mechanics have been used to analyse and determine long-term settlement. In this context, such methods are highly empirical.

Historically, long-term landfill settlement has been regarded as a combination of mechanical creep, physico-chemical corrosion, biodegradation and ravelling (Sowers, 1973). For the purpose of analysis, these processes are lumped together and defined as a function of time. Several methods have been proposed for the interpretation of long-term landfill settlement. These time-dependent methods are an exercise in curve fitting; they are highly empirical and should only be applied observationally or to near identical waste and landfill circumstances.

3.3 Time Frame for Landfill Settlement Analysis

In view of the general lack of systematic waste placement records, an early step in the project was therefore to establish a conceptual landfill settlement framework for the purposes of this study. Figure 1 identifies the main settlement processes and their incidence during the life of a landfill. For the purpose of representing landfill void volumes and as a benchmark for numerical analyses, there is an uncompressed, un-degraded waste volume, shown in the figure as a column. The waste in this state is considered with its as-placed (as-compacted) density. The components of waste settlement are described below.

- **Primary compression**: during filling, the compressive effect of the weight of overburden soon exceeds that of compaction and an in situ waste density profile evolves. This is primary compression.
- **Creep**: regarded as significant during the filling phase but decreasing into the long-term.
- **Biodegradation-related settlement**: may also be significant during the filling phase but equally if not more significant into the long-term.
The secondary settlement phenomena of creep and biodegradation are conventionally treated as post closure phenomena but, in fact these processes originate in the filling phase. Inappropriate interpretation of the origin of these processes seriously undermines simple landfill settlement analyses. In the operational phase, with filling and compaction occurring, self weight compression will dominate settlement. Some creep and biodegradation-related effects occur during this phase with the latter predominantly in the lower and older waste layers. The operational phase can vary significantly in length from one to two years to in excess of ten years. On completion of filling, and disregarding capping, further settlement comprises physico-chemical and mechanical creep, and decomposition. During the filling phase, they are seen as contributions to settlement directly related to the amount of accumulating waste. During the post-closure phase, they are shown as monotonically decreasing (creep) and accelerating after closure to then decrease with time (biodegradation). In fact the pattern of displacement may be much more complicated than this with biodegradation-related processes being dependent on the evolution of a range of landfill conditions and not just time.

Additional events such as placement of stockpiled materials on to the waste mass will result in further compression and secondary effects of such additional loading will include increased creep rate and potential reductions in hydraulic conductivity.
4.0 DATA ACQUISITION

4.1 Data Requirements for Assessing Landfill Settlement

The data acquisition requirements for assessing landfill settlement were to obtain sufficient, suitable information from a range of different landfill types and filling scenarios to apply to the HBM model so that it can be validated. The required information comprised details of landfill settlement and other specific influencing factors. These data were obtained from a range of different landfill types (e.g. quarry and land raise, deep and shallow, different waste types, and different climatic environments).

Settlement and associated data were obtained from operating landfills within the UK and also overseas. The inclusion of data sets from non-UK sources was important as this allowed the HBM model to be validated for a range of waste types, operational conditions and climate not experienced in the UK. This has enabled a more robust validation to be carried out to facilitate future extrapolation for modified waste compositions likely to be experienced in the UK (e.g. in response to pre-treatment and legislation-led practice).

The key input data requirement for the HBM model is the assembly of waste deposition and landfill performance data in order that existing characteristics, trends, and other influencing factors might be identified and quantified, such that future predictions could be derived based on previous operational trends. From the function and determinability of all the HBM input parameters, three distinct types of parameter can be identified: site-specific, waste-specific and generic. The relationship between these types of parameter is presented in Figure 2.

