Appendix A4.2 Assessment of Predicted Settlement

Technical Note

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Project	**Kerdiffstown Landfill Remediation Project**
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1. Introduction

1.1 Purpose of this Technical Note

This Technical Note covers the computer-based numerical assessment of the magnitude and duration of future waste settlement, due to waste degradation processes at the Kerdiffstown Landfill, together with information on calibrations of previous applications of the waste settlement model.

1.2 Restrictions

It is intended that this memo is read in conjunction with the following documents and drawings:

- Drawing Number 32EW5604-00-020 – Re-profiled Site Contours
- Drawing Number 32EW5604-00-022 – Remediation Contours
- Drawing Number 32EW5604-00-023 – Post Settlement Contours.

This work has been undertaken in advance of the additional ground investigation being undertaken for the site remediation works and thus the settlement predictions should be re-confirmed following receipt of the results of the ground investigation.

1.3 Application of the Numerical Assessment of Waste Settlement

To achieve the planned post-settlement profile for placed wastes, it is necessary to predict accurately the "percentage value" of the post-capping waste settlement which will occur following the profiling and capping of the waste which will remain in place, on completion of the remediation works for the site. The best means of determining the value which will apply to the waste in the site, is by the application of a reliable, numerical predictive waste settlement model, based on waste degradation processes. In addition, an amount of immediate elastic settlement which will occur on placement of the capping system and any other loading applied above the capping system.

With these data, the usual approach for most landfill related projects is to determine the necessary, corresponding pre-settlement profile which is required for the planned post-settlement profile to be achieved. In the case of the Kerdiffstown remediation project, an appropriate pre-settlement profile has been developed based on restoration proposals including earthworks and materials balance requirements. The post-settlement surface has been modelled from the results of the numerical study of site-specific waste settlement potential and its suitability has been examined. With local adjustments to the pre-settlement profile, a satisfactory post settlement profile has been demonstrated.

Waste settlement issues, the in-house numerical, predictive waste settlement model and the approach to confirm that the developed waste placement profile which enable a suitable post-settlement profile to be achieved, are explained below.

2. Post-capping Waste Settlement Issues

2.1 The result of underestimating the post-capping waste settlement value

Underestimation of the true magnitude of post-capping waste settlement can have serious and potentially costly environmental and engineering consequences in the medium to long term. If the post-capping waste settlement percentage is underestimated, over time the surface profile will fall to below the intended post-settlement profile for a site, as illustrated in Diagram 1.

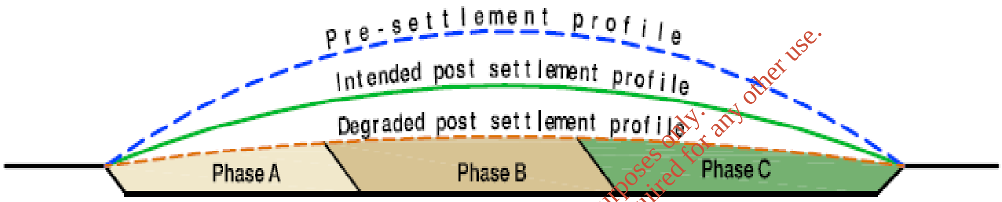

Diagram 1: Effects of underestimating post-capping waste settlement

The resultant degraded post-settlement profile will either be a dome which is too shallow, a near-flat surface or a dished surface. In all cases, there is high potential for the ponding of surface water to occur which can lead to cap degradation and breach of the capping system.

The reason why problems often arise with the actual post-settlement profile achieved after the completion of landfilling is as follows. Traditionally, for landfill site development, pre-settlement contours have been derived from assumptions made on the magnitude of post-capping settlement which will occur at a site. Percentage settlement ranges quoted in (UK) Waste Management Paper 26B (1995) are between 15% and 20% with the 15% value having been most commonly applied in the past in the design of pre-settlement profiles. The ranges quoted in Waste Management Paper 26B had been based on the range of settlement which had been observed largely only in the earlier years following the completion landfills. However, application of the numerical predictive waste settlement model has shown that the typical range of post capping waste settlement for municipal solid waste (MSW) landfills is most commonly between 25% and 35% and this range is confirmed by the calibrations of waste settlement carried out for two thirds of the modelled landfill sites.

Problems with the achieved post-settlement profile can be prevented by provision of an appropriate pre-settlement profile which takes correct account of post-capping waste settlement.

