# Ground Improvement of Municipal Landfill Using Stone Columns

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## ABSTRACT

Westlink M7 was one of Australia's largest urban road projects and 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 12-13m. To control settlement of the road built over the landfill, a series of stone columns were installed in the landfill, using the dynamic compaction (DC) and dynamic replacement (DR) techniques. The stone columns were extended to about 6-7m depth founding on compacted waste material. Due to the complex composition and variability of the waste material, it was difficult to predict the long term performance of the landfill. Worldwide research in this area has continued over the last few decades and some information has become available for the design of landfill treatment. Detailed 3-dimentional numerical modelling was carried out to simulate the expected settlement of the landfill and predict the impact of settlement on the pavement. In-situ tests were carried out in the landfill before and after the DC/DR treatment to demonstrate improvement of landfill properties. The treated landfill was also preloaded for a period of time and settlement monitored to confirm effect of the treatment. Prediction of long term settlement of the landfill was also performed based on a hyperbolic function.

## 1 INTRODUCTION

A section of an onload/offload ramp at an interchange of the newly developed Westlink M7 (M7) in Sydney Australia was constructed over an existing landfill area. This section of the ramp was about 200m long and 30m wide. The fill height of the ramp ranged between 2m and 7m, whilst the existing landfill thickness was up to 12-13m. The landfill was understood to comprise mainly municipal solid waste and was last capped when the capacity was reached in 1994, 10 years before the development of M7.

Pavement constructed over landfill may experience large and ongoing 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 are present, 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 had been considered for this site 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 the stone column treatment using the dynamic compaction (DC) and dynamic replacement (DR) techniques would be most effective. Pressuremeter testing was undertaken before and after the DC/DR treatment to confirm improvement of ground properties. Three-dimensional numerical modelling was carried out to investigate the effectiveness of the treatment. Preloading of the DC/DR treated area with settlement monitored was conducted to allow observation of the landfill performance. The settlement data was further back analysed based on a hyperbolic function for prediction of long term settlement.

## 2 SETTLEMENT OF LANDFILL

Several boreholes were drilled in the landfill area to investigate the characteristics and extent of the landfill. The subsurface conditions encountered generally included a thin clay capping layer of about 0.5m thick at surface overlying the landfill of varying thicknesses up to 12-13m 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. The landfill was underlain by weathered shale and siltstone. Groundwater was not observed in the boreholes. The long and typical cross sections of the landfill are shown in Figure 1. It is noted that the sloping pavement surface has been levelled for ease of analysis and all the other layer levels have been adjusted relative to the pavement level.

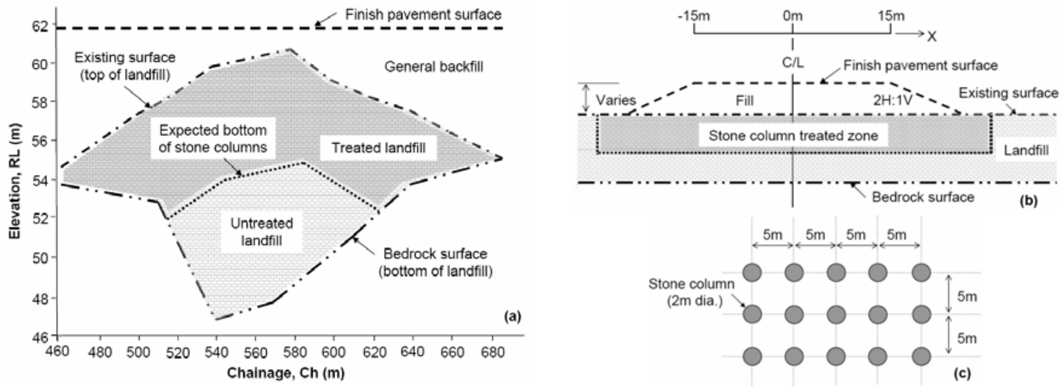


Figure 1: Long section (a), typical cross section (b), and stone column arrangement (c)

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. That is, the voids within the landfill are reduced resulting from 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 the soil mechanics theory may apply for the prediction of the mechanical compression of the landfill, provided that the material properties are correctly assumed.