![HBM Model: Function and Determinability of Input Data](image-url)

**Legend**
- Geometry: operational, climate
  - H = (z, z1): Waste height (base, surface elev)
  - FR = Filling rate/sequence
- Hydraulic
  - α, n = van Genuchten parameters
  - k = residual volumetric moisture content
  - ks = saturated volumetric moisture content
- Biodegradation
  - B = enzymatic hydrolysis rate
  - kg = product inhibition
  - k = half saturation constant
  - k = methanogenesis specific growth rate
  - k = methanogen death rate
  - Y = yield coefficient
  - SDF = solid degradable fraction
  - VFA = initial VFA
  - MBI = initial MBI
  - D = diffusion coefficient
- Mechanical
  - k = elastic stiffness
  - λ = elasticplastic stiffness
  - v = Poisson's ratio
  - σ = yield stress
  - γ = creep viscosity
  - Ω = decompostion-induced void change
  - Ω = hardening parameter
  - ρ = dry density (as placed)
  - Gsd = specific gravity (inert fraction)
  - Gsd = specific gravity (degradable fraction)

**Figure 2: HBM Model: Function and Determinability of Input Data**
A summary of these types of input parameter and their inter-relationship is presented below:

- **Site-specific:** These input data describe a site in terms of its geometry, filling schedule and operational circumstances, e.g. leachate recirculation and compaction. The filling schedule is important; it enables the HBM model to capture a variation of waste properties with depth, even if the other parameters used are set to default values.

- **Waste-specific:** This term relates to the parameters that define the material being landfilled. For a region or waste type not previously modelled, some effort to characterise the waste may be required. This type of parameter is obtained through relatively simple laboratory testing, e.g. waste classification, loss on ignition, or through compositional analyses of typical waste streams.

- **Generic:** These comprise several parameters controlling fundamental system behaviours, especially the biochemical system. For example, the interaction of VFA (volatile fatty acids) and MB (methanogenic biomass) in the HBM model enables microbiologically mediated phenomena such as VFA souring, methanogenesis and (subsequently) hydrolysis-limited digestion, to be captured. A programme of testing for this type of parameter would be a significant undertaking. The default set contained within the HBM model is based on a literature review of anaerobic processes in general. Model testing has shown that this data set provides a credible interpretation of observed landfill behaviour. Modification of the default generic parameters should be made within the context of sensitivity analysis.

### 4.2 Availability and Acquisition of Data

Landfill operators are required by their permits to record data to demonstrate that their operations are in compliance with current permitting requirements. The following information was requested as HBM model input parameters as this information should be readily available to landfill operators as part of their operational reporting requirements:

- Settlement records;
- Cell/landfill dimensions (areas, waste depths);
- Filling sequence;
- Waste composition (types and quantities);
- Rate of filling;
- Lift thicknesses and compaction equipment;
- Time of capping;
- Landfill gas generation data;
- Leachate management (e.g. was recirculation carried out); and
- Climatic records.

Settlement monitoring records were requested for the following:

- During filling; and
- Post-filling.
To assess the adequacy and reliability of each specific data indicator type, details of the actual period, frequency and method of data collection were also requested. This information was required to facilitate the evaluation and ranking of the data sets.

4.3 Extent of Search for Data

The acquisition of data for the project was positively supported by major landfill operators, both UK and internationally.

Data sets were sought to be representative of a wide range of landfills and waste compositions, including old mineral workings, land raise disposal sites, municipal waste landfills and sites taking mainly commercial and industrial waste. Some operators who expressed support for the project were unable to provide data as they were considered either commercially confidential or not available in an accessible format.

Each of the data sets received was reviewed and scrutinised for evidence of relationships between indicators and controlling conditions as part of a pre-selection process before assembly and use in the model. The data sets obtained are summarised below.