In this regard, in 2002 Enviros, a predecessor company of Jacobs, developed a reliable in-house, numerical method to accurately predict post-capping waste settlement, based on the modelling of waste degradation processes which act on the actual waste types and tonnages deposited over time at a subject landfill. This settlement prediction method utilises the mathematical representations of waste processes developed by Dr Alan Young in association with Enviros – Young (1992). The numerical, predictive waste settlement model considers waste processes and determines post-capping settlement with time, based on the mathematical prediction of mass loss due to waste degradation over time, from the commencement of the placement of waste. Post-capping waste settlement is directly related to mass loss due to waste degradation. The model is described in detail in Thomas and Cooke (2007), which includes illustrative data taken from previous practical applications of the model. Further explanation is presented in Section 3 below.

2.2 Definition of Landfill "Profiles"

Settlement issues are discussed in subsequent text with reference to the four relevant landfill restoration surface profiles shown in Diagram 2.

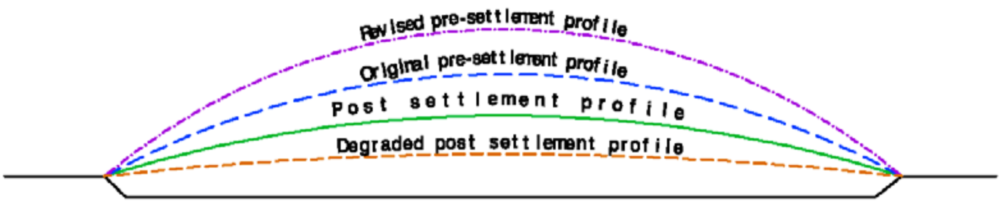

Diagram 2: Definition of four reference landfill surface profiles

The "Post-settlement profile" is the planned final profile of the landfill after all settlement has taken place. The "Original pre-settlement profile" is the level to which waste is originally placed and this profile is developed from the planned post-settlement profile based on an estimate of the likely total settlement which will eventually take place.

If the total waste settlement is underestimated at the design stage, the post-settlement profile will fall to a lower level than planned, which is shown in the diagram as the "Degraded post-settlement profile". The "Revised pre-settlement profile" shown in the diagram is the one which takes correct account of waste settlement. This will eventually settle to the planned "Post-settlement profile".

3. Numerical Predictive Waste Settlement Modelling

3.1 The In-house Numerical Predictive Waste Settlement Model

The Jacobs in house numerical, predictive waste settlement model is a proven numerical method.

When applied to remediating a completed or part-completed landfill, where it has become apparent that in the original design of the pre-settlement profile, the post-capping waste settlement percentage had been underestimated, the total waste input with time for each waste stream for a particular cell of landfilling is input to the model. The model calculates the mass loss due to the degradation of waste from the commencement of waste placement and onwards for a total of up to 200 years from the commencement of waste placement.

The waste settlement model is directly applicable to the prediction of post-capping waste settlement, since virtually all post-capping waste settlement is due to mass loss due to waste degradation. The advantage of this approach is that the model considers the site-specific nature of all of the waste landfilled, in terms of waste types, tonnages and rates of input. In addition, the model takes into account the estimated mean moisture content, temperature and pH of the waste. The model is described in the paper of Thomas and Cooke (2007).

An alternative approach is used for the determination of the appropriate input data for the model in the case of a completed landfill where comprehensive waste input records are not available. This approach assesses the nature of the landfilled waste components from boreholes drilled into the waste, which are logged specifically for this purpose. These data are processed and are directly input to the model to calculate the rate and magnitude of ongoing waste settlement from the time of the drilling of the boreholes to the time of completion of the waste settlement at the landfilled site. This is the approach which has been adopted for the Kerdiffstown Landfill. However, this approach cannot define the nature of the waste content of the landfill as accurately as the more common approach of processing continuous site records of the total waste input with time, for each waste stream for a particular cell of landfilling.

3.2 Mathematical Modelling of Waste Processes

As outlined above, predictive mathematical models of waste processes were developed as part of a research contract for the UK Department of Trade and Industry (DTI) with Enviros working in association with Dr Alan Young, then of the University of Oxford Mathematical Institute (Young 1992). The numerical, predictive waste settlement model uses these mathematical models of waste processes and their output of mass loss due to waste degradation. Prior to the development of the numerical, predictive waste settlement model, the same core mathematical models were used to develop the Enviros in-house numerical, predictive landfill gas production model. In terms validity of the approach, the first point which should be noted is that the same core mathematical models used in the development of the "GasSim" model; the model endorsed by the Environment Agency (EA), of England and Wales.

