PREDICTING LONG-TERM SETTLEMENT OF LANDFILLS USING A FUNDAMENTAL MODEL OF WASTE BEHAVIOUR

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SUMMARY : The prediction of the long-term settlements of landfilled wastes is crucial not only to agreeing with planning authorities the pre-settlement contours of a landfill, but also to understanding and managing the lifecycle of a landfill. In September 2006, Defra (a department of the UK government) awarded a research project to evaluate and extend an existing fundamental model and to prepare a protocol for the analysis, interpretation and prediction of the magnitude and time to completion of long-term landfill settlement. The hydro-bio-mechanical (HBM) model has been under development for several years (e.g. McDougall & Pyrah, 2001, 2003; McDougall & Silver, 2005; and McDougall, 2007) and comprises individual, proven constitutive descriptions of hydraulic, biodegradation and mechanical behaviour coupled within a single modelling framework. This was undertaken in response to the difficulties of analysing biodegradation-dominated landfill settlement as a simple time-dependent process, including changes in waste types and interrupted waste disposal. The HBM model is implemented using the finite element method with which it is possible to account for material and operational features such as complex section geometry, waste heterogeneity, anisotropic hydraulic conductivity and simulation of the filling phase, be this continuous or interrupted

1. INTRODUCTION

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 used to designate when landfill sites have stabilised to the point that all management can

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be removed. Landfill settlement is complicated by the occurrence of biodegradation-related effects, so in the HBM model, three types of settlement are considered (see Figure 1):

- 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 may be more significant into the long-term.

The secondary settlement phenomena of creep and biodegradation are conventionally treated as post-closure phenomena, although these processes originate in the filling phase. Inappropriate interpretation of the origin of these processes seriously undermines simple landfill settlement analyses. Figure 1 gives a simplified interpretation of the main settlement processes and their incidence during the life of a landfill.