4.4 Data Sets Obtained for the Project

The information obtained from the various UK and overseas landfill operations is listed below. The source of each data set has been identified; however, the UK sites have been identified anonymously. The Hong Kong Government has approved the acknowledgement of the Hong Kong site as the NENT Landfill:

- Seven sites – UK, SITA #1 to #7;
- UK, Viridor #1;
- Five sites – UK, BRE#1 to #5;
- NENT Landfill, Hong Kong;
- Lyndhurst Landfill, Victoria, Australia (data obtained from published paper); and
- Sandtown Landfill, Delaware Solid Waste Authority, Central Solid Waste Management Center (CSWMC), USA (data obtained from published paper)

4.5 Challenges in Data Acquisition for the HBM Model

The main challenge in the acquisition of data for the HBM model has been obtaining reasonably complete site-specific and waste-specific data in a format which was readily assembled as HBM model input parameters. In England and Wales, site-specific data are recorded as part of the PPC permit (now the Environmental Permitting (England and Wales) Regulations 2007) or earlier Waste Management Licence requirements. In addition, for some operators, data are recorded and compiled for the operator’s own operational and commercial reasons.

The quality and completeness of the data sets improved in the more recent records, as the appreciation of the benefits of systematically recording data and of compiling them into an
integrated data set increased. The ideal data set would be the complete list of data as defined in the waste settlement protocol and would enable the influence of all the input parameters to be assessed, from the initial filling of a landfill site through to final mechanical equilibrium, and in terms of the environmental conditions for each of the hydraulic, biodegradation and mechanical systems.

Based on the availability of settlement data, and accompanying information on waste composition and filling sequencing, the following sites, or discrete cells within landfill sites, were selected for comparisons between the HBM model and the site-derived settlement data:

- UK, Viridor #1;
- NENT;
- UK, SITA #2
- UK, SITA #3; and
- UK, BRE #4.

These sites also provided a range of waste types, ages and compositions. UK, Viridor #1 provided the most complete information about filling and the shortest time between filling and the onset of settlement monitoring. UK, BRE #4 provided a broad range of settlement data from the different ages and settlement magnitudes. SITA #2 and SITA #3 settlement data were derived from settlement profiles and also contained variable and irregular filling sequences, useful for assessing these influences within the HBM modelling. For the NENT site, weekly and monthly data on waste mass composition were provided for a nine year period, together with settlement data recorded fortnightly at 54 settlement markers over a 3.5 year period.
5.0 HBM MODEL OVERVIEW

5.1 Conceptual Framework

The HBM model provides a framework for the integrated analysis of the hydraulic, biodegradation and mechanical behaviour of landfilled waste or other degradable soils (McDougall, 2007). Building on individually-proven models of hydraulic, biodegradation and mechanical behaviour, the HBM model gives a synergistic interpretation of landfill behaviour with relatively light input parameter requirements.

The HBM model comprises three main system models and link routines, through which the algorithm passes, as shown in Figure 3. It is in the link routines that the most recent system variable values are used to update the conditions within each system model.

![Figure 3: Schematic Representation of the HBM Conceptual Framework (McDougall, 2007)](image)

As isolated system models, the hydraulic and mechanical models are close to practice, and are the basis of well established design tools. However, in the HBM framework each system model can modify parameters in other systems. These system interdependencies are the innovative aspect of the HBM model.
6.0 MODEL VALIDATION

This section includes generic landfill modelling, compared to measured settlement data for a variety of landfills. This is supplemented in the final report for this project with parametric studies, then validation against site-specific settlement data, with site-specific input parameters and waste geometry.

6.1 Generic Modelling

The generic models represent a 30 m high landfill and have been represented using a two-dimensional modelling mesh measuring 50 m wide. The model has vertical sides which represent roller boundary conditions. This therefore models a section of the landfill at the centre of the site, unaffected by geometric edge effects. For the simplified modelling, the filling sequence was omitted, allowing a direct comparison between the influence of modelling parameters. To allow comparison with the all of the site-derived data, the model was run to a total of 9,800 days (27 years). This allowed the long and short-term influence of modelling variations to be considered.