The above-mentioned in-house numerical, predictive landfill gas production model had been developed and refined over a number of years and successfully used to predict landfill gas production at a large number of sites in the UK and overseas. The model has been applied at new and existing sites and the results used for landfill gas control and gas utilisation purposes.

Examples of its use in the British Isles include Merseyside International Garden Festival Site, Liverpool; Bryn Posteg Landfill, Powys; Greenoak Hill Landfill, Glasgow and Baskets Town Landfill, County Meath, Republic of Ireland. Examples of its use overseas include Taman Beringin Landfill, Malaysia and a project comprising three landfill sites in Durban, Republic of South Africa: Bisasar Road, Mariannhill and Le Mercy. In this project, the Enviros model was used to validate carbon emission reductions for the World Bank regarding a landfill-gas-to-energy project under the Prototype Carbon Fund (PCF). This was the first PCF project of its type in Africa.

Since the in-house predictive, numerical waste settlement model uses most of the mathematical formulae used in the in-house numerical, predictive landfill gas production model, it has comparable validity. Furthermore, the numerical, predictive waste settlement model has been used to predict post-capping waste settlement in 39 phases of landfilling at 18 sites in UK, the Channel Islands, the Republic of Ireland and Finland since 2002 and to provide a sound numerical basis for determining revised restoration profiles to remediate landfill sites by remedial waste placement. It has also been examined in detail in a Public Inquiry for the Shakespeare Farm Landfill, where the model had been applied to modify pre-settlement profiles. The outcome of this Inquiry was in favour of the Biffa, Enviros' client. Interpretation of calibrated waste settlement prediction data from previous application of the waste settlement at a number of UK landfill sites is presented in Cooke, Walker and Thomas (2007). Thomas and Cooke (2011) includes coverage of calibration and remedial works implementation.

3.3 Validity of the Waste Settlement Model

It is considered that the foregoing information demonstrates the mathematical and computational validity of the in-house numerical, predictive waste settlement model. It is added that the background to the model, the reliability and accuracy of the modelling approach and coverage of calibration and remedial works implementation have been covered in the peer-reviewed papers of Thomas and Cooke (2007), Cooke, Walker and Thomas (2007) and Thomas and Cooke (2011).

4. In-house Waste Stream Biodegradability Research from 2002 to 2007

Since the numerical, predictive, waste settlement model was developed in 2002, considerable effort has been applied to refining waste stream characterisation based on published data, detailed discussions with the operators of the various landfills on which waste settlement modelling has been undertaken and literature reviews on biodegradability of waste fractions.

As stated previously, the waste settlement model has been used to predict post-restoration waste settlement in 39 phases of landfilling at 18 sites in UK, the Channel Islands, the Republic of Ireland and Finland since 2002. Calibration of the model output by periodic, site specific waste surface survey has been undertaken at modelled phases or at completed phases adjacent to modelled phases, at approximately two thirds of the phases which have been modelled. This body of information and experience was taken further forward by additional, in-house waste stream biodegradability research undertaken between 2002 and 2007.

A literature review was conducted of source literature to clarify figures (source terms) for individual waste stream fractions in terms of their long term (150 years) biodegradability in a landfill. In addition the review was used to assess the accuracy and usefulness of GasSim assumptions when calculating biodegradability of waste (which is directly related to landfill settlement); and to formulate recommendations regarding the assumptions that should applied when GasSim data are used in the predictive modelling of landfill settlement.

Detailed explanation of the research of 2002 to 2007 is beyond the scope of this report, but the majority of the references set out in the Bibliography were part of the literature review which contributed to the research findings. (The remaining references in the Bibliography comprise a small selection of documents associated with the subject of landfill waste settlement.)

5. Modelling Settlement of the Waste Landfilled at Kerdiffstown Landfill

5.1 Method

To assess the biodegradability of the wastes within the site borehole logs from the 2012 Phase 2 Geotechnical Ground Investigation were interrogated. A representative sample of borehole logs was selected based on:-

- Spatial representation across the site;
- Quality of the recorded descriptions of the wastes and strata; and
- Boreholes which did not hit early obstructions and terminate early.

This resulted in the assessment of nine borehole logs – BH52, BH45, BH44, BH40B, BH39B, BH36B, BH34, BH26, and BH25C. The borehole logs provided relatively detailed descriptions of the waste arising from the retrieved samples including categories such as municipal waste, wood, paper, plastic, textile, cardboard, clay and gravel. Each of these descriptions had been provided with an assessment of the percentage of that material within each depth extracted from the borehole e.g. borehole depth 2 to 4m wood 20%, paper 5% etc. These descriptions and percentages were used to calculate (pro-rata) the overall composition of the full depth of the borehole based on the provided descriptions.