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 are dependent on the moisture level, organic content, waste composition, density, temperature, age, etc. It is obvious that the nature of the waste material is highly heterogeneous and its engineering properties are hard to determine.

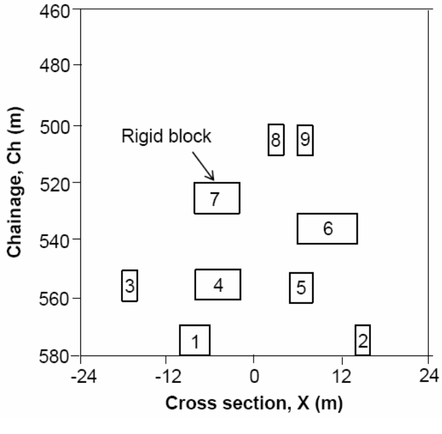
Literature on this issue has reported that landfill could settle up to 20% to 40% of its thickness and the settlement caused by biodegradation could contribute to half of this settlement. It is expected that the mechanical settlement of the landfill could occur over a relatively short period of time 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 cessation of landfill activities (Wall and Zeiss, 1995).

## 3 GROUND TREATMENT

To control landfill settlement, a combination of dynamic compaction (DC) and dynamic replacement (DR), based on the Menard/Austress Freyssinet (M/AF) techniques, was chosen. The dynamic compaction method involves dropping a heavy concrete block or steel plate from a height onto the landfill. This effectively crushes the landfill material with large voids (mechanical compression) and has an influence depth up to 4-5m depending on the weight of the block and the height of drop. The dynamic replacement technique involves ramming a series of stone columns into the landfill using a steel block. The stone columns are expected to extend to 6-7m depth and found on compacted waste material. The influence depth of compaction of the landfill with the DR treatment is expected to be up to 10m. With landfill being further compacted, the long term settlement is expected to be reduced. However, some long term settlement will still occur, 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 0.5m thick working platform consisting of compacted sandstone over the landfill. The stone columns were of 2m diameter each and were constructed at 5m c/c spacing on a square grid (see Figure 1 for stone column arrangement). 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 13.5t pounder (1.2mx1.2mx2.5m) dropped from a height up to 18m and filling the prints with rock. The last phase was done using a 13.5t ironing plate (2.4mx2.4mx0.625m) dropped from a height of 10-15m. 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.

M/AF, based on their experience on sanitary landfill in Germany and France, suggested that a long term biological settlement of DC/DR treated landfill was in the order of 2% of the total landfill thickness. This approximation is applicable for fills with an organic content of 25% or less, a mineral content of 50% or more, and cessation of landfill activity by no less than 10 years. M/AF further suggested that as the pressuremeter test results indicated the organic content of the M7 landfill being less than 10%, a reduced factor of 1% was considered more realistic for the prediction of long term landfill settlement. As a result, for a maximum landfill thickness of 12-13m the predicted long term settlement was in the order of 120-130 mm.



| 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 2: Landfill in plan with randomly assumed rigid inclusions

## 4 NUMERICAL MODELLING

Due to the heterogeneity and variability of the landfill, long term differential settlement is likely to occur which could affect the performance of the pavement. A numerical approach, based on the 3D finite element method using PLAXIS 3D Tunnel (PLAXIS BV, V1.0, 2000), was adopted to investigate the effect of differential settlement on the pavement. The numerical modelling was carried out for two cases: Case 1 – The landfill was assumed to consist of homogeneous and uniform material for each of the treated (stone column) and untreated zones, with different stiffnesses, and was forced to settle up to approximately 1% of the total landfill thickness by artificially increasing the material unit weights. Case 2 – Columns of rigid inclusions up to more than half of the untreated landfill thickness from the base of the landfill were randomly added to the Case 1 model to simulate the non-uniformity and heterogeneity of the landfill (see Figure 2). Due to the limitation of the computer program, only one portion of the ramp built on the landfill was simulated, i.e. Ch 460m to Ch 580m, and the sloping layer surfaces were assumed to be stepped.

