LANDFILL SETTLEMENT EFFECTS

CASE STUDY

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ABSTRACT: Settlement of landfills can be significant and needs to be considered in their design. There is evidence of surface settlements of up to 40% from finished levels at some landfills. Allowances for settlement have often been much less than this. Underestimating settlement can result in the need for extensive works to achieve a surface profile suitable for the intended end use. It can also result in the loss of valuable air space for refuse filling. In the 1990's several papers were presented on landfill settlement. This paper follows up on a presentation by Warren Pump at the WasteMINZ Conference 1998. At Envirowaste's Greenmount Landfill in East Tamaki, Auckland, settlement of refuse was measured intermittently over a period of approximately 17 years. Measured settlements have been found to be much greater than originally allowed for when determining filling profiles. Warren Pump's "FILLS" landfill settlement model has considered and its concept applied to determine more accurate long-term settlements at Greenmount. The model was adjusted, taking into account actual measured settlements. Observations confirmed Pump's prediction that rapid and possibly irregular initial settlement would be followed by a linear long term settlement on log time. The author has been involved in the design and operation of Greenmount Landfill as well as a slightly smaller Envirowaste landfill and aftercare of two closed landfills. Based on his experience, recommendations are provided for settlement allowance, cover thickness, finished cover grades and desirability of fixing finished levels in consents.

1. PAST STUDIES

Settlement of refuse can be significant and needs to be considered in the design of landfills. Studies indicate that 20m of refuse can eventually settle to only 12m. Such settlement, if not allowed for, can result in depressions in finished surface. This can result in loss of enjoyment of the site, raise environmental, health and safety issues and require expensive remedial work.

Various studies have been undertaken of settlement of refuse. Several authors (Edil et al, 1990; Bjarngard & Edgers, 1990; Fassett et al, 1994; Manassero et al, 1996; Pump, 1998) have written articles that suggest settlement of municipal landfills can be up to 40%.

Bjarngard & Edgers (1990) based their findings on actual municipal landfill performance data and concluded that there are three phases of settlement; initial, intermediate and long term. Initial settlement is rapid and irregular; the intermediate phase is distinctly slower and shorter. The long term settlement phase is steady and appears as a straight line on log time scale. This is shown in graphical form in Figure 1.

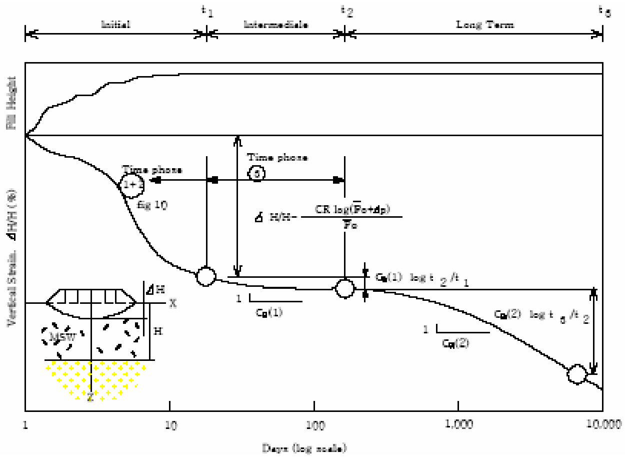

Figure 1: Idealised settlement model (Pump, 1998 after Bjarngard & Edgers, 1990)

Fassett et al (1994) concluded that the intermediate and long term phases are in fact only one phase and that this phase is site specific. Manassero (1996) differs from Bjarngard & Edgers (1990) in that he suggests that there are five phases of settlement and the long term settlement phase is a parabolic line on a log time scale. The five phases of settlement are as follows:
Phase 1: Physical compression and creep
Phase 2: Migration of small particles into voids
Phase 3: Viscous behaviour and consolidation
Phase 4: Decomposition settlement
Phase 5: Collapse of components due to physico-chemical changes
These phases usually overlap each other and several phases can occur at the same time.

