LANDFILL TREATMENT FOR WESTLINK M7

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ABSTRACT

Westlink M7 is one of Australia's largest urban road projects and was a key missing link in Sydney's orbital road network of motorways. A section of an onload/offload ramp of an interchange was constructed over an existing landfill comprising municipal solid waste with a depth up to 12-13 m. To control settlement of the road built over the landfill, a series of stone columns were installed in the landfill, known as dynamic compaction (DC) and dynamic replacement (DR). The stone columns were extended to about 5-6 m depth founding on compacted waste material. Due to the complex composition and variability of the waste material, it is difficult to predict the long-term performance of the landfill. Worldwide research in this area has continued for 30-40 years and some information has become available for the design of landfill treatment. Detailed 3-dimensional numerical modelling was carried out to simulate the expected settlement of the landfill and predict the impact of this settlement on the pavement. *In situ* tests were carried out in the landfill before and after the DC/DR treatment to demonstrate improvement of the landfill property. The treated landfill was also preloaded for a period of time and settlement monitored to confirm the effect of the treatment.

1 INTRODUCTION

A section of the onload/offload ramp at the Old Wallgrove Road Interchange of the newly developed Westlink M7 (M7) in Sydney Australia has been constructed over the existing landfill of the Eastern Creek Waste Management Services. This section of the ramp is about 170 m long and 25 m wide. The fill height of the ramp ranges between 2 m and 7 m, whilst the existing landfill thickness is up to 12-13 m. The landfill is understood to comprise mainly municipal solid waste and was last capped in 1994 when the capacity was reached.

Pavement constructed over landfill may experience large and continuous settlement in the long-term. Excessive and differential settlement will affect the performance of the pavement. Greater settlement may be anticipated in areas where deep landfill is present, whilst differential settlement could occur at any locations where substantial variations of subsurface conditions occur, for example, at the quarry boundaries or areas underlain by different types of waste material. Due to the heterogeneous nature of the landfill material the problems associated with landfill settlement are difficult to quantify. An engineering solution is therefore needed to be developed to overcome the uncertainties of the landfill and reduce undue risks.

A number of ground improvement measures have been considered to control the long-term settlement of the landfill including preloading and surcharging, impact rolling, dynamic compaction, stone columns, timber piling, etc. It was assessed that a combination of dynamic compaction (DC), together with stone columns using the dynamic replacement (DR) technique, was most effective. Testing using a pressuremeter was undertaken before and after the DC/DR treatment to confirm ground improvement, 3-dimensional numerical modelling was carried out to investigate the effectiveness of the treatment and preloading with settlement monitored was conducted to allow observation of the landfill performance. The settlement data were further used for prediction of long-term settlement using a published approach. Photos 1 to 8 show the pressuremeter testing as well as the DC/DR treatments.

2 PROJECT OVERVIEW

The 40km Westlink M7 was one of Australia's biggest urban road projects and was a key missing link in Sydney's orbital road network of motorways.

Westlink M7 is the link between the M2, M4 and M5 motorways in the western Sydney suburbs. The dual-carriageway motorway was constructed between the M5/Hume Highway at Prestons and the M2 at West Baulkham Hills and connected with the M4 at Eastern Creek. It replaces the Cumberland Highway as the National Highway link through Sydney, providing an important new route for the transport industry and taking large numbers of heavy vehicles off local roads. The M7 route plan is shown in Figure 1.

The motorway is owned and operated by Westlink Motorway Limited whose shareholders are Macquarie Infrastructure Group, Transurban, Abigroup Contractors and Leighton Contractors. The Abigroup Leighton Joint Venture was appointed by Westlink Motorway Limited to design and construct the M7, whilst Maunsell SMEC Joint Venture provided the design services.

The NSW Roads and Traffic Authority (RTA) coordinated the project's development, environmental assessment and planning approval. During implementation, the RTA administered the project deed and ensured that the scope and approval conditions were met.

Major construction of the M7 started in July 2003 and it was open to traffic by the end of 2006.