For Case 1, the predicted pavement surface level after settlement along and across the alignment is presented in Figure 3. 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. For Case 2, the predicted pavement surface level after settlement along and across the alignment is presented in Figure 4. The maximum instantaneous change in grade was estimated to be 0.26% and 0.20% in the longitudinal and transverse direction respectively and was considered acceptable. These numerical results demonstrate the anticipated differential settlement can be effectively controlled by the implemented ground treatment.

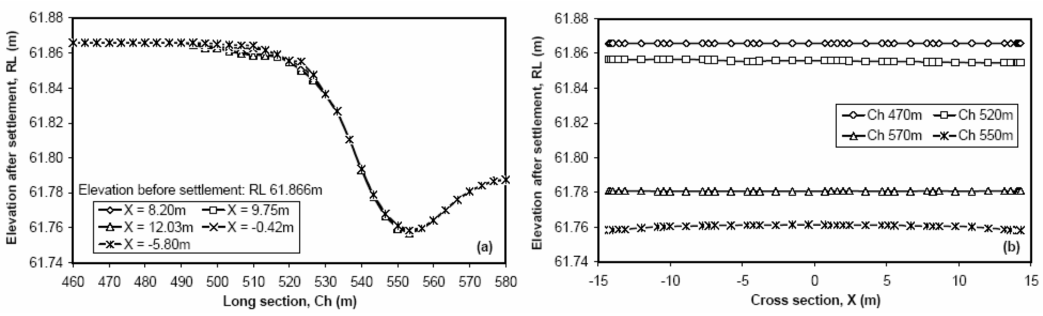


Figure 3: Case 1 – calculated surface level along the long section (a) and cross section (b)

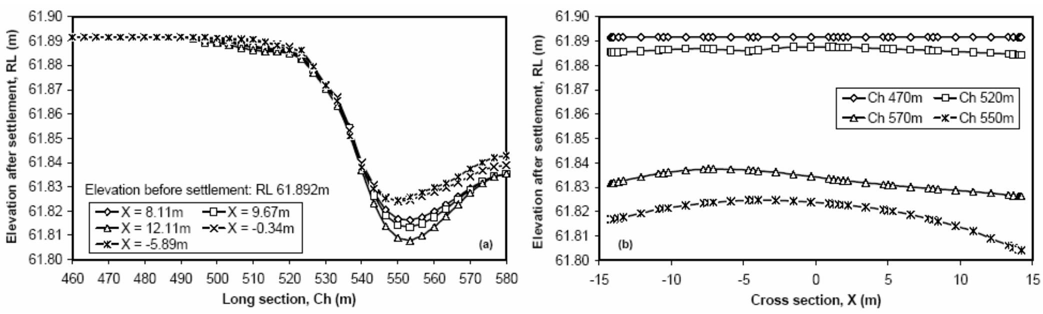


Figure 4: Case 2 – calculated surface level along the long section (a) and cross section (b)

## 5 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, and 11-22 bars in the upper 6m of landfill outside the stone columns and 12-17.5 bars below 6m depth. Substantial stiffness improvement has been achieved within the landfill due to the influence of dynamic compaction.

Three settlement plates SPT1 (Ch 520m), SPT2 (Ch 570m) and SPT3 (Ch 620m) 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 2m above top of SMZ. The measured settlements with respect to the various filling stages are presented in Figure 5.