2. THE GREENMOUNT LANDFILL STUDY

Greenmount Landfill commenced taking municipal, industrial and controlled[1] waste in 1979 and closed in 2005. The rate of filling varied between 500 tonnes per day to 2,000 tonnes per day. Until 1994 cover was limited to weekly application and since 1994 daily cover was applied. The depth of the landfill varies between 6m and 30m and the total volume is 5,700,000 tonnes spread out over a footprint of 40ha. Refuse was compacted with a range of equipment from bulldozers to landfill compactors of various sizes.

The primary purpose of this study was to determine the likely degree of settlement at the Greenmount Landfill so that the finished levels for refuse placement could be determined. The consented finished landfill levels are specified as being after settlement. The settlement study was carried out in an area where daily cover was not applied. At that time daily cover was not required by consents.

In the mid 1980s five settlement marks were established and regularly monitored until 1991 to determine the amount of settlement. In 2002 the refuse levels at four locations

[1] Waste that requires special handling during disposal for environmental, health or safety reasons. E.g. asbestos, contaminated soils, sludge, dead animals

were also measured. The data was then modelled as per Bjarngard & Edgers (1990) to determine the likely settlement over a 30 year period.

3. MONITORING DATA

3.1 Settlement Marks

In 1985 four settlement marks, A, B, C and E were installed on top of refuse and their levels measured, initially on a monthly basis for a period of three months and then at three monthly intervals until 1991. In 1987 a fifth mark was installed and monitored at the same time and for the same period as the other four marks. Prior to installing the mark the top of the refuse was compacted and rolled to a smooth finish. The settlement mark, a 20mm diameter steel pipe about 600mm long, was driven into the refuse. The top of the pipe was flush with refuse. The cover over the refuse was about 400mm. At the settlement mark the cover was very thin so that the mark could be easily accessed.

At Mark A refuse was placed in five lifts; the first three lifts completed in March 1983 and the last two lifts in July 1984. Mark A was installed one year after the fifth lift was completed in that area.

At Mark B refuse was placed in four lifts; the first two lifts completed in August 1984 and the second two completed in February 1985. Mark B was installed six months later.

At Mark C refuse was placed in two lifts; the first lift completed in August 1984 and the second lift completed in February 1985. Mark C was installed six months later.

At Mark E refuse was placed in two lifts within a four month period and finished in June 1985. The settlement mark was installed one month later.

At Mark F refuse was placed in five lifts; the first two completed in August 1984, the third completed in January 1985 and the last two completed in May 1987. The mark was installed in October 1987. There is a complicating factor at Mark F in that there is some older refuse from the late 1960s and early 1970s placed below the landfill liner. The bulk of the older refuse consisted of quarry stripping and is up to 6m thick.

The levels of the marks were measured monthly for the first three months and then at three monthly intervals up until October 1991. Mark C was destroyed in September 1990 when the area was reworked. Mark E was covered with further lifts of refuse after August 1989. There was no monitoring after October 1991 until July 2002.

In July 2002 holes were dug down to the refuse surface at the locations of Marks A, B, C and F. Past records show that the ground in the vicinity of Marks A, B and F was not disturbed since 1991, although the settlement marks were not found. Levels were taken on top of the refuse to provide measurements of settlement since 1991. It was assumed that the surface of the refuse was equivalent to the top of the settlement marks. Records showed that in the vicinity of Mark C the refuse had been reworked.

After reworking, the refuse at Mark C was about 0.6m higher than that prior to reworking.

3.2 Difficulty in Measuring Settlement

At Greenmount refuse was filled by the area method[2] with refuse being placed in lifts over a period of time ranging from a couple of months to several years. A filling area was 1,500m^2 to 2,500m^2 and a lift took up to two weeks to complete. Filling would progressively move away from that area and it would then be some months before the second lift was placed. Subsequent lifts were placed anywhere from a few months to about a year following the previous. The number of lifts at each settlement mark ranged from two to five. The time span between lifts meant that the settlement could not be measured from 'day one'. The time span for each mark is shown in Table 1 below:

TABLE 1
TIME BETWEEN FIRST LIFT AND MARK INSTALLATION

Mark	Completion of first lift	Completion of last lift	Installation of settlement mark	Time between first lift and mark installation
A	Jan 1983	Jul 1984	Jul 1985	30 months
B	Jun 1983	Feb 1985	Jul 1985	25 months
C	Jun 1983	Feb 1985	Jul 1985	25 months
E	Mar 1985	Jun 1985	Jul 1985	4 months
F	Mar 1983	May 1987	Oct 1987	55 months

The shortest time span was at Mark E where it was four months from the first lift to the installation of the settlement mark. Pump (1998) made reference to other published articles that short term settlement generally occurs rapidly within the first month. In view of this short term settlement could not have been measured at any of the settlement marks. The short term settlement was estimated and is described in Section 3.3 below.