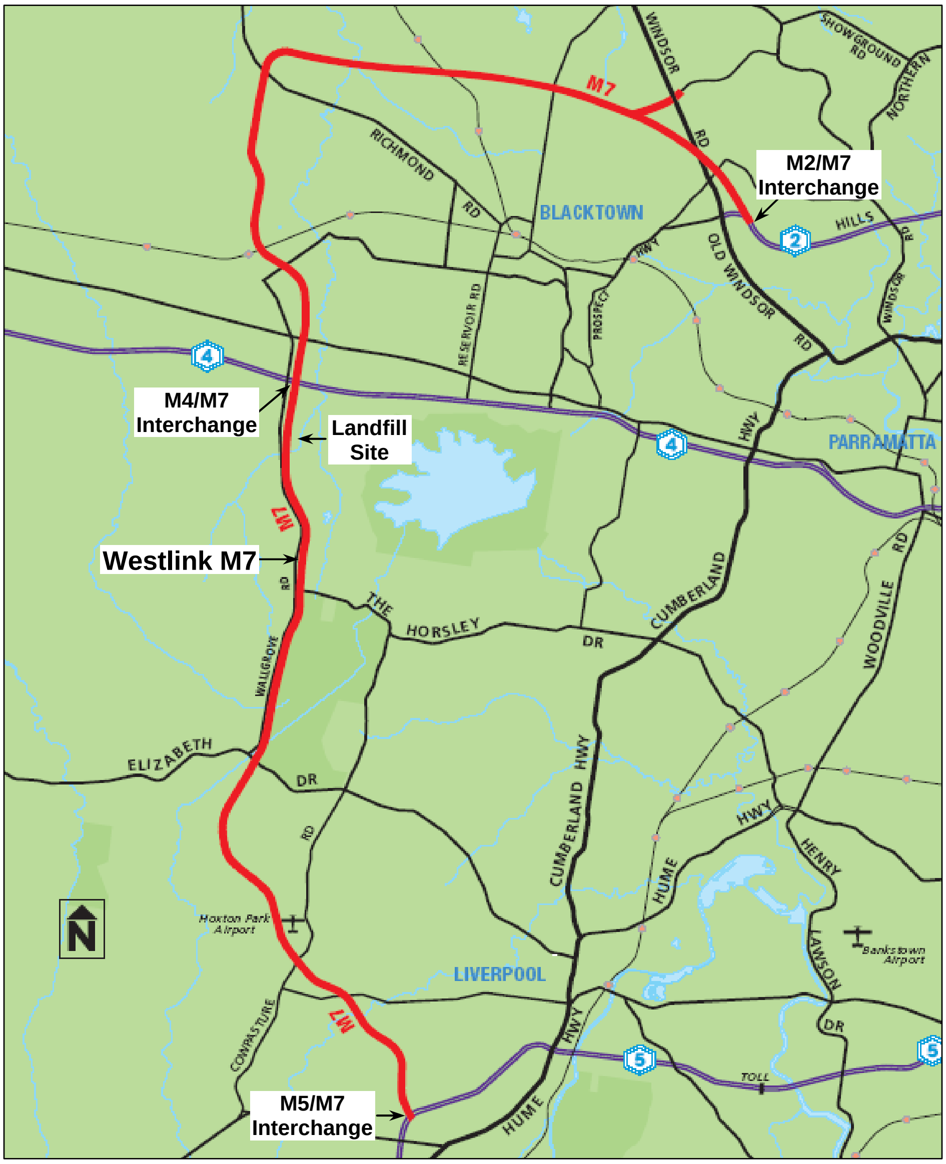


Figure 1: Project route plan.

3 SETTLEMENT OF LANDFILL

The section of the onload/offload ramp at the Old Wallgrove Road Interchange constructed over the existing landfill is about 170 m long and 25 m wide. Several boreholes were undertaken in this area to identify the characteristics and extent of the landfill. The subsurface encountered generally included a thin clay capping layer of about 0.5 m thick at surface overlying landfill of varying thicknesses up to 12-13 m at the centre of the ramp. The landfill was found to be mainly domestic waste material comprising rubbish (plastic sheets, wood, glass, paper, metal, etc.) with a strong organic odour, mixed with some ripped/crushed shale. It is understood the landfill was last capped in 1994 when the capacity was reached. The fill height of the ramp ranged between 2 m at the centre and 6-7 m at the two ends of the ramp. The long section of the landfill is shown in Figure 2. This figure shows the top and bottom surfaces of the landfill, the zone to be treated with stone columns and the finished surface of the pavement. The site plan of the ramp is shown in Figure 3.

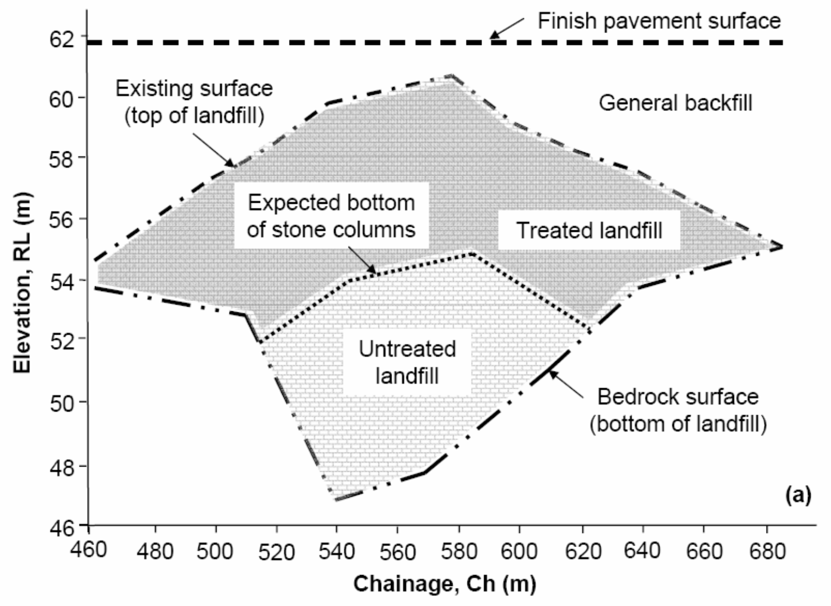


Figure 2: Long section of landfill.

Due to the complex composition and variability of the waste material, it is generally difficult to predict the long-term performance of the landfill. However, worldwide research in this area has continued for 30-40 years and some useful information has become available for the design of landfill treatments to control the long-term settlement (e.g. Wall and Zeiss, 1995; Ling *et al*., 1998; McDougall and Pyrah, 2001; Yuen and McDougall, 2003).

It is understood that the settlement of the landfill may comprise primary settlement and secondary (creep) settlement. Primary settlement and part of the secondary settlement are caused by the mechanical compression of the landfill as the voids within the landfill are reduced due to the imposed loads and rearrangement of the solid waste. The amount of this settlement is dependent on the density of the landfill and the magnitude of the loading. The mechanism of this settlement is similar to that of soils undergoing consolidation and creep and thus soil mechanics theory may apply for the prediction of the mechanical compression of the landfill provided that the material properties are correctly assumed.