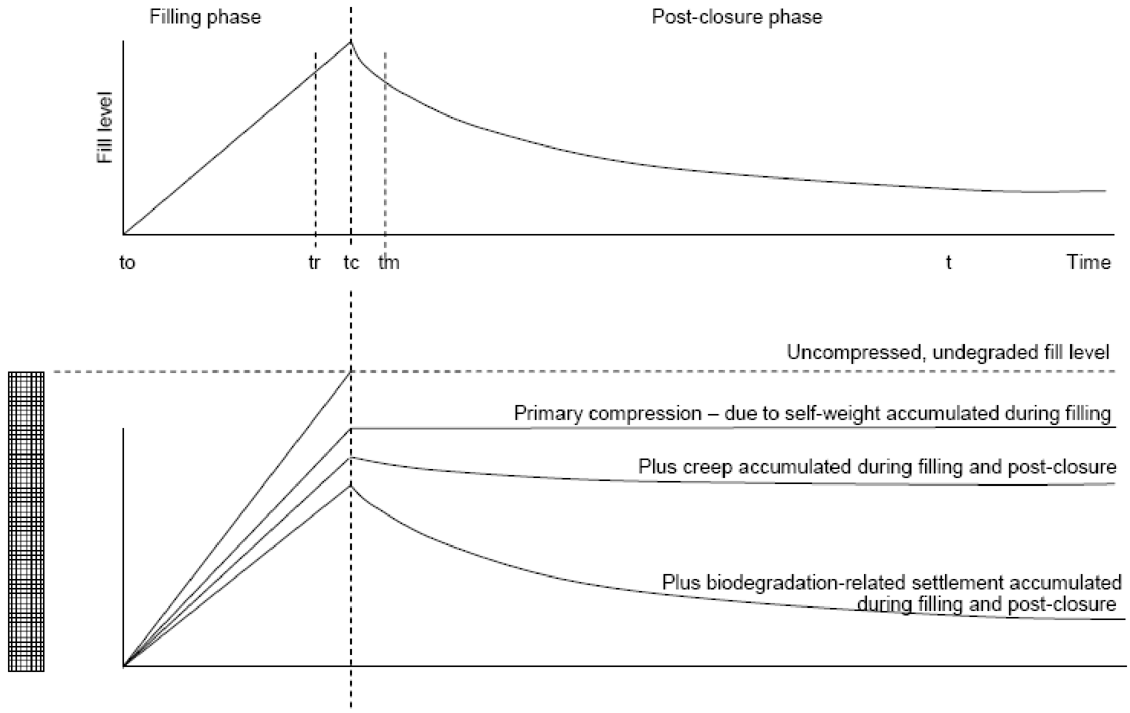


Figure 1 Settlement components

Despite the refinement of existing, time-dependent methods of settlement prediction, they have serious shortcomings in handling the organic fraction and the many factors that control its decomposition. They are unable to account for changing landfill conditions, such as waste types and breaks in the filling phase. They are, therefore, difficult to use in a predictive manner and require recalibration for changing waste streams.

2. DEFRA RESEARCH PROJECT

A Defra Research Project entitled "Landfill settlement: controlling the time to completion" has been undertaken by Golder Associates (UK) Limited and Napier University, Edinburgh, with review by Loughborough University. The project has focused on the acquisition of landfill settlement measurements and of site-specific and waste-specific data which will 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 research project had the key objectives of:

- The evaluation of the HBM model using actual landfill data sets and identification of beneficial refinements to the model; and

- The development of a landfill settlement protocol on the practical prediction of landfill settlement.

3. DATA COLLECTION

The acquisition of data for the project was positively supported by a number of major landfill operators, both UK and internationally. The inclusion of data sets from non-UK sources was important to facilitate validation of 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 allow future extrapolation for modified waste compositions likely to be experienced in the UK (e.g. in response to pre-treatment and legislation led practice). 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.

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 following information was requested as HBM model input parameters on the basis that 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 and history;
- 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
- Post filling

Data acquisition and the challenges encountered in obtaining reasonably complete data sets are discussed by Needham *et al*. (2007).

A summary of the acquired settlement data is given in Figure 2. The settlement traces in Figure 2 are corrected such that time zero corresponds to the start of filling and the time of the first appearance of any particular trace denotes the delay in settlement monitoring. This adjustment means the settlement traces are positioned according to the age of the waste, as depicted by the time at which filling began (time zero), and the start of the monitoring programme. From some of the data sets, it can be seen that settlement monitoring usually began about two years or more after filling commenced. Strain is plotted to normalise landfills of differing depths and is calculated as a change in height as a percentage of the original height.