3.3 Amount of Settlement

Pump (1998) developed a FILLS programme that enables assessment of surface settlement from 'day one'. That model was used to estimate short term settlement for Rio Vigne Landfill in Italy and compare with actual short term site measurements. The estimate values from FILLS model showed good agreement with actual measurements. The type of refuse in that landfill was similar to that in Greenmount Landfill, but the compaction is most likely to be of higher standard. In addition, daily cover was used at Rio Vigne. Refuse at Greenmount was compacted in 300mm layers and daily cover was not applied. Pump's estimate for short term settlement for Rio Vigne Landfill was accepted as a likely scenario for short term settlement at Greenmount. It is possible that the short term settlement for Greenmount may be

[2] Refuse is laid out generally on the flat next to the previous lift and built up in layers to the full depth of the lift.

greater than that for Rio Vigne because compaction at Rio Vigne may be of higher standard. Pumps example for Rio Vigne was used to determine the likely short term settlement prior to the installation of the settlement marks at Greenmount Landfill. This likely short term settlement (or prior settlement) was added to the measured settlement to determine the total settlement from placement of the first lift to July 2002 and is shown in Table 2 below. Mark E was not considered at July 2002 as that mark was buried under 12m of refuse placed after its installation.

TABLE 2
TOTAL SETTLEMENT TO JULY 2002

MARK	Prior settlement (1) (from Pump, 1998)	Measured settlement (2) (monitoring by ESL)	Total settlement to July 2002
A	7.8%	16.1%	23.8%
B	5.8%	17%	22.8%
C	4.5%	17.6%	22.1%
F	7.8%	17%	24.8%

(1): Short term settlement from placement of first lift of refuse to when the settlement marks were installed.
(2): Measured settlement from installation of settlement marks to July 2002.

The data in Table 2 in conjunction with other measured values are shown in Figures 2 and 3. Figure 3 shows percentage settlement versus time in years. The settlement curves do not start at zero time to reflect the delay between placement of refuse and start of monitoring. Figure 4 shows percentage settlement versus log time in days. The settlement lines between the last two points have been extrapolated in a straight line to reflect linear long term settlement (Bjarngard & Edgers, 1990).