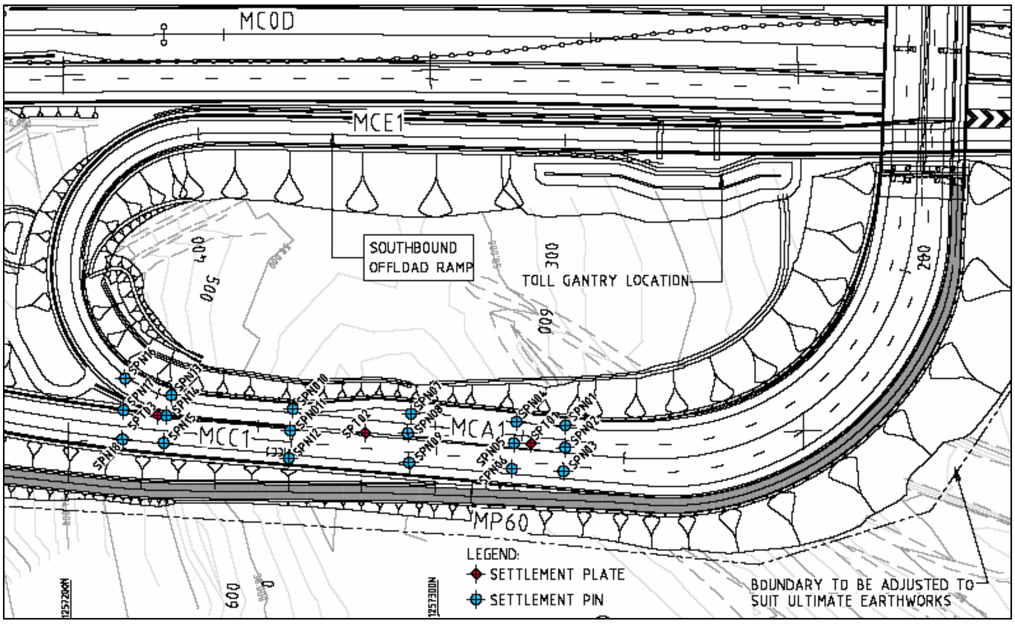


Figure 3: Site plan of ramp.

However, a portion of the long-term settlement (creep) of the landfill is caused by biodegradation of the organic waste. This process creates new voids within the landfill resulting in further compression of the landfill. The magnitude and rate of this settlement is dependent on the moisture level, organic content, waste composition, density, temperature, age, etc. As the waste material is highly heterogeneous its engineering properties are hard to obtain.

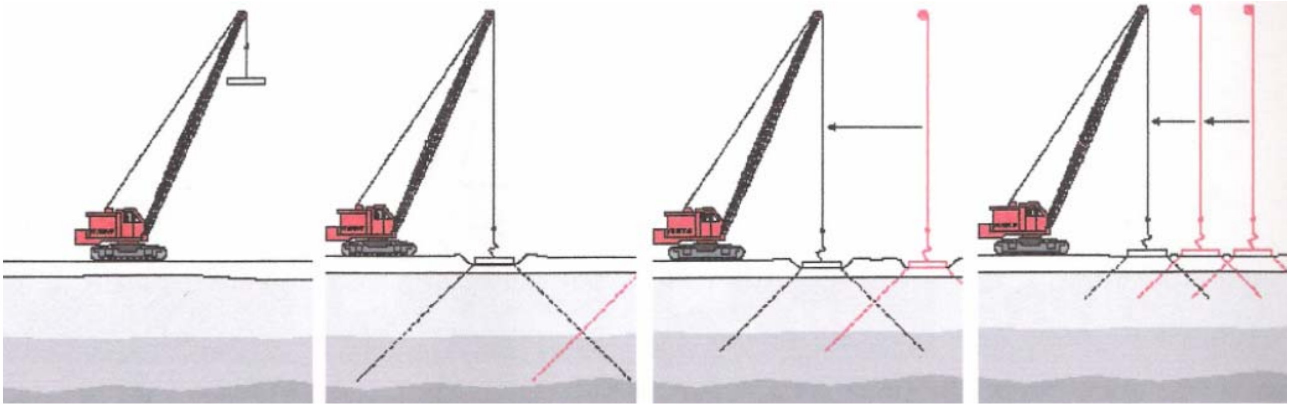
Literature on this issue has reported that landfill could settle up to 20% to 40% of its height and the settlement caused by biodegradation could contribute to half of this settlement. It is expected that the mechanical settlement of the landfill could occur over a relatively short period of time due to large void spaces and high hydraulic conductivity. However, biodegradation will take tens of years to complete. It was also reported that settlement of the landfill could continue over a period of 30 years after landfill activities ceased (Wall and Zeiss, 1995).