The following table provides a summary of the waste composition data:

	Percentage composition								
	Soils, gravels, clays etc.	Metals & wire	Wood and timber	Textile and cloth	Paper and cardboard	Plastics	Rubber	General MSW	Ash
BH52	46.1	11.3	21.1	3.9	10.5	7.2	0.0	0.0	0.0
BH45	57.2	6.7	12.6	4.9	6.2	11.1	1.3	0.0	0.0
BH44	37.4	7.9	18.4	6.3	10.2	13.4	0.0	2.6	0.0
BH40B	98.8	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0
BH39B	27.3	11.5	43.0	5.6	8.9	3.6	0.0	0.0	0.0
BH36B	17.4	6.6	46.5	9.1	5.9	14.5	0.0	0.0	0.0
BH34	20.5	8.1	20.1	17.9	10.6	20.2	2.6	0.0	0.0
BH26	35.0	0.0	31.2	16.1	6.9	3.9	0.0	0.0	7.0
BH25C	13.0	0.6	23.0	13.4	21.7	30.6	0.0	0.0	0.0
Average	**39.2**	**5.9**	**24.1**	**8.6**	**9.0**	**11.6**	**0.4**	**0.3**	**0.8**

Table 1: Summary of Waste Composition

For use in the Jacobs settlement modelling it was considered that the following groups of waste should be modelled as inert waste (i.e. zero degradability) – soils, clays and gravel, metals and wire, plastics, rubber and ash. Although some of these fractions will degrade over-time, this is generally over a time period which will become irrelevant to the objectives of the settlement modelling, i.e. after 134 to 150 beyond the present and corresponding rates of settlement will be very small.

The approach provided the following summary of waste composition for input to the model.

	Percentage composition				
	Inert (Soils, plastics, metals etc.)	Wood and timber	Textile and cloth	Paper and cardboard	MSW
Average	**57.85**	**24.10**	**8.60**	**9.00**	**0.3**

Table 2: Derived Waste Composition Percentages

The above data were used as the raw input data to the Jacobs settlement model. The biodegradability of each waste fraction being based on research into the biodegradability of waste collated through the Jacobs literature review and research described above in Section 4. The values of biodegradability within the model take account of the overall biodegradability of each waste fraction (i.e. available carbon) based on cellulose, hemi-cellulose and lignin content, and also apply rates of degradation based on this. Lignin is somewhat resistant to degradation and a further assumption is made within the model that a large percentage, although not all of the lignin will degrade over the time period covered by modelled output. Using this approach the output from the model corresponds to virtual completion of waste degradation, in this case approximately 134 years beyond the present.

The focus of this study is on pre-filled waste which have been in-place for a significant time period, the models biodegradability and degradability rates were adjusted as the model has been developed predominantly for mimicking the landfilling of 'fresh waste'. For the Kerdiffstown model it was assumed that a proportion of the rapidly degradable proportion of the waste would have already degraded, and that a large proportion of what is left will be the medium rate and slow rate biodegradable fractions.

Since at this time the landfill is "full", a model was set up to mimic the presence of a nominal 1,000 tonnes of the waste, based on the composition discussed above. Thus, the model operates from the present time rather than from the time waste deposition had commenced. The following provides a visual summary of the model inputs:

The model inputs interpreted from the borehole logs, showing the different fractions are summarised in Figure 1.