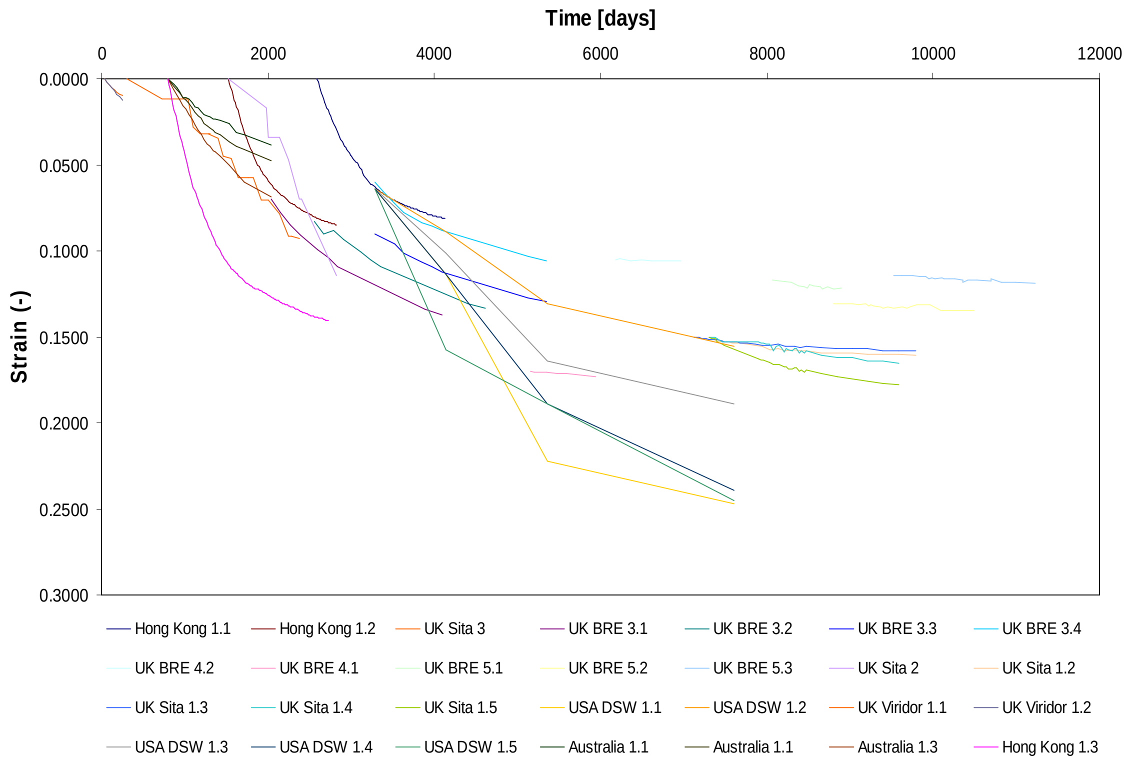


Figure 2 Assembled settlement strain data presented as strain curves.

4. HBM MODEL

The HBM model is a numerical model for waste behaviour which 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 separately proven models of hydraulic, biodegradation and mechanical behaviour, the HBM model gives a synergistic interpretation of landfill behaviour with relatively few input parameter requirements.

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. For example, the mechanical consequences of decomposition have, until now, received little attention in either the landfill or geotechnical research communities. But the potential rewards are significant. If the interdependencies can be sensibly understood, then hitherto disparate behaviour can be analysed in a much more meaningful and coherent manner. In this example the HBM model takes the effects of decomposition and updates void ratios and stiffness properties accordingly.