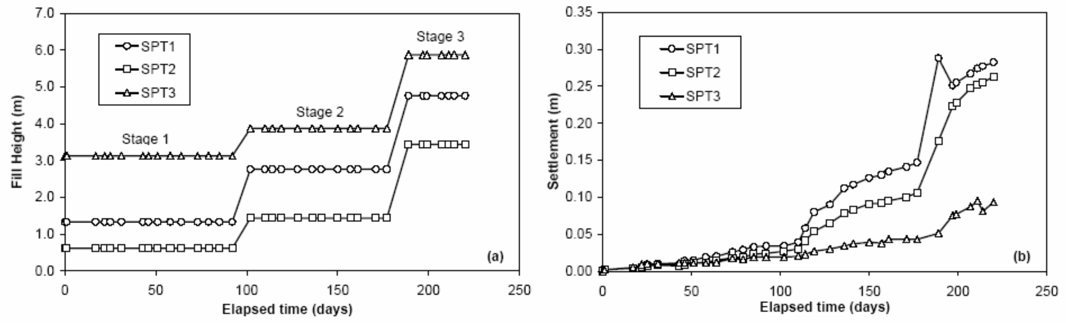


Figure 5: Measured fill height (a) and settlement (b)

## 6 BACK ANALYSIS AND PREDICTION

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 settlement data. These methods largely rely on curve fitting and appear to be able to reasonably predict the long term settlement.

An empirical approach approximating the time dependent settlement behaviour of the landfill using a hyperbolic function was adopted to predict the long term settlement of the landfill (Ling et al., 1998). The correlation achieved by the hyperbolic function was far superior to that achieved by more conventional logarithmic and power functions. Furthermore, the hyperbolic function offered the flexibility to start at any time of interest, rendering it most useful for landfill settlement measured under changing load conditions.

The hyperbolic expression relating settlement and time can be expressed as, $S=t/(1/\rho_0+t/S_{ult})$, 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. $S=S_i-S_0$); $\rho_0$ = initial rate of settlement; and $S_{ult}$ = ultimate settlement as time approaches infinity. The parameter $S_{ult}$ was determined by transforming the above equation through t/S versus t relationships and conducting a linear regression analysis, i.e. $t/S=1/\rho_0+t/S_{ult}$, 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 $S_{ult}$.

The settlement plate data was analysed according to the above described approach for each of the loading stages. 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 a further 2m 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 6 (for Stages 2 and 3 only).

Based on the fitted lines, the $S_{ult}$ values can be calculated for each of the correlations. The SPT3/Stage 2 data, as shown on Figure 6, appears to deviate from all the other data sets. When this data (SPT3/Stage 2) is excluded, The predicted final settlements, taken as 95% of $S_{ult}$, were calculated to be between 100mm and 260mm. The settlement occurred by the end of each loading stage had been between 50 and 160mm. As a result, it can be estimated that the remaining settlement taken as the difference between the predicted final settlement and the measured settlement at the end of each loading stage is in the range of 50mm to 100mm. These estimated long term settlements are consistent with that estimated as described earlier based on the past experience, i.e. 1% of landfill thickness.

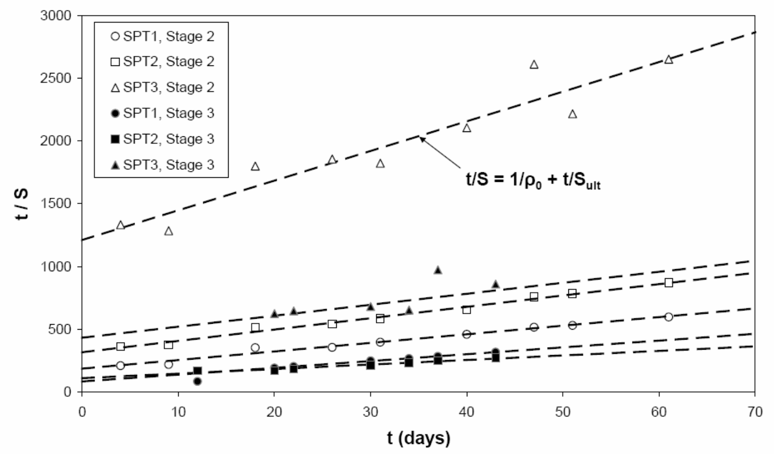


Figure 6: Curve fitting of settlement data based on a hyperbolic function

## 7 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 lack of establish 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.

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