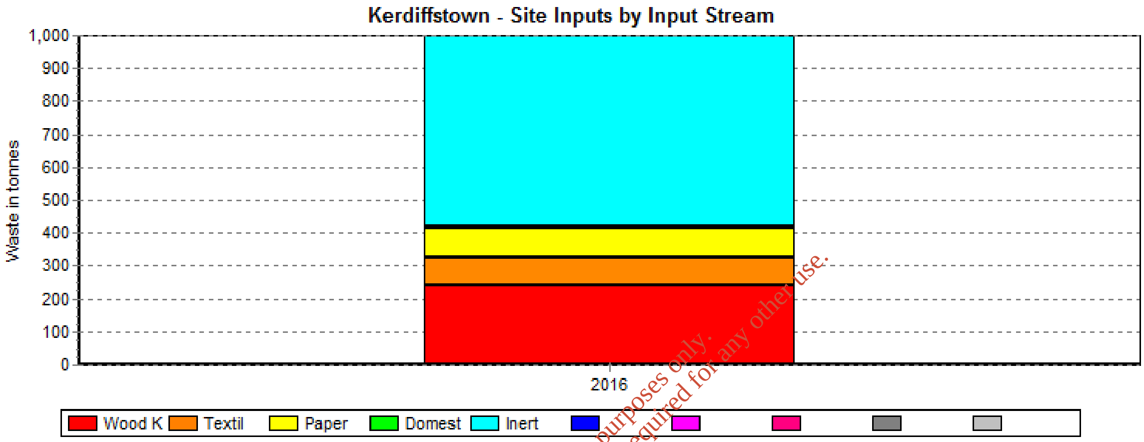

Figure 1: Site Inputs

Model inputs, showing input tonnage based on degradation rates are summarised in Figure 2.

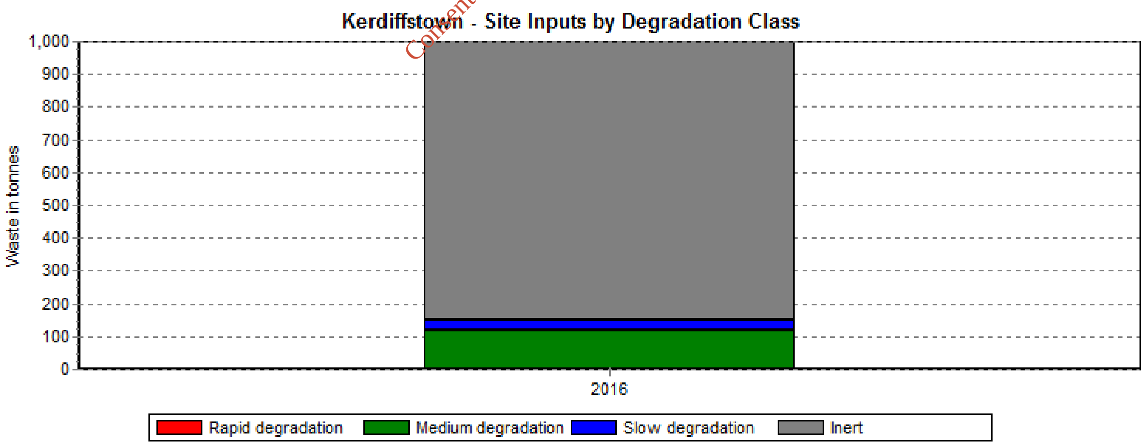

Figure 2: Site Inputs by Degradation Class

5.2 Results

The Jacobs model has user defined inputs for pH, moisture content and temperature and these factors can influence the rate of biodegradability, but not the overall biodegradability. As data to define these parameters were not available, and the focus on the study is more the overall biodegradability rather than the rate at which that will occur, model defaults were selected which mimic a 'typical' landfill. Thus, under these circumstances, the changing rates of settlement which will apply over the settlement period cannot be exactly estimated by the model.

The model was run using a nominal end date of 2150 and that covered a134 year period. The model outputs are presented below. These demonstrate that the waste degradation processes had, in fact essentially reached completion at this time, as discussed below.

Model output showing overall site contents, degradation rates, and the modelled settlement over time are shown in Figure 3.

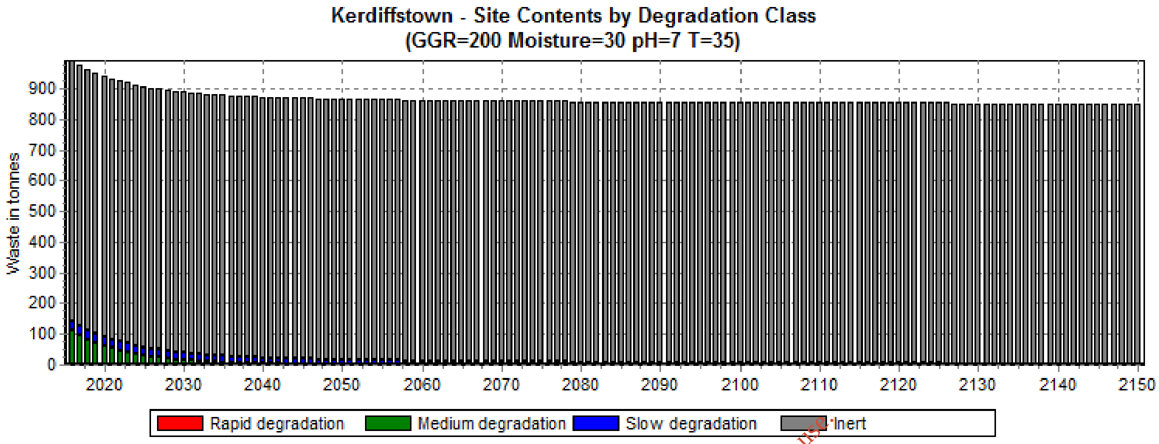

Figure 3: Site Contents Over Time, by Degradation Class

Model output showing calculated waste mass settlement percentage over time (but only representing provisional rates of settlement over the settlement period) are shown in Figure 4.