5. USE OF THE HBM MODEL

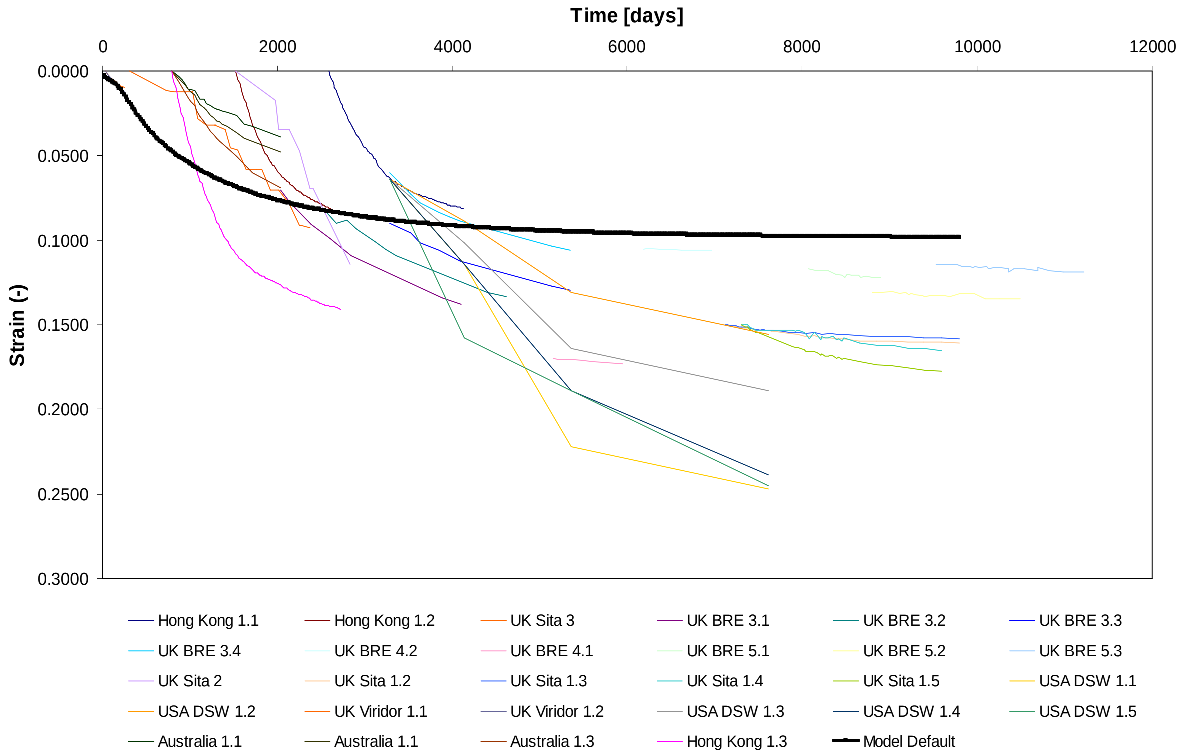
5.1 Usability of the HBM model

As part of the project, the HBM model was applied by consultants to assess the usability of the model in a commercial context. As the model is a finite element code, care must be taken to avoid treating the model as a "black box". An understanding of the formulation is required before the model can be applied. The graphical user interface allows users easier access to the code, enabling them to concentrate on the theory of the code, rather than on the process of composing input data files.

5.2 Generic Modelling

The generic HBM models that have been run 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 fixed in the horizontal direction, therefore modelling a section of the landfill at the centre of the site, unaffected by geometric edge effects. For simplified modelling, the filling sequence is omitted, allowing a direct comparison between the influences of modelling parameters. To allow comparison with the all of the site-derived data, the model was run for a total of 9800 days (27 years). This allowed the long and short-term influence of modelling variations to be considered.

Figure 3 shows a comparison between the modelled data using the HBM models 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 3: Modelling Results as a Comparison to the Predicted Behaviour

Using the HBM model points to the importance of accurately representing the filling sequence. 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 Figure 4. It can be seen that with 3000 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. The model default does not have a filling sequence; hence there is a lag in settlement as the biodegradation processes commence. In the long term a 300 day filling sequence has little influence on the total settlement magnitude compared to a model with no filling.

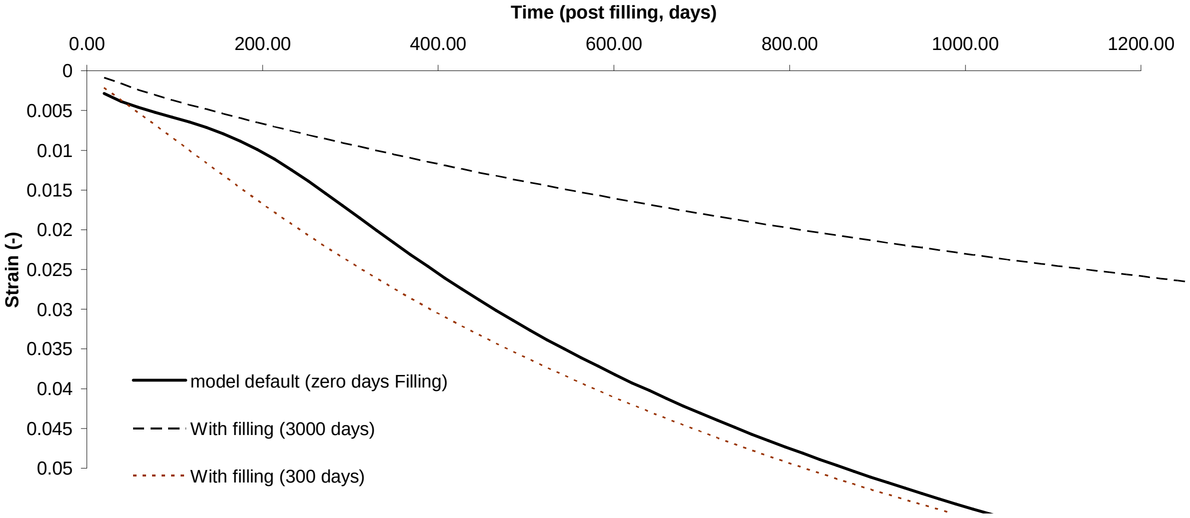


Figure 4 Generic model with filling sequence (short term, post filling)