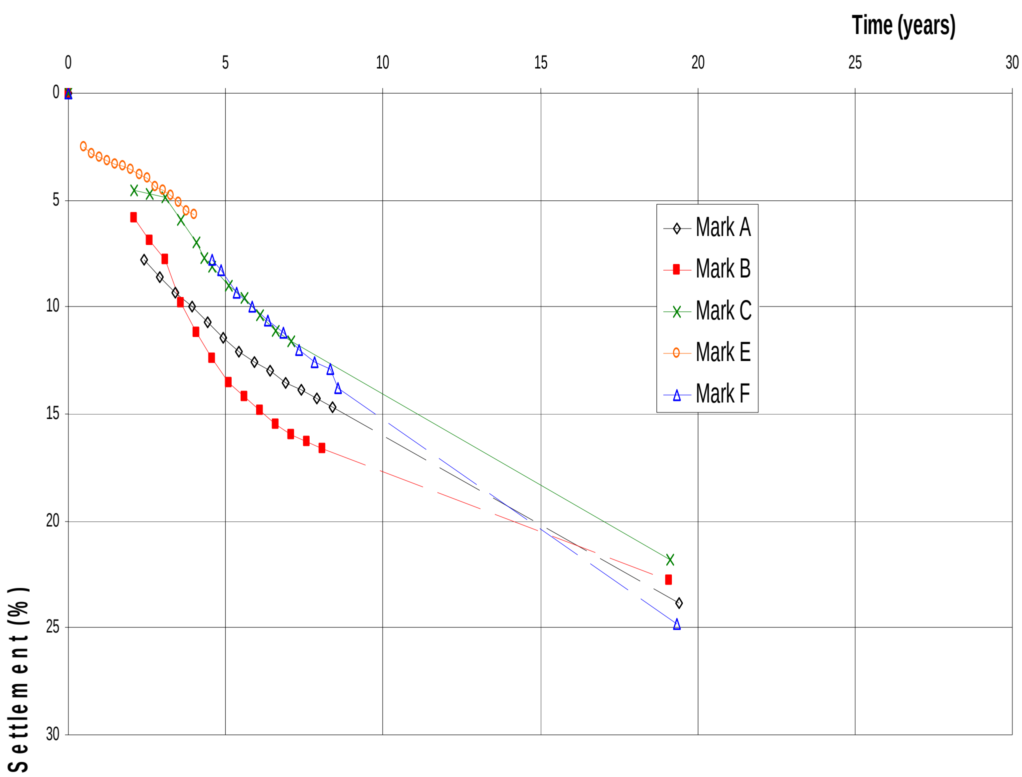

Figure 2: Measured Greenmount settlement on normal time

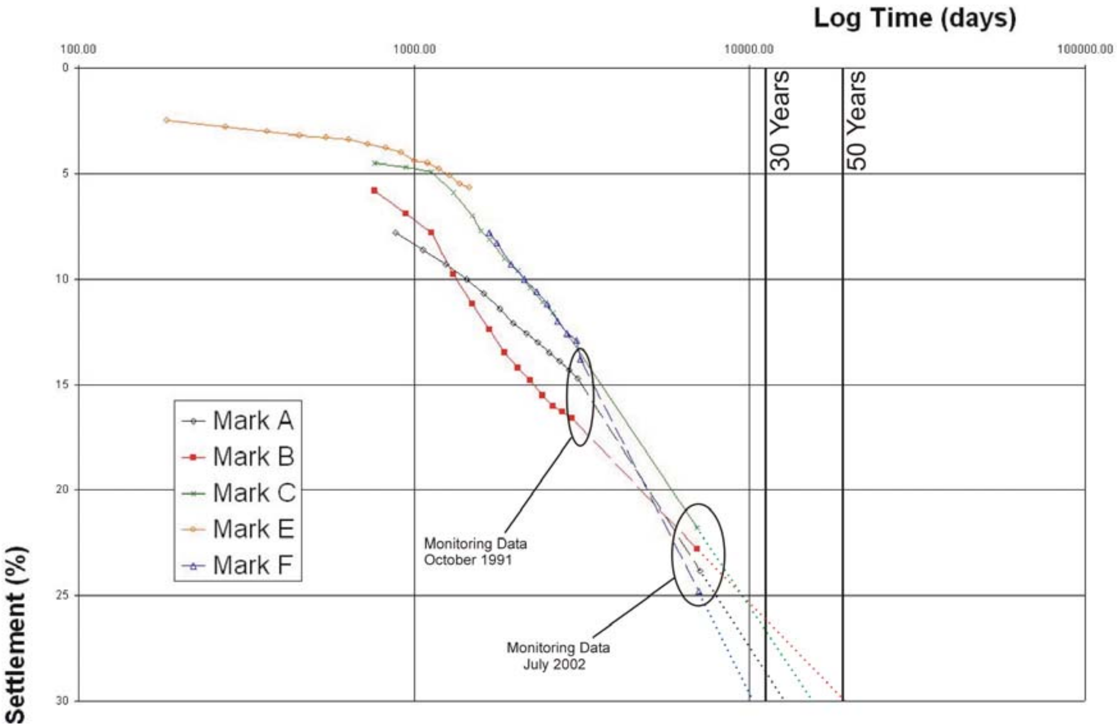

Figure 3: Greenmount settlement on Log time (Linear extrapolation)

3.4 Peer Review

Greenmount Landfill has a Peer Review Panel whose objective is to ensure that all construction works achieve design specifications under the Resource Consents. The settlement investigation report was submitted to the Panel for review. The Panel reviewed all monitoring data, the extrapolation of that data and the technical literature used to draw conclusions about likely future settlement. The Panel accepted that the approach to assessing settlement and thus final completion levels could be based on the methods set out in the report using the recorded data from settlement Marks A and B.