4 GROUND TREATMENT

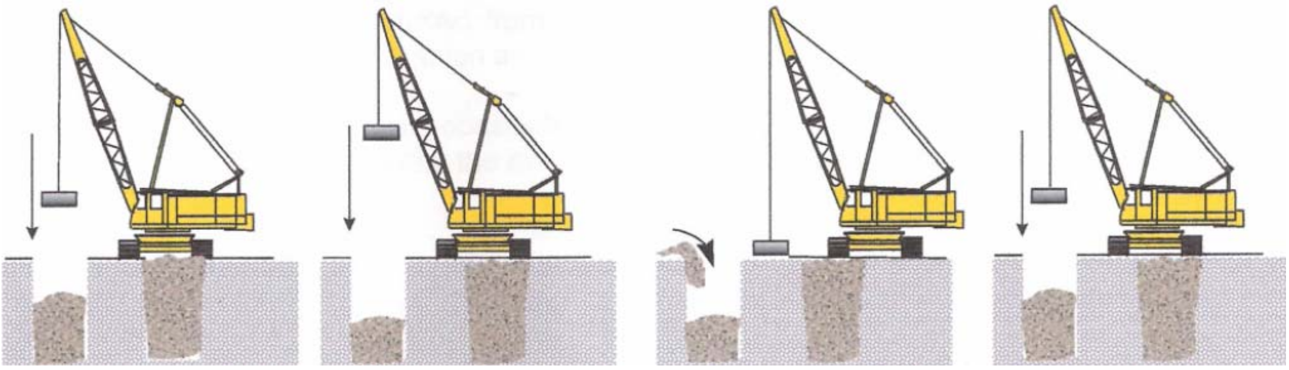
To control the landfill settlement, a combination of dynamic compaction (DC) and dynamic replacement (DR), based on the Menard/Austress Freyssinet (M/AF) techniques, was chosen. These methods are described as follows:

- *Dynamic Compaction* - Drop a heavy concrete block or steel plate from a height onto the landfill. This will effectively crush the landfill material with large voids (mechanical compression) and has an impact depth up to 4-5 m depending on the weight of the block and the height of drop.
- *Dynamic Replacement* (Stone Columns) - Ram a series of stone columns into landfill using a steel block to support the pavement. The stone columns installed by this method are expected to extend to 6-7 m depth and will be founded on compacted waste material. The influence depth of compaction of the landfill is expected to be up to 10 m. With landfill being further compacted, its long-term settlement is expected to be greatly reduced. However, some long-term settlement will still be expected, largely due to biodegradation of the landfill as the mechanical compression is achieved by dynamic compaction. The process of biodegradation may be hindered due to reduced air flow in compacted landfill.

The stone columns were installed from a 0.5 m thick working platform consisting of compacted sandstone over the landfill. The stone columns were of 2 m diameter each and were constructed at 5 m c/c spacing on a square grid. The DC/DR treatment was undertaken in three phases, being the deep primary treatment, the intermediate secondary treatment and the final shallow compact. The first two phases were performed using a 13.5 t pounder (1.2 m x 1.2 m x 2.5 m) dropped from a height up to 18 m and filling the prints with rock. The last phase was done using a 13.5 t ironing plate (2.4 m x 2.4 m x 0.625 m) dropped from a height of 10-15 m. Further to the DC/DR treatment, a bridging layer consisting of compacted sandstone was constructed directly above the treated area. The bridging layer was designed to overcome anticipated differential settlements of the landfill and to ensure the required pavement performance was met. The typical installation sequence of the DC/DR treatment is shown in Figure 4 and the general cross section and arrangement shown in Figure 5.



(a) Dynamic compaction.



(b) Dynamic replacement.

Figure 4: DC/DR installation sequence (courtesy of Menard/Austress Freyssinet).

M/AF from their experience on sanitary landfill in Germany and France suggested a long-term biological settlement in the order of 2% of the initial untreated total landfill thickness for fills with:

- Organic content of 25% or less,
- Mineral content of 50% or more and
- Landfill of 10 years or older.

M/AF further suggested that the pressuremeter tests indicated that the organic content of the landfill was less than 10%. Therefore a reduced settlement of 1% of the landfill thickness was predicted for the long-term landfill settlement. As a result, for a maximum landfill thickness of 12-13 m the predicted long-term settlement was 120-130 mm within 10 years.

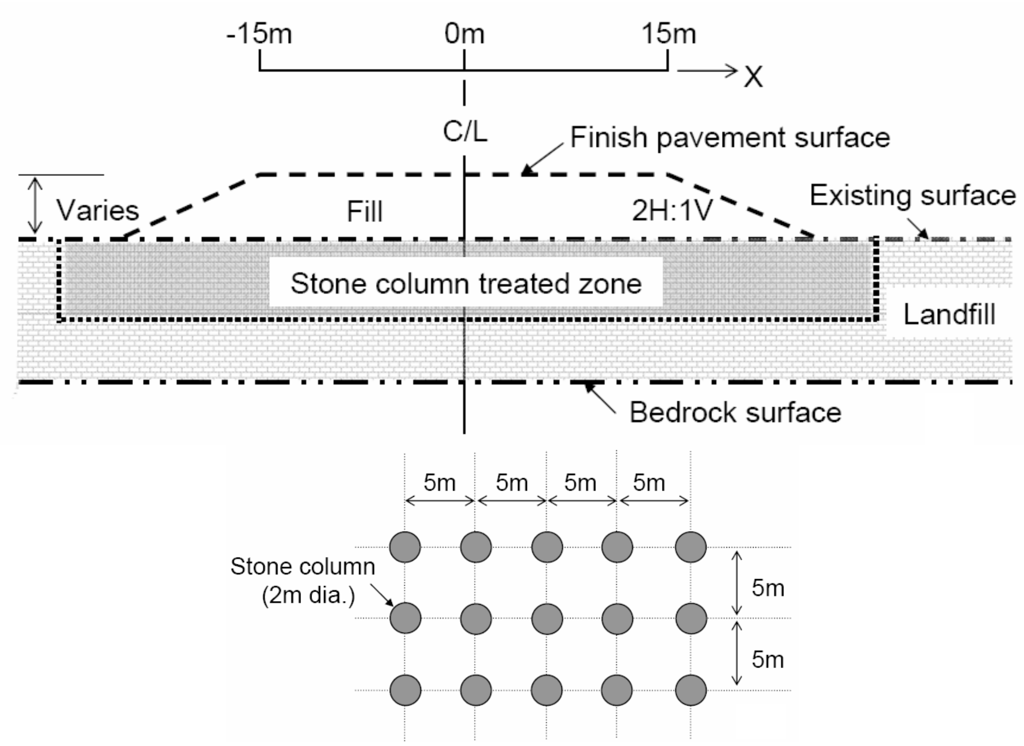


Figure 5: Typical cross section and arrangement of DC/DR treatment.