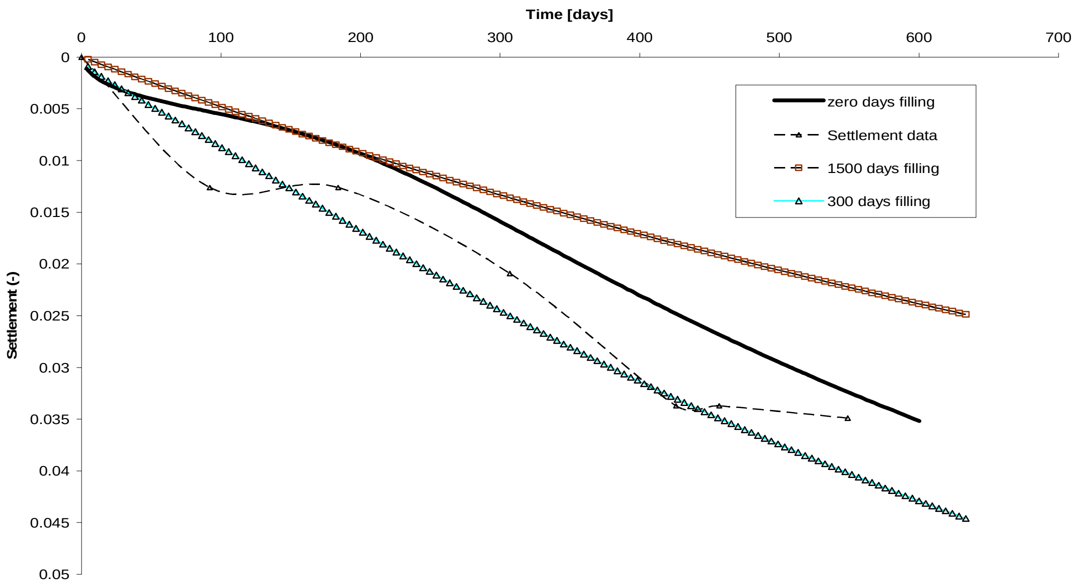


Figure 5 Measured and Modelled Post-Filling Settlement at a UK landfill

5.3 Validation of the HBM model

Figure 5 shows a comparison between the measured and modelled settlement at a UK landfill. A basic model was run assuming a full filling height from the beginning of the model (zero days filling) and model was then run with a reported fast filling sequence of 300 days, and slower 1500 days filling period derived from surveys of the cell area. When an appropriate filling time is taken into account, the model gives an acceptable comparison with the measured data.

The lack of specific information on the waste makes validation challenging; however, this investigation has shown that using default values, combined with limited site-derived information, acceptable correlations between the measured and predicted settlement traces can be achieved.

6. WASTE SETTLEMENT PROTOCOL

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, based on (i) systematic site and waste-specific data recording and on (ii) a fundamental analytical approach. 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.

Table 1 Required site specific information for waste settlement prediction (Golder, 2008)

Site, Operational and Waste Information	
Site Geometry	Side slope geometries
	Maximum filling depths
Filling Sequence *Definition of the filling sequence is required to identify chronological position in the degradation sequence.*	Start and End of filling
	Location (within cells) of filling
	Approximate filling rate
	Breaks in filling
	Compaction used
	Time and type of temporary & permanent capping/s
	Types of daily cover used
Waste classification. *Classification of the waste in terms of chemical and physical components.*	Dry unit weight as placed (from sampling of as placed waste)
	Waste composition
	Biodegradable content
	Digestibility
Monitoring	
Settlement monitoring *Settlement monitoring is required to validate*	3 monthly surveys during filling phase including during filling breaks
	Settlement monitoring on survey stations immediately following completion of permanent capping and at 3

model performance and calibrate forward predictions.	monthly intervals for the first 5 years, annually thereafter (minimum 1 point/hectare at large sites but preferably 2 or 3/hectare at smaller sites and at landfill margins)

Table 1 contains the desirable site, operational and waste information, and monitoring data for landfill settlement prediction. 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. Additional monitoring as itemised 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 (Golder, 2008)