![Figure 4: Modelling Results as a Comparison to the Predicted Behaviour](image)

Error! Reference source not found. shows a comparison between the modelled data using default input parameters and the landfill settlement from multiple landfill sites. The settlement has been normalised to unit strain (dimensionless parameter) to allow direct comparisons. The generic input parameters show a reasonable comparison between the default parameters and the overall settlement profile, falling within the bounds identified by the site-derived data set. It is evident from the dataset that there is significant variability associated with the reported settlement data.
Figure 5: Generic model with filling sequence (short term, post filling)
The default model has been run for 300 day and 3000 day filling sequences, representing filling rates of 0.01 m day$^{-1}$ and 0.1 m day$^{-1}$ respectively. The results of this analysis are shown in Error! Reference source not found.. It can be seen that with 3,000 days filling, the post-filling settlement is significantly reduced as degradation, particularly in the lower layers of waste in the model, has slowed due to limited availability of solid degradable material.
7.0 PROPOSED LANDFILL SETTLEMENT PROTOCOL

7.1 Introduction

This section describes a proposed protocol for the monitoring, analysis and prediction of landfill settlement, as developed from the findings of this project. The proposed protocol sets out the key steps involved in each part of the process to enable reasonably reliable predictions of landfill settlement to be made. Improvements in the understanding of certain parameters used in the model and in the ease of use of the model will provide the opportunity to make the proposed protocol more robust and available for wider use.

7.2 Data Collection and Monitoring Framework

Table 1 contains the desirable site, operational and waste information and monitoring data for landfill settlement prediction.

Table 1: Required Site Specific Information for Waste Settlement Prediction

<table>
<thead>
<tr>
<th>Site, Operational and Waste Information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site Geometry</strong></td>
</tr>
<tr>
<td>Site slope geometries</td>
</tr>
<tr>
<td>Maximum filling depths</td>
</tr>
<tr>
<td><strong>Filling Sequence</strong></td>
</tr>
<tr>
<td>Start of filling</td>
</tr>
<tr>
<td>Location (within cells) of filling</td>
</tr>
<tr>
<td>Approximate filling rate</td>
</tr>
<tr>
<td>Compaction used</td>
</tr>
<tr>
<td>Breaks in filling</td>
</tr>
<tr>
<td>End of filling</td>
</tr>
<tr>
<td>Time and type of temporary capping/s</td>
</tr>
<tr>
<td>Time and type of permanent capping</td>
</tr>
<tr>
<td>Types of daily cover used</td>
</tr>
<tr>
<td><strong>Waste classification</strong></td>
</tr>
<tr>
<td>Classification of the waste in terms of chemical and physical components.</td>
</tr>
<tr>
<td>Dry unit weight as placed. This can be based on bulk unit weight and (assumed) moisture content.</td>
</tr>
<tr>
<td>Waste composition (European waste classification as a minimum requirement, with MSW breakdown)</td>
</tr>
<tr>
<td>Biodegradable content</td>
</tr>
<tr>
<td>Digestibility</td>
</tr>
<tr>
<td><strong>Settlement monitoring</strong></td>
</tr>
<tr>
<td>Settlement monitoring is required to validate model performance and calibrate forward predictions.</td>
</tr>
<tr>
<td>Three monthly surveys during filling phase including during filling breaks</td>
</tr>
<tr>
<td>Settlement monitoring on survey stations immediately following completion of permanent capping and at three monthly intervals for the first five years, annually thereafter. (Minimum 1 point/hectare at large sites but preferably 2 or 3/hectare at smaller sites and at landfill margins.)</td>
</tr>
</tbody>
</table>

Table 2 shows additional monitoring which would be beneficial to validating the model performance. Whilst this list of requirements has been developed by using the HBM model, these are considered to be universally applicable requirements for the reasonably accurate prediction of landfill settlement behaviour by any method. This additional monitoring as itemised in Table 2 would also be useful for gaining a better understanding of the waste
degradation behaviour and to utilise the gas generation prediction function of the HBM model. It should be noted that there is an emphasis on the filling sequence because identifying the relative spatial and chronological position of individual elements of waste allows much more accurate representation of the behaviour of the overall waste mass.