There have been empirical methods developed to predict the long-term settlement of landfill, as presented in a number of publications (Wall and Zeiss, 1995; Ling *et al*., 1998; McDougall and Pyrah, 2001; Yuen and McDougall, 2003). However, these methods have largely been based on curve fitting of the settlement measurements to derive the settlement-time correlations, e.g. logarithmic functions, power functions and hyperbolic functions. A unique correlation can be obtained for each individual case and a generalized correlation is not available.

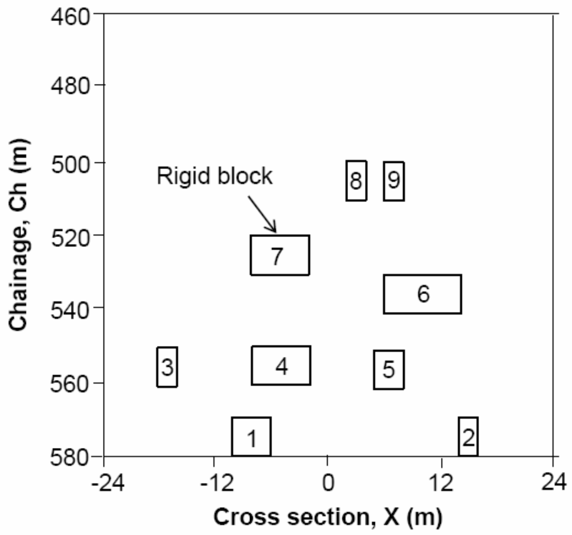
The accuracy in predicting the long-term settlement based on this approach depends on the duration of settlement measurements. As described earlier, the mechanical settlement of the landfill could occur within a short period of time, followed by the long-term biodegradation-induced settlement. If the field measurements used for the curve-fitting span only a short duration, the measurements will therefore not include the settlement caused by biodegradation and, as a result, the prediction of the long-term landfill settlement based on limited data will not be reliable.

Due to the difficulties in predicting the long-term landfill settlement an engineering solution will have to be developed to control such settlement and reduce risks. To optimise the design of landfill treatments and to minimize the risk, a numerical modelling approach was adopted to simulate the potential problems and hence derive the most effective treatment measures.

Additional geotechnical tests and trials were used to form the basic ground models for the proposed numerical modelling. Sensitivity studies were carried out to investigate the impact of varying subsurface conditions on landfill treatment. A robust solution was then developed to reduce risks to a minimum.

5 NUMERICAL MODELLING

Pavement constructed over landfill may experience large and continuous settlement in the long-term. Excessive and differential settlement will affect the performance of the pavement. Greater settlement may be anticipated in areas where deep landfill is present, whilst differential settlement could occur at any locations where substantial variations of subsurface conditions occur, for example, at the quarry boundaries or areas underlain by different types of waste material. Due to the heterogeneous nature of the landfill material the problems associated with landfill settlement are difficult to quantify. The DC/DR treatment will allow removal of some uncertainties. Other treatments in conjunction with DC/DR may also be required to reduce undue risks and satisfy the pavement performance requirements.



Rigid block no.	Thickness of untreated landfill (m)	Thickness of rigid block from base (m)
1	6	4
2	6	4
3	8	6
4	8	4
5	8	6
6	4	2
7	2	2
8	2	2
9	2	2

Figure 6: Landfill in plan with randomly assumed rigid inclusions.

A numerical approach, based on the 3D finite element method using the PLAXIS 3D Tunnel program, has been adopted to investigate the long-term performance of the landfill taking into consideration the predicted settlement and the proposed construction method. The numerical modelling has been carried out for the following two cases:

Case 1 – The landfill is assumed to settle up to 1% of its thickness within the DC/DR treatment area after completion of the embankment and pavement construction. The landfill thickness varies along the alignment as shown in Figure 2. To achieve efficiency of the 3D modelling only half of the landfill along the alignment (Ch. 460-580m) is considered in the analysis. The fill placed over the landfill is considered to be compacted sandstone and the thickness varies between 2m at Ch. 580m and 7m at Ch. 460m.