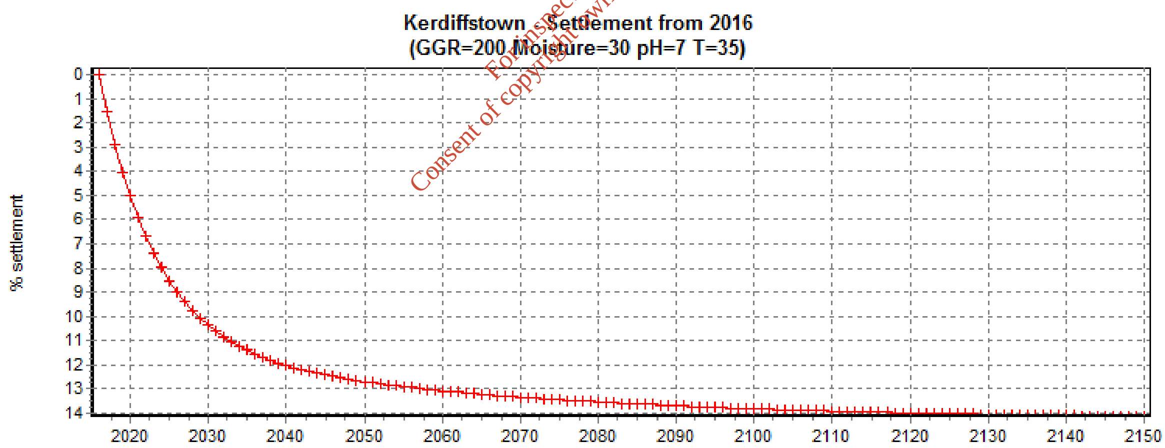

Figure 4: Total Settlement, Duration of Settlement and Provisional Representation of Rates of Settlement

The model outputs provide an estimate of approximately 14% total settlement over the modelled 134 year settlement period. Since assumed values have had to be applied for waste pH, moisture content and mean temperature in the model, the changing rates of settlement over the settlement period cannot be exactly estimated by the model. Even so, judging by the shape of the graph this appears to represent the asymptotic point for the decay curve. Although it should be noted that if longer time periods are considered i.e. beyond 134/150 years from the present, then potential further biodegradation of other waste fractions such as the plastics and rubber should be considered. However, it is likely that the corresponding ongoing settlement and additional total settlement will be comparatively small.

6. Results of the Waste Settlement Modelling

1. The model output predicts that the remaining waste settlement potential for the wastes landfilled at the Kerdiffstown Landfill is approximately 14% of the waste thickness at any given point on the surface.

2. Effectively, the ongoing waste settlement will have ceased by approximately 2150.

7. Confidence in the Waste Settlement Prediction for Kerdiffstown Landfill

The development, calibration and extensive commercial application of the numerical, predictive waste settlement model (see Section 3), together with the extensive research which has been carried out on waste stream biodegradability (refer Section 4), demonstrate the overall validity of the model.

The likely accuracy of the predicted settlement from the modelling of the landfilled waste at Kerdiffstown is supported by consideration of two previous applications of the waste settlement modelling at two other landfills where the overall waste biodegradability was comparatively low. The following results should also be considered in the context of the typical range of post-capping waste settlement for municipal waste landfills is most commonly between 25% and 35% and this range is confirmed by the calibrations of waste settlement carried out for two thirds of the sites which have been assessed by the in-house waste settlement model.

A previously modelled cell of landfilling which contained a high proportion of contaminated soils yielded a total waste settlement percentage of 16% which would be achieved at approximately 150 years post capping. Another previously modelled cell of landfilling which contained a high proportion of inert materials and wood, yielded a total waste settlement percentage of 21% which would be achieved at approximately 150 years post capping. Both cases were subjects of settlement calibration based on periodic site surface survey.