The report suggested considering a period of 30 years to estimate settlement which will continue beyond 30 years. The settlement marks were in an area where daily cover was not used and prior to diversion of green waste away from landfills. For about half of the total tonnage placed in the landfill daily cover was used and those areas are likely to settle less than the area of the settlement marks. For this reason it was considered that 30 years was adequate for considering long-term settlement for the whole landfill. By the end of the aftercare period a substantial portion of refuse will have been in place for close to 50 years. Any significant settlement that may not have been accounted for in the design can be addressed at the end of the aftercare period by surface restoration works.

The Panel considered that data for Marks C and F were in doubt. Mark C was disturbed during remedial works in 1991 and data for that location could not be extrapolated with certainty. Data for Mark F was compromised by the presence of indefinable older refuse below the liner and settlement may appear to be greater than actual. The Panel considered that measurements for settlement Marks A and B was the only factual data available to predict the likely future settlement of the landfill.

3.5 Greenmount Settlement Model

Based on the Peer Review Panel's recommendation the measured values for Marks A and B were used to develop the settlement model for Greenmount and this is shown in Figure 4 below. The model is the average of values for Marks A and B to July 2002. Beyond that time the graph was extrapolated in a straight to estimate future settlement. The model shows that settlement will be 27.3% at 30 years and 32.1% at 50 years.

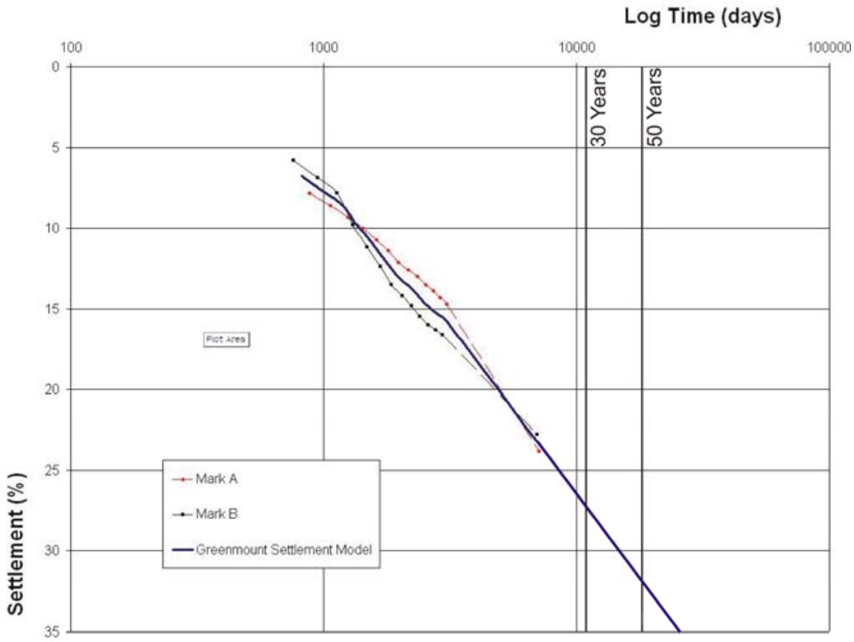

Figure 4: Greenmount Settlement Model (settlement v's log time)

3.6 Design Application

The consented levels for the completed landfill are post settlement but the settlement period was not defined. To achieve the consented levels, it was assumed that the 30-year settlement will be a reasonable allowance to determine the finished landfill levels.

To determine the finished landfill levels the following procedure was adopted:

a) From the consented contour plan points were selected that indicated a change of grade or a significant feature. The landfill floor and existing filling plans were examined for any points of significant features that could have impacted on determination of settlement and those points were added to the list.
b) From filling plans the depth and age of each lift of refuse was determined.
c) The remaining settlements for existing and future lifts arising from the remaining refuse filling were estimated using the Greenmount Settlement Model in Figure 4.
d) The total settlement at each point is the sum of the estimated settlement for each lift.
e) The total settlement in (d) was added to the corresponding level in (a) to determine the finished landfill level.

Steps (b) to (d) were done in tabular form as below.