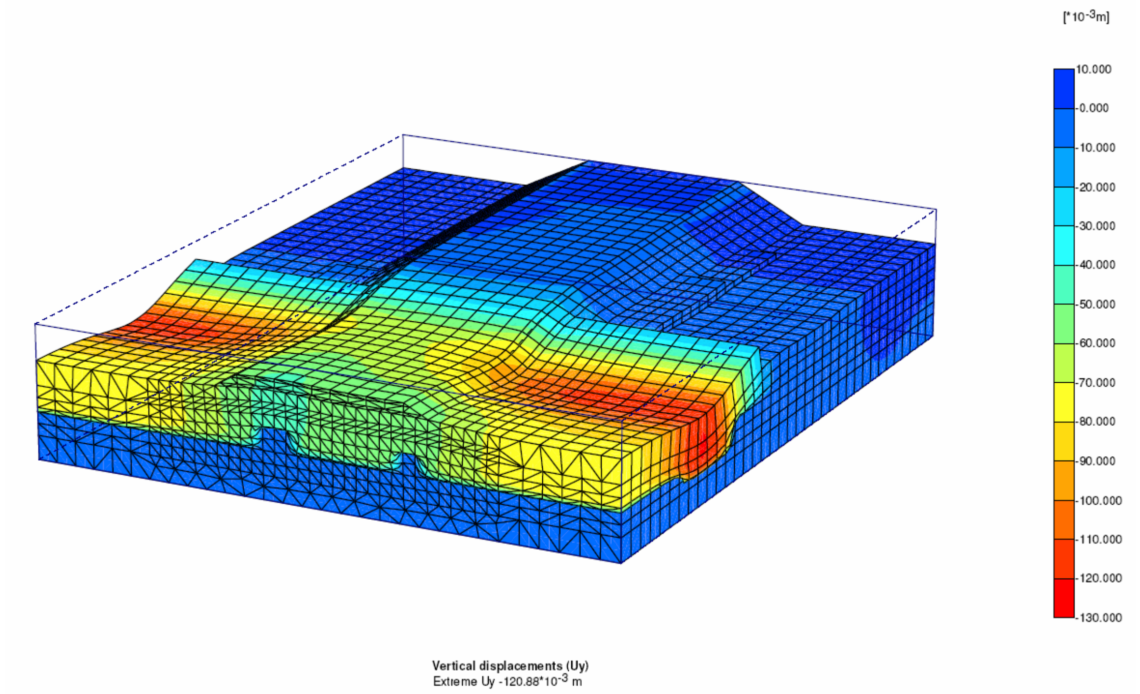


Figure 7: 3D finite element mesh for Case 2.

Case 2 – Columns of rigid inclusions up to more than half of the untreated landfill thickness are randomly added to the above model to simulate the non-uniformity and heterogeneity of the landfill (see Figure 6). The 3D finite element mesh including these rigid blocks is shown in Figure 7. Greater differential settlement is predicted for this case.

For Case 1, the predicted pavement surface level after settlement along and across the alignment is presented in Figure 8. The maximum instantaneous change in grade is estimated to be 0.22% in the longitudinal direction and 0.19% in the transverse direction. For a design speed limit of 80 km/hr, a maximum change in grade in the order of 0.6% is considered acceptable.

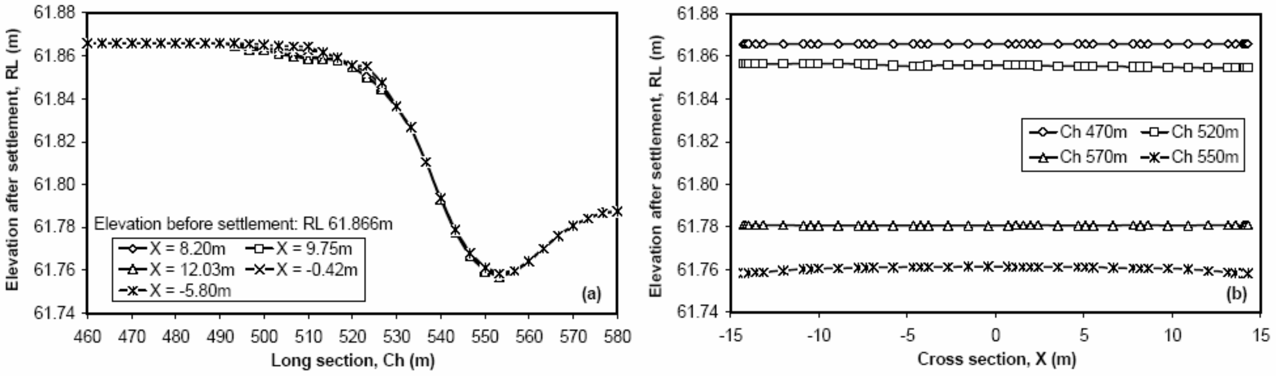


Figure 8: Case 1 – calculated surface level along the long section (a) and cross section (b).

For Case 2, the predicted pavement surface level after settlement along and across the alignment is presented in Figure 9. The maximum instantaneous change in grade is estimated to be 0.26% and 0.20% in the longitudinal and transverse direction respectively and is considered acceptable. These numerical results demonstrate the anticipated differential settlement can be effectively controlled by the implemented ground treatment.

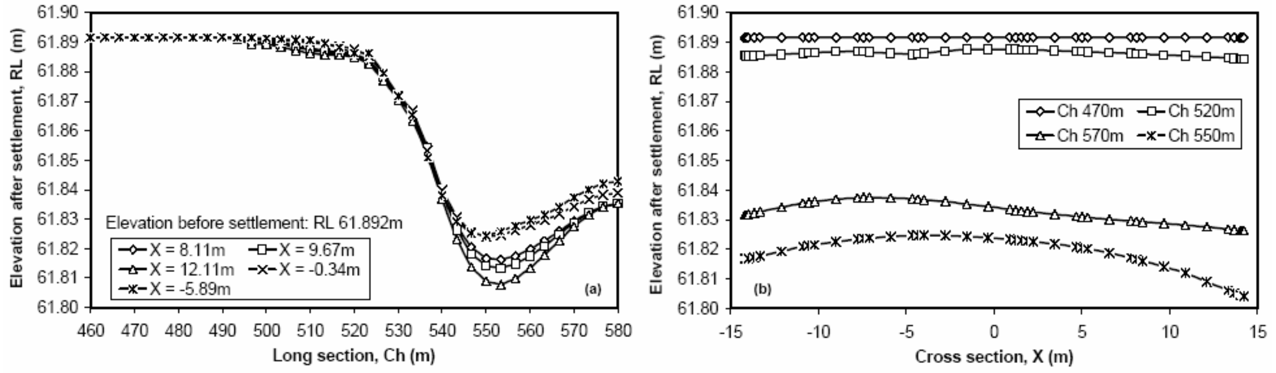


Figure 9: Case 2 – calculated surface level along the long section (a) and cross section (b).