Additional Monitoring	
Leachate and Gas Production *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.*	Leachate quantity on a cell specific basis
	Leachate quality
	Details of any recirculation carried out including time, volumes and distribution.
	Gas quantity by cell or, if not available, by other defined areas
	Gas quality by cell or, if not available, by other defined areas
Waste decomposition *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*	Physical sampling during any intrusive investigation/installation to assess mass degraded and further potential biodegradability

7. SETTLEMENT PREDICTION

Simple time-dependent 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. A hierarchy of waste settlement prediction techniques is shown in Figure 6. Current practice is typically towards the lower end, with consideration of time dependency, but not of the varying waste age or actual settlement processes.

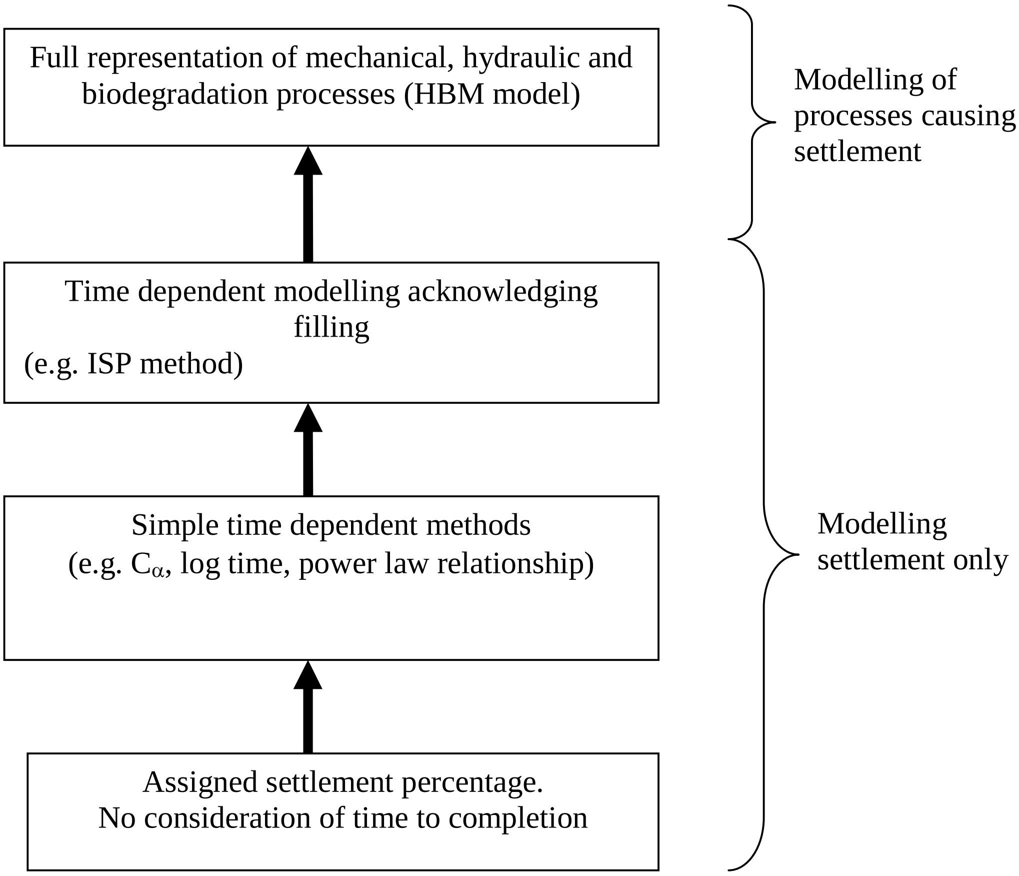


Figure 6 Settlement prediction model hierarchy (Golder, 2008)

8. FURTHER WORK

8.1 HBM Model Parameter Research

8.1.1 Solid degradable fraction and digestibility

The solid degradable fraction is the amount of solid matter that will be lost during the degradation process. Digestibility controls how rapidly the material will be degraded, thus allowing the proportion of waste components such as paper, food water and wood to be taken into account. A waste classification system (e.g. the European Waste Catalogue) could be adapted to include a digestibility factor and solid degradable fraction for use in such analyses allowing consistency in the derivation of the model input parameters.