**Table 2: Beneficial Additional Monitoring**

<table>
<thead>
<tr>
<th>Additional Monitoring</th>
<th>Leachate and Gas Production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Comparison between the measured and modelled gas and leachate production allows calibration of the model to site specific characteristics, thus allowing more accurate forward predictions to be made.</td>
</tr>
<tr>
<td>Leachate quantity on a cell specific basis</td>
<td></td>
</tr>
<tr>
<td>Leachate quality on a cell specific basis</td>
<td></td>
</tr>
<tr>
<td>Details of any recirculation carried out including time, volumes and distribution.</td>
<td></td>
</tr>
<tr>
<td>Gas quantity by cell or, if not available, by other defined areas</td>
<td></td>
</tr>
<tr>
<td>Gas quality by cell or, if not available, by other defined areas</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waste decomposition</th>
<th>Physical sampling during any intrusive investigation/installation (e.g. retro-fitting wells) and laboratory testing to assess mass degraded and further potential biodegradability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whilst it is not regarded to be a primary settlement parameter, it will contribute to calibration of the model and to a better understanding of the waste degradation process at the site</td>
<td></td>
</tr>
</tbody>
</table>

### 7.3 Settlement Prediction Protocol

A hierarchy of settlement prediction methodology is proposed in Figure 6. This identifies the increasing complexity from time dependent to full process modelling.

Simple time-dependant methods identify a simple mathematical function to “best fit” previously observed settlement behaviour and, whilst methods that include filling will improve accuracy and acknowledge the differing behaviour of waste throughout the waste profile, they still do not fully address the actual processes occurring within the waste.

Current practice is typically towards the lower end, with consideration of time dependency, but not of the varying waste age or actual settlement processes.
7.4 Simplified Settlement Prediction Protocol

For any settlement prediction method, an understanding of the age of the waste is essential. For time-dependent methods, generic time-dependency factors ($C_a$) are typically applied irrespective of waste type and age of waste, and this leads to errors in the prediction of settlement behaviour. For settlement prediction using these techniques, the filling sequence and settlement monitoring should still be recorded as suggested in Table 1. It is also important to record the waste composition as this assists in applying an appropriate $C_a$ value.

7.5 HBM Model Settlement Prediction Protocol

The Settlement Prediction Protocol must recognise the range of HBM model input parameter types. There exists within the model a default parameter set, which means that the model can be run with minimal input information, i.e. data relating to the geometry of the site only. At the other end of the spectrum, where quantitative accuracy is necessary, landfill behaviour can be controlled using geometry, waste type, detailed operational circumstances and fundamental process data.

It is neither likely, nor desirable, to sample and test for each and every HBM model input parameter. Some are fundamental parameters controlling the simulation of microbial
processes and unlikely to be sensitive to the ‘waste’ domain and the macro-scale. The type or role of input parameter should be recognised and efforts to validate input data concentrated accordingly. The validation effort may be further fine-tuned according to any specific interest, e.g. hydraulic, biodegradation and/or mechanical.
8.0 CONCLUSIONS

8.1 Landfill Settlement Monitoring

The settlement of completed landfills has to be monitored on an annual basis as a permit requirement both during the operational filling stage and in the aftercare period. This frequency is insufficient to evaluate the settlement performance of the landfill, particularly during filling but also in the early years after closure. No method of settlement monitoring is specified in the relevant regulations, so general topographical surveys, which are suitable during the filling stage, are also often carried out after closure. These surveys allow only a coarse and inaccurate evaluation of settlement across the landfill surface, compared to repeat measurements on settlement markers installed in the landfill surface.