6 CONSTRUCTION PERFORMANCE

Pressuremeter tests were performed before and after the DC/DR treatment. These were carried out within and outside the stone columns in order to observe the stiffness improvement of the landfill. It was found that prior to the treatment, the mean recorded limit pressure Pl was in the range of 6 bars and 13.6 bars. After treatment, the mean Pl was about 18 bars within the stone columns, 11-22 bars in the upper 6 m of landfill outside the stone columns and 12-17.5 bars below 6 m depth. Substantial stiffness improvement has been achieved within the landfill due to the influence of dynamic compaction.

Three settlement plates SPT1 (Ch 520 m), SPT2 (Ch 570 m) and SPT3 (Ch 620 m) along the centre line of the alignment were installed after the DC/DR treatment and prior to filling. Settlement data were obtained during preloading for further assessment of performance of the treated landfill. Three distinct filling stages were recorded: Stage 1 – filling to below top of select material zone (SMZ), Stage 2 – filling to top of SMZ, and Stage 3 – filling to 2 m above top of SMZ. The measured settlements with respect to the various filling stages are presented in Figure 10.

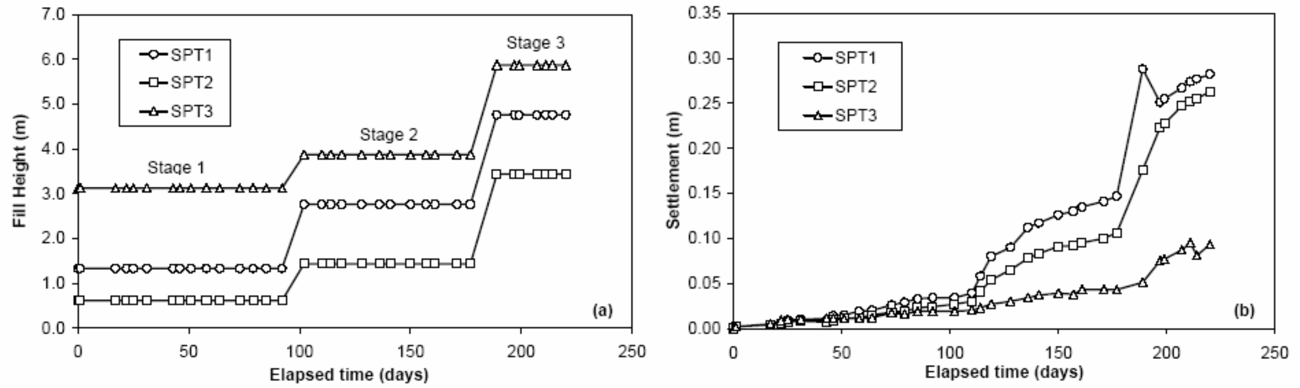


Figure 10: Measured fill height (a) and settlement (b).

7 BACK ANALYSIS AND PREDICTION

7.1 MONITORING AND OBSERVATIONAL PROCEDURE

To date, there has been no established theoretical method developed for the prediction of landfill settlement. However, some empirical approaches have been developed to predict the long-term landfill settlement based on the monitored landfill settlement data. These methods largely rely on curve fitting and appear to be able to reasonably predict the long-term landfill settlement.

An empirical approach approximating the time dependent settlement behaviour of the landfill using a hyperbolic function has been adopted to predict the long-term settlement of the landfill. This approach was presented in the technical paper by Ling *et al.*, 1998. The authors used nine sets of settlement measurements from three landfills to examine the accuracy of the hyperbolic function and concluded that the hyperbolic function provided a good agreement between measured and fitted values.

The correlation for the obtained monitoring data achieved by the hyperbolic function was superior to that achieved by more conventional log t and power functions. Furthermore, the hyperbolic function offered the flexibility to be started at any time of interest, rendering it most useful for landfill settlement measured under changing load conditions.

7.2 HYPERBOLIC FUNCTION

The following hyperbolic expression relating settlement and time was presented in the paper by Ling *et al.* (1998):

$$S = \frac{t}{1/\rho_0 + t/S_{ult}} \tag{1}$$

where t = difference between time of interest, t_i, and time of start of measurement, t_0, (i.e., $t = t_i - t_0$); S = difference between settlement, S_i, at time t_i and that measured, S_0, at time t_0 (i.e., $S = S_i - S_0$); ρ_0 = initial rate of settlement; and S_{ult} = ultimate settlement as time approaches infinity.

The parameter S_{ult} was determined by transforming Equation (1) through t/S versus t relationships and conducting a linear regression analysis:

$$\frac{t}{S} = \frac{1}{\rho_0} + \frac{t}{S_{ult}} \tag{2}$$

where the reciprocal of the slope gives S_{ult}. The paper by Ling *et al.* (1998) suggested that the final settlement S_{final} of the landfill would likely be 80% to 95% of the ultimate settlement, i.e. $S_{final} = 0.80$ to $0.95\ S_{ult}$.

It was noted in the paper of Ling *et al.* (1998) that no actual ultimate settlement results were available for comparison with the values predicted by the hyperbolic function, and the curve-fitting exercise for any site should be refined as additional data became available.