8.1.2 Decomposition induced void change parameter.

The decomposition induced void change parameter (Λ) 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 volume. McDougall and Pyrah (2004) discuss the theoretical derivation and application of Λ. However, McDougall (2007) acknowledges that there are little data currently available for quantification of Λ. This primarily affects 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, all of which is likely to be load-dependent, i.e. varying with depth.

This is an area which requires further investigation in order to understand more fully 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 when retro-drilling well installations through the waste mass. This is a topic for future research.

8.2 Data Collection and Recording

Waste and site-specific data are already collected by landfill operators as part of their permit conditions. It is apparent from this project that the potential benefits from a more consistent method of recording the data are currently being missed in many cases. Development of guidelines or permit conditions 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 from current legal requirements but would provide the opportunity of material benefits to operators, and improve the understanding of landfill behaviour in the short and long-term for all stakeholders.

8.3 HBM Model Development Requirements

The model is currently usable and this presents significant benefits over current practice, however, commercial application requires significant experience in the use of the model. Definition of the filling process, infiltration events and the initial moisture profile could be simplified to aid the user. It would be a useful improvement of the model to allow for additional loading increments to the upper boundary of the model. This would allow the application of capping, restoration soil loading and additional stockpiles thus allowing them to be sequenced within the correct timeframe. This is particularly important in light of the deformation of the mesh during filling and the lower than specified height being achieved if filling is specified, as a material cannot easily be specified in the correct position to represent the capping layer.

9. CONCLUSIONS

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, implementing this aspect of the Landfill Directive. 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 which allows only a coarse and inaccurate evaluation of settlement across the landfill surface, compared to repeat measurements on settlement markers or stations installed in the landfill surface

Current state of practice for landfill settlement predictions is to use a time dependent "curve fitting" methods based on experience of previous landfill behaviour. The HBM 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.

Attempts have been made to compare the model to 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. A lack of complete data sets (with waste composition, filling sequence, filling rate, capping date, and subsequent full settlement record, cell specific gas production, leachate production and quality) 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 landfill processes is important in order to use the model with confidence. 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-dependent methods. Sensitivity and parameter analyses can be readily incorporated in the analyses.

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REFERENCES

Golder Associates (UK) Ltd. (2008) Landfill Settlement Estimating Time to Completion. Defra funded Research Project WR0301. Final Report May 2008.

McDougall, J.R. & Pyrah, I.C. (2001) *Settlement in landfilled waste: extending the geotechnical approach*. Sardinia 2001, 8th Intl Waste Man. & Landfill Symp, S.Margherita di Pula, eds. Christensen, Cossu & Stegmann, CISA Cagliari, Vol 3, pp 481-490.

McDougall, J.R. & Pyrah, I.C. (2003) *Modelling load, creep and biodegradation settlement in landfill*. Sardinia 9th Intl Waste Man. & Landfill Symp, S.Margherita di Pula, eds. Christensen, Cossu & Stegmann, CISA Cagliari, CD only.

McDougall, J.R. & Silver, R. (2005) *Hydro-bio-mechanical modelling of landfilled waste: Real insights*. Sardinia 10th Intl Waste Man. & Landfill Symp, S.Margherita di Pula, eds. Cossu & Stegmann, CISA Cagliari, CD only.

McDougall, J.R. (2007) *A hydro-bio-mechanical model for settlement and other behaviour in landfilled waste.* Computers and Geotechnics, Elsevier, doi: 10.1016/j.compgeo.2007.02.004.

Needham, A.D., Jones, D.R.V., McDougall, J.R., Dixon, N., Braithwaite, P. and Rosevear, A. (2007) *Assessment of Landfill Settlement Data for Evaluation of a Hydro-Bio-Mechanical Settlement Model*. Proc. Sardinia 2007, 11th Intl Waste Man. & Landfill Symp., S.Margherita di Pula, eds. Cossu, Diaz & Stegmann, CISA Cagliari, CD only.