Point	Lift depth	Lift age	Remaining settlement (%)	Settlement of each lift (m)	Total settlement remaining	Consent level	Finished landfill level

Once all the finished levels had been calculated then a finished landfill contour plan was drawn. The levels were checked and if necessary, adjusted to ensure that the surface grades were not less than 5%, as lesser grades can be adversely affected by differential settlement resulting in development of local depressions that may hold water or develop water trap in gas reticulation pipes.

4. DISCUSSION OF SETTLEMENT DATA

The Greenmount settlement model estimates that in parts of the landfill, the settlement will be 27.3% at 30 years, 32.1% at 50 years and eventually 35% at around 100 years (from Figure 4). This is of similar order as estimates by several published articles which have suggested that total municipal landfill can settle by up to 40%. The authors of those articles may have considered landfills that may have had higher content of organic refuse and may have had lesser compaction than that at Greenmount. It must be remembered that the settlement marks were in a part of the landfill where there was possibly a higher organic content refuse than elsewhere in the landfill. In addition, daily cover was not used in the area of the settlement marks. These two factors will reduce the total settlement to less than that shown in Figure.

The long term settlement for marks A and B were assumed to be linear as per Pump, 1998. On that basis the settlement lines were extrapolated to estimate settlement at 30 years and 50 years. A close examination of the data prior to 1991 shows that the lines are curved and that the best fit between 1991 and 2002 points are curves rather than straight lines. This scenario fits in with Manassero et al (1996), that the long term settlement is parabolic on log time. If the Greenmount data were extrapolated on the curve to 30 years and 50 years, then the settlement values may be more than what has been estimated in Figure 4. To check the validity of this the monitoring at Greenmount needs to be extended over a longer period.

In Figure 2 the settlement graphs for Marks A, B, C and F indicate that the rate of settlement was reducing over the years leading up to year 8 (1991) after placement, when monitoring of the marks ceased. If those graphs were extended in a similar curve then the settlement would be less than what was actually measured in 2002. This suggests that for settlement to be as high as actually measured in 2002, then sometime between 1991 and 2002 the rate of settlement must have increased. To determine the possible causes for the increase in the rate of settlement, the site records were examined. The records showed that there were no unusual or extra activities in the area of the marks apart form the installation of the gas wells in 1991/92.

Three wells were installed around Mark A and one near Mark B. The rate of gas extraction from that area was steady up until 2000 and then started to decline. Recently new refuse has been added in that area and gas volumes have increased. It is accepted that gas production is indicative of reduction in organic content due to biodegradation (converting organic matter into heat, gas and liquid). The process would create void spaces that would be filled in by particle migration. This would tend to increase the rate of settlement. However it is not certain if active extraction of gas could have increased the biodegradation rate and thereby increased the rate of settlement as inferred from Figured 2.

5. OBSERVATIONS OF SETTLEMENT EFFECTS

The author of this paper has been involved in landfill design and operation for over 15 years. During that time he had the opportunity to observe landfill performance at first hand. Some of the observations made are listed below.

The moisture content of refuse has a significant impact on mechanical compaction of refuse, the rate of biodegradation and disentangling and rearrangement of particles. All this affects the amount and rate of settlement. More mechanical compaction during placement of refuse reduces the total settlement. Purpose built refuse compactors with carron type feet, or similar, are recommended as they achieve the best compaction. If the refuse is dry then addition of moisture can significantly improve compaction. Consideration should be given to use of leachate for adjustment of moisture content at the tip face, provided odour and contamination can be contained to the satisfaction of the regulatory authorities. Recirculation of leachate at Greenmount and at another Envirowaste landfill showed that addition of moisture accelerates biodegradation and speeds up disentangling and rearrangement of particles.

Migration of particles to fill in voids is a significant activity at the interface of refuse and final cover and in the final refuse lift. Where the surface of the landfill is flat and ponding of surface water is likely to occur, infiltrating water can wash the cover material into voids in the refuse. This process appears to accelerate (possibly due to pumping) if there is vehicular traffic using the landfill. In older landfills where the cover was less than 1m thick refuse has protruded through the cover as cover soil migrated around it and into the voids below. To avoid that occurring large objects should not be placed in the top 1m of refuse and final cover should be increased to about 2m thick. It is worth noting that this thickness of cover is about twice as much as that recommended in Landfill Guidelines by CAE (2000). The top layers of refuse should be compacted thoroughly and at least three times more compaction than normal should be carried out.