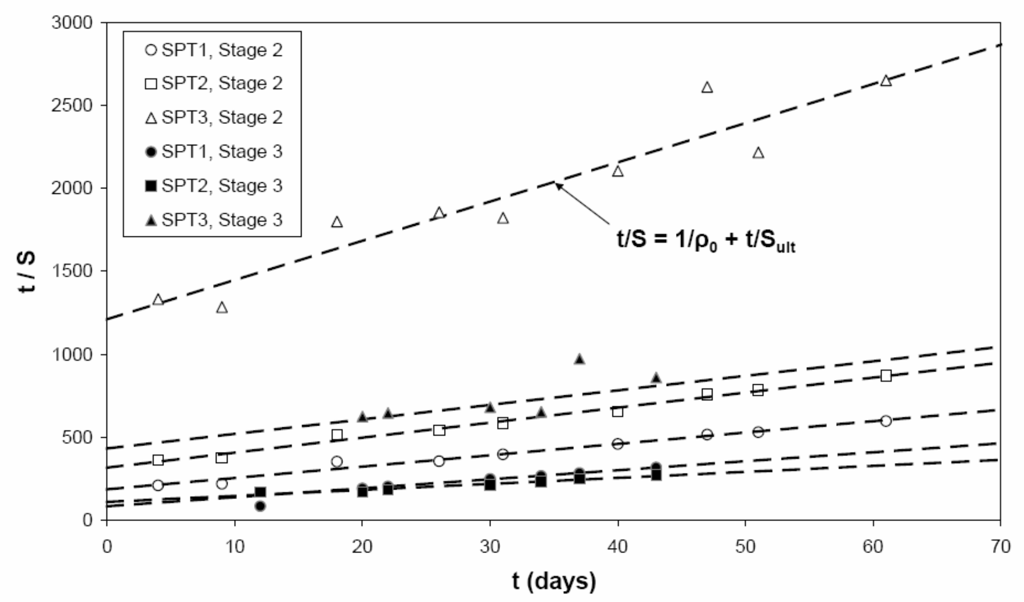


Figure 11: Curve fitting of settlement data based on a hyperbolic function.

7.3 ANALYSIS RESULTS

The settlement plate data was analysed according to the described approach. Due to the different loading conditions, the data for each plate was analysed as three separate sets, i.e., one set of data for before building up to the top of the SMZ, one set of data for after building up to the top of SMZ, and the third set of data for under the 2 m of surcharge loading (i.e. under the 2 m of additional fill placed on top of the SMZ). In total, nine sets of settlement data were analysed.

It was found that for the data collected prior to the build up to the top of the SMZ (Stage 1), the correlation between the data and the hyperbolic function was poor. However, the data measured after the embankment was built up to the top of SMZ (Stage 2) and subsequently the data measured under the surcharge (Stage 3) fitted very well with the hyperbolic function. For the graphs presenting the measured data and the fitted hyperbolic function refer to Figure 11 (for Stages 2 and 3 only).

The predicted final settlement, taken as 95% of S_{ult}, with and without surcharge loading using the above approach is summarised in Table 1. The remaining settlement is the difference between the predicted final settlement and the current measured settlement at the end of each loading stage.

Table 1 shows that when the landfill is under the surcharge load (i.e. the 2 m high fill above the pavement surface level), the predicted long-term settlement is up to 106 mm, and is greater than the predicted settlement where the landfill is subjected to preload up to the top of SMZ. This leads to the conclusion that after the surcharge is removed, the remaining long-term settlement will be below the predicted long-term settlement for when the landfill is under the surcharge load.

The 2 m of additional fill placed on top of the SMZ will be removed to bring the finish level of the pavement back down to its design level. It is envisaged that after the removal of this 2 m of surcharge, the remaining settlement of the pavement will not exceed 100 mm over the next ten years.

Table 1: Summary of predicted settlement based on the hyperbolic function.

From Monitoring Data		**Predicted Final Settlement (mm)**	**Settlement Occurred To Date† (mm)**	**Remaining Settlement (mm)**
SPT01	Without surcharge	138	102	36
	With surcharge	174	135	39
SPT02	Without surcharge	105	70	35
	With surcharge	263	157	106
SPT03	Without surcharge	40	23	17
	With surcharge	108	50	58

†Taken to be the difference in settlement magnitude between the start and the end of each loading stage.

8 CONCLUSIONS

Stone columns based on the dynamic compaction (DC) and dynamic replacement (DR) techniques have been used to support an onload/offload ramp of the Westlink M7 constructed over an existing municipal landfill. The improvement of the landfill area after treatment was confirmed by pressuremeter testing. Due to the lack of established theories, prediction of long-term settlement caused by biological degradation has been made based on past experience. Differential settlement that could arise from the varying landfill conditions was overcome by the DC/DR treatment in conjunction with an overlying bridging layer. The effectiveness of the landfill treatment was investigated by 3D finite element modelling which confirmed the required differential settlement criterion was met. As a precautionary measure, preloading and surcharging over the treated landfill were carried out to further iron out potentially undesirable settlement. The measured settlement data during preloading and surcharging was back analysed based on a hyperbolic function. This approach allowed further prediction of long-term landfill settlement, which confirmed the estimate based on past experience.

9 REFERENCES

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Photo 1: Pressuremeter.

Photo 2: Pressuremeter testing.

Photo 3: Dynamic compaction (DC).

Photo 4: DC prints.

Photo 5: Dynamic replacement (DR).

Photo 6: DC hole.

Photo 7: DC hole.

Photo 8: Backfilling of DC hole.