The wastes at Kerdiffstown Landfill are likely to have been in place for a period in the order of two decades, thus the present overall degradability would be comparatively low and would be somewhat similar in that regard to the overall biodegradability of the two other cases described above. The predicted total waste settlement percentage for the Kerdiffstown landfill is 14%, with waste settlement continuing for approximately 134 years. Thus, the general similarity of the predicted total waste settlement for Kerdiffstown landfill and the other two sites, provides confidence in the waste settlement prediction for Kerdiffstown Landfill.

In this regard it should be noted that calibration carried out on landfills where waste settlement modelling has been carried out has shown that the accuracy of the initial output of the model has steadily increased since its development in 2002. This is a result of extensive research which has been carried out on waste stream biodegradability from 2002 to 2007 as outlined in Section 4. However, in each of these cases, continuous site records of the total waste input with time for each waste stream, for a particular cell of landfilling, had been available for processing, to obtain the input for each model. Figure 5 illustrates one of several cases since 2005 where calibration has demonstrated that no adjustment is required to output from the predictive modelling of post-capping waste settlement. This case is also presented in Thomas and Cooke (2011).

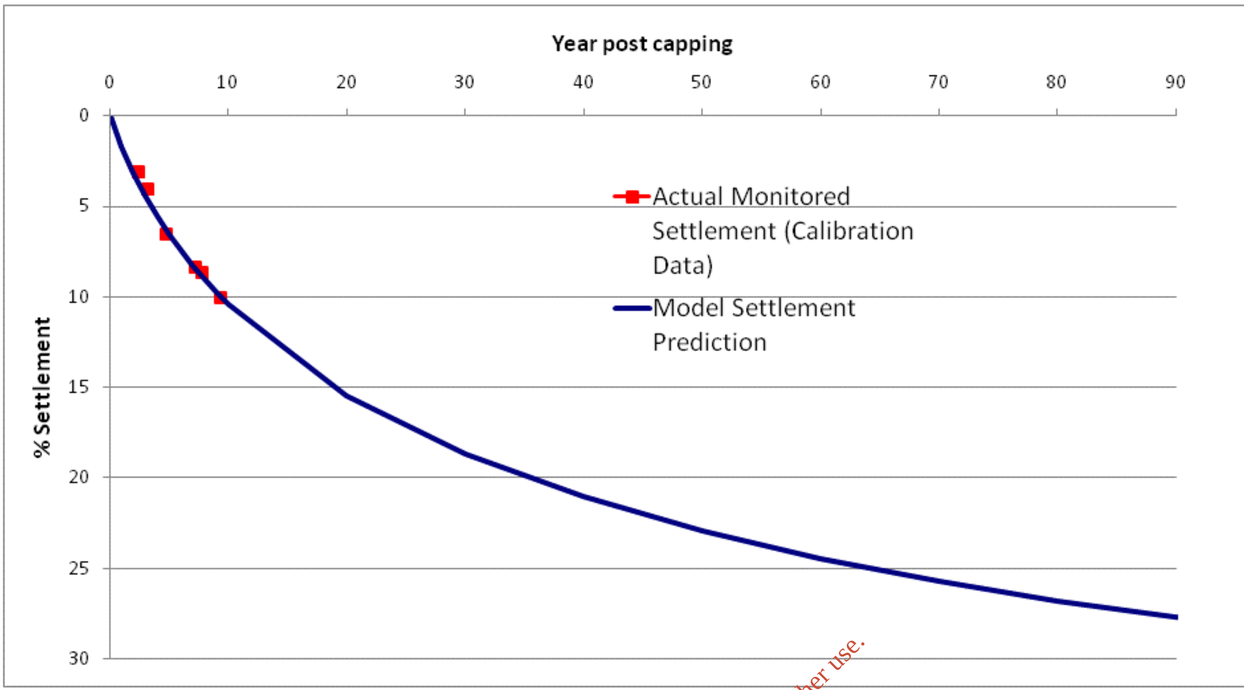

Figure 5: Post-capping settlement calibration data points for a 9 year 4 month period shown on part of an unadjusted predictive model of settlement for a single phase of landfilling.

8. Waste Settlement Modelling

8.1 Immediate Settlement Due to Re-profiling Works

Substantial waste re-profiling works are proposed as part of the restoration proposals. Where waste placement occurs settlement will be induced in any underlying waste materials and / or natural materials.

Settlement induced in the waste materials is expected to occur immediately during construction, reflecting anticipated generally free draining characteristics of the bulk waste materials present at the site.