Differential settlement can cause surface maintenance problems and damage the integrity of the landfill cover. Maintenance problems include depressions holding water, development of blockages in gas extraction pipes, mowing problems and possible adverse effect on vegetation. Damage to the integrity of landfill cover can allow excessive infiltration of surface water, accelerated local settlement, increased leachate generation and high concentrations of landfill gas to escape causing odour nuisance or breach of consent conditions. To reduce the impacts of differential settlement the following recommendations are suggested:

i) Avoid concentrating high content organic material in one spot.
ii) Avoid burying piles of soil or hardfill in one area.

iii) Build the final cover to at least 5% grade.

iv) Thicken the final cover to minimise cracks propagating through the full depth of cover.

At Greenmount resource consents require achievement of a specified landfill surface profile post settlement. This can lead to difficulties as landfill settlement is not fully understood and is open to interpretations of different concepts which give a range of scenarios. Variability in refuse content and differential settlement adds to the difficulty of achieving the specified profile which can lead to disagreements between operators and regulators. An alternative could be to fix the maximum profile of the landfill and agree on values for settlement. The intention should be to design the profile to meet the end use rather than capping the tonnage for the landfill. There are advantages in fixing the maximum refuse profile and setting upper and lower limits for finished surface grades. This would allow the regulatory authority and the landfill operator to easily check compliance for the filling profile. If later settlement modelling shows a variance from assumptions used for consents then that should be taken into consideration for the filling profile.

Some of the older closed landfills are now valuable real estate and have been considered for building development. Plausible reasoning has been put forward to support the effectiveness of dynamic compaction to accelerate settlement and thereby render sites suitable for building development. Such reasoning overlooks the fact that the primary cause of long term settlement is biodegradation and collapse of components and these are not affected by dynamic compaction. These processes will continue after buildings are constructed and lead to further settlement that could cause structural damage to buildings. Biodegradation will result in generation of landfill gas, a serious potential environmental, health and safety issue, particularly for those who may be unaware of the presence of a landfill. Some old landfills have high leachate/groundwater levels. If those levels drop in the future, then voids will be created and biodegradation may be accelerated. This may increase gas generation and possibly increase the rate of settlement.

6. CONCLUSIONS

Accurately predicting long term settlement of landfills is a challenge because of the diversity of the waste stream. By carrying out settlement monitoring over a 15-year period it is possible to develop a settlement model for the Greenmount site that allows estimation of future settlement. The model cannot accurately predict settlement for the whole landfill because waste streams in different parts of the landfill will vary and is usually beyond the control of the operator. The Bjarngard & Edgers (1990) model is a good approximation and the Manassero (1996) model appears to be more accurate for long term settlement.

To accurately measure settlement, refuse should be placed using a sloping face[3] method rather than plan area method (see footnote on page 4). This allows quicker

[3] Refuse is laid out and compacted on a continuously advancing sloping face for the full depth of the lift.

placement of refuse for the full depth of the lift (normally one day) at a particular point where a settlement mark can be placed. The lift should be as thick as possible and the settlement mark should be installed immediately. To monitor separate lifts consider using a settlement mark on each lift. At Greenmount the settlement marks were concentrated in one corner of the landfill. The results would have been more representative if the marks were spread out over the whole landfill at perhaps one mark per 5ha.

The estimated settlement for Greenmount Landfill for 30-year period is 27.3% and the total settlement could be up to 35%. The results at Greenmount are of the order of values suggested in other published articles that indicate that total landfill settlement could be up to 40%.

The total amount of settlement is dependent on the amount of mechanical compaction applied when placing refuse, the percentage of organics in the waste stream and the refuse to soil ratio within the landfill. Mechanical compaction will reduce voids in the refuse pile and allow placement of a greater tonnage of refuse within a profile fixed by consent but there are other processes that affect settlement after placement. They include particle migration[4], biodegradation and collapse of matter. These processes may increase the rate of long term settlement.

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[4] Particle will migrate into the remaining voids after mechanical compaction and into new voids created by biodegradation and collapse of matter.

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