Operators have different approaches to settlement monitoring depending on the importance placed on the need to have settlement data for their forward operations or financial forecasting. The frequency can range from fortnightly to annually. The benefits to operators of frequent level monitoring and settlement prediction during the filling stage are not widely appreciated and their broader acceptance should be advantageous to the waste industry.

8.2 Collection and Assembly of Data other than Settlements

In addition to settlement data, the Landfill (England and Wales) Regulations 2002 require operators to provide information on an annual basis during the operational phase on the structure and composition of the landfill body. The required information is defined as:

- The surface occupied by waste;
- The volume and composition of the waste;
- The methods of depositing;
- The time and duration of depositing; and
- The calculation of the remaining capacity still available at the landfill.

The data required by the Regulations (including gas and leachate monitoring records in addition to those listed above) effectively cover all the elements of data for application in the HBM model. Instead of annually, more frequent recording of the data during landflling and for several years post-completion would again provide a better understanding of landfill behaviour, this being beneficial to landfill operators, planning authorities and regulators.

8.3 Data Collection and Assembly

It is apparent that as the data requirements are set by existing national legislation, a standardised format could be introduced in the UK so that the data are collected, assembled, reported and stored in a common compiled manner. Consistent reporting across all areas of the country could then be achieved instead of highly variable standards of reporting developed on an area or operator basis. This would facilitate review by regulators as well as enabling
operators to make use of the data for their operational and commercial benefit. It is apparent that the form and detail of the reporting are unclear and are regulated inconsistently.

It is concluded that clear guidance on these data reporting requirements should be prepared and issued as a matter of some urgency to remove any current uncertainty caused by lack of detail of the requirements. Written guidance could be supported or extended by the preparation of data management software in the form of a database, following consultation with industry, and made available to industry.

It is recommended that the required frequency of level surveys and data collection is increased to a minimum of quarterly during the operational phase and, for the first five years following completion of landfiling in an area, increasing to annually thereafter. While this is an increase above the statutory requirements (although some landfills do already have quarterly reporting requirements and others carry this out for their own purposes), it is important to recognise that acquisition of these data will provide a better understanding of the behaviour of the landfilled wastes and will enable more reliable projections of future settlements to be made and updated with time.

The HBM model not only computes future settlement but can also be used to forecast gas generation rates in specific areas and depths in a landfill, enabling a more holistic understanding of the degradation behaviour of the landfilled wastes to be developed. This is also important in the procedure to assess when the landfill site is no longer a threat to the environment and that all management can cease.

It is recommended that the potential for gas monitoring on a cell-by-cell basis is investigated. The benefit would be that gas monitoring data would become much more useful in developing the understanding of waste degradation and gas generation within the cells of landfills, which can then also be linked to settlement records and predictions.

8.4 Changing Waste Streams

As the HBM code works from a fundamental process-driven perspective, rather than a curve fitting process based on previously obtained waste settlement data, it is ideally suited use with changing waste streams. It is therefore important that research into input parameters for new waste types is carried out at a sound theoretical level, as this will allow an understanding to be developed of the changes that will occur in future settlement behaviour as waste types change.

8.5 Conclusions on Modelling

The model provides a theoretically robust approach with consideration of the waste mechanics and chemical processes which control settlement. The HBM model is unique in that it provides a coupling between the, hydraulic, biodegradation and mechanical components of waste behaviour.
Comparisons have been made between settlements predicted by the model to measured landfill settlements and it has been shown that the model can be used to reproduce measured settlement traces for a number of landfills with markedly different waste and site characteristics. A lack of complete data sets does mean that a fully rigorous validation is currently beyond the scope of the available data sets.

The model is complex in its formulation and despite a very effective graphical interface, it remains a relatively complex tool to implement. As with all finite element software, particularly bespoke codes such as this, it cannot be treated as a “black box”, and a sound understanding of the theory is required in order to implement the code. In its present form, it is considered to be an extremely useful research tool. However, users with the requisite experience and theoretical understanding can currently apply the model with relatively little effort to real cases and obtain settlement predictions with a sounder technical basis than the presently used time-dependant methods. Sensitivity and parameter analyses can be readily incorporated into the analyses.