The natural material underlying the site are indicated by available ground investigation information to be predominantly granular in nature (sands and gravels) hence, settlement induced by waste re-profiling works in the natural deposits underlying the site is also expected to occur relatively instantaneously during construction.

On the above basis it can be assumed that the waste re-profiling works will not directly affect post restoration settlement profiles.

8.2 Settlement Due to Waste Degradation

The majority of post restoration settlement will occur as a result of waste degradation.

To determine the magnitude of total waste settlement (in metres) which will apply at any point on the surface profile, the underlying thickness of the waste (in metres) is multiplied by the predicted total waste settlement percentage, as a "decimal" value. The total predicted percentage waste settlement is 14%, thus, as a decimal value, this is 0.14.

The calculated 14% total settlement value has been applied to the waste placement profile which will apply following the remodelling of the site as part of the remediation works. The waste profile has been iteratively modified over comparatively small areas to provide a suitable post-settlement profile for the site.

Where modifications were required to accommodate changes to the cut and fill proposals and materials balance, the suitability of the waste placement profile was re-checked and confirmed to remain suitable.

The final proposed waste profile is illustrated in drawing 32EW5604/044 - Re-profiled Top of Waste Contours and the end of remediation capping profile in drawing 32EW5604/046 - Remediation Contours. Post settlement contours are illustrated in drawing 32EW5604-047 - Post Settlement Contours.

8.3 Zone 3 Sensitivity Check

Ground investigation records are not available to characterise the waste materials currently placed within the Zone 3 area. Furthermore, the placement of unprocessed surface wastes from Zones 2 and 4 into the Zone 3 area is proposed. Consequently, there is a possibility that the waste materials within the Zone 3 area will contain a higher degradable content than other wastes at the site.

To account for the possibility of waste materials within Zone 3 area with an increased degradable content, sensitivity analysis was undertaken considering an increased waste settlement percentage of 20%. This demonstrated that the post-settlement profile remained acceptable.

8.4 Capping System Induced Settlement

Immediate elastic settlement will also result from the placement of the capping and restoration system, together with any other regulating or profiling inert materials should be determined. Since the present proposal for the majority of the capping system is for a comparatively thin, 650mm system, immediate elastic settlement following its placement will be comparatively small.

At all locations, almost certainly it will be no greater than the thickness of the capping system itself. However, it is recommended that when the additional GI has been completed, immediate elastic settlement is calculated for the placement of the capping system. This will refine the definition of the post-settlement profile which will be achieved across the site.

8.5 Loading Above Capping System

The current settlement assessment has not considered additional settlement that may be induced by loading above for the capping system (e.g. by the placement of landscape fill). Depending on the extent of loading applied this may result in substantial additional settlement and resulting deformation of the capping system which would require separate assessment.

9. Conclusions and Recommendations

From this study it is concluded that:-

1. Settlement induced by waste re-profiling works will predominantly occur during construction, with post restoration settlement occurring as a result of waste degradation and to a minor extent settlement associated with the placement of the capping system.

2. Post restoration settlement potential for the wastes landfilled at the Kerdiffstown Landfill is estimated be approximately 14% of the waste thickness at any given point on the surface.

3. Effectively, the ongoing waste settlement will have ceased by approximately 2150.

4. There is potential for very slow degradation of waste fractions such as plastics and rubber to continue beyond 134/150 years from the present, but corresponding ongoing settlement and additional total settlement will be comparatively small.

5. Since assumed values have had to be applied for waste pH, moisture content and mean temperature in the model, the changing rates of settlement over the settlement period cannot be exactly estimated by the model.

6. Application of the 14% total settlement value to the intended final capping profile (see Drawing 32EW56-046 'Remediation Contours') to demonstrates that a suitable post-settlement profile will result (see Drawing 32EW5604-047 'Post Settlement Contours').

7. Additional application of an extreme, nominal post-capping waste settlement percentage of 20% to the waste placement profile for Zone 3 demonstrated that the post-settlement profile would remain satisfactory under such extreme conditions.

8. Since the present proposal for the majority of the capping system is for a comparatively thin, 650mm system, immediate elastic settlement following its placement will be comparatively small. At all locations, almost certainly it will be no greater than the thickness of the capping system itself therefore numerical calculation of capping induced settlement is not considered necessary.

9. It is recommended that when the additional GI has been completed, settlement predictions are reviewed to account for any changes in inferred waste thicknesses and / or waste composition.

10. Should substantial loading above the capping system be required, supplementary settlement calculations should be undertaken to confirm deformation of the capping system remains within acceptable tolerances.

JACOBS

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