A simplified version of the model could in future be developed to be used in conjunction with the landfill settlement monitoring protocol and an improved waste classification scheme. The theoretically complex parameters could be hidden from the user. In their place qualitative input values could be developed in lieu of the absolute values.
9.0 FUTURE DEVELOPMENTS

9.1 Data Collection and Recording

Waste and site-specific data are already collected by landfill operators as part of their permit conditions. This project has shown that the potential benefits from a more consistent and thorough method of recording and compiling the data are currently being missed in many cases. Development of guidance for data collection and reporting would encourage or require the collection and reporting of the data in an integrated and much more usable form, with little additional effort in collection and reporting. More frequent data measurement or recording (e.g. quarterly settlement surveys) would entail additional effort but would improve the understanding of landfill behaviour in the short and long-term for all stakeholders as well as facilitating commercial benefits to operators.

9.2 HBM Model Parameter Research

Whilst a greater understanding of waste mechanics in general is still required, several key parameters have been identified. The decomposition induced void change parameter ($\Lambda$) has a direct controlling influence on the biodegradation parameter, and the solid degradable fraction and digestibility can effect the settlement magnitude and time to completion.

9.2.1 Decomposition Induced Void Change Parameter ($\Lambda$)

This parameter controls the relationship between decomposition induced volume change and the resulting settlement. Where decomposition occurs, it results in a loss of the solid degradable fraction, and an increase in void. McDougall and Pyrah (2004) discuss the theoretical derivation and application of $\Lambda$. However, McDougall (2007) acknowledges that there are little data currently available for quantification of $\Lambda$. This primarily impacts the magnitude of settlement experienced by the waste. In practice, this may be further complicated by collapse events and the waste structure becoming looser and weaker due to degradation, with particle reorganization and void reduction then occurring driven by overburden loading.

This is an area which requires further investigation in order to fully understand the link between biodegradation induced solid phase loss and the resulting, if any, settlement that occurs. Whilst physical sampling would be a costly exercise, it may be possible to carry out such investigations using samples collected when retro-drilling well installations through the waste mass. This is a recommended topic for a future research and development project.

9.2.2 Digestibility and Solid Degradable Fraction

The amount of degradable material and the rate at which a waste mass degrades are fundamental factors in controlling the time to completion of a landfill site. The digestibility of components should relate to the degradable percentage and type of material. A classification framework is required to allow operators to classify their waste and to derive
the solid degradable fraction and digestibility. Each category in the *Consolidated European Waste Catalogue* could be assigned a digestibility rate factor and, from the percentage concentrations, both the overall solid degradable material and digestibility (rate) can be assigned to the waste mass.

### 9.3 Settlement Prediction Guidance

Currently there are no regulations or guidance on the procedures or methodology to be used in predicting settlements. This causes difficulties for planning authorities, regulatory agencies and operators in agreeing predicted settlements as different methods of varying assumptions and complexity (or, more usually, simplicity) and site-specific nature are submitted with planning applications. It is expected that this deficiency will become more acute when applications for ‘piggy-back’ extensions are being considered.

It is concluded that guidance on settlement prediction should be prepared and issued for the benefit of all stakeholders.

### 9.4 Gas Generation Prediction

Further work and validation on the gas generation function of the HBM model would be beneficial, together with assessing the potential to linking the model with other gas generation assessment models e.g. GasSim2. Data on gas generation on a cell basis would facilitate this research.

### 9.5 Probabilistic Analyses

The HBM model is currently a deterministic model. It could be adapted to include probabilistic analyses, however, this would require a significant increase in available processing power.
References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.


The HBM model and graphical user interface are freely available at http://www.sbe.napier.ac.uk/HBM