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The effect of impact roller compaction on closed landfill settlements

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ABSTRACT: Nowadays, by developing cities and urban areas, closed landfills may be located in urban areas; and sometimes it is necessary to use these areas for reconstruction. One of the most important concerns of reusing landfill areas is primary and creep settlements of landfills. Accordingly, it is necessary to improve landfills by an appropriate method such as preloading, which needs more time compared to other methods of improvements. In this paper, the effect of applying impact roller compaction (IRC) method on reducing the preloading time is investigated numerically using Plaxis 2D, a finite element based software. The settlements of one assumed landfill in case of just applying preloading for 3 and 6 months are calculated and compared to the results for the case in which IRC is used. The numerical results indicate that applying impact roller compaction method can decrease the time of preloading from 6 to 3 months.

1 INTRODUCTION

In recent years, the population of the cities have considerably increased, which leads to cities developments and increasing the rate of "municipal solid waste" (MSW) production. Landfilling is one of the most common methods of managing MSW. On the other hand, there are some closed landfills in urban areas, while reusing them is highly important for reconstruction, as a result of land scarcity. Since control of settlement is one of the most crucial factors in super structures on landfills, improving engineering properties of landfill sites are essential. There are a variety of methods contributing to soil improvement including, surface and deep compaction, stone columns, cement grouting, chemical stabilization, and consolidation through preloading (Boazza & van Impe 1997). However, according to environmental protection rules, the landfill components should be restrained and confined. Therefore, using some of these methods such as "dynamic compaction" (DC) cannot be a practical alternative of improvement in some cases. As an example, in landfills in which geosynthetic clay liner (GCL) is used as a hydraulic barrier to landfill leachate, DC may not be an appropriate method of improvement because of possible damage to this layer. Preloading is one of the most suitable and safe methods for improving landfills materials, in which a temporary surcharge is placed on a loose or soft soil, aiming to minimize future settlements (Manassero et al. 1996). Since preloading is considerably time consuming in some projects, vertical drain is a method of decreasing the time of applying surcharge. However, vertical drains cannot be used in landfills because they provide a route in which the hazardous substance can be released (Mitchell & van Court 1992). That being so, it is essential to look for other methods to reduce the preloading time without any damage to the cover system. Impact roller compaction can be one of the alternatives.

Concept of using impact roller compaction system was first introduced in South Africa (Munfakh 2002), and it is applied today for compacting various materials with less dependence to moisture content (Pinnard 1999, Avalle 2004b). The main principle of impact roller compaction is reducing the air voids volumes by applying impact rolled mass to densify existing fills, raised or impact lands or landfills, mine haul roads, etc. Figure 1 shows a 3-sided impact roller compaction machine. In general, the weight of the rolling mass is between 8 and 16 tonnes and the number of passes are from 3 to 5. Practical speed of compacting is 8 to 11 km/hr.

There are some case studies in which the impact roller compaction method has been used for improving landfills upper layers up to 2 m (Avalle & McKenzie 2005, Avalle & Grounds 2004). In these case studies, upper layers of landfills were compacted and different types of in-situ geotechnical tests were performed before and after compaction, including Continuous Surface Wave (CSWS), Dynamic Cone Penetration (DCP), Cone Penetrometer Test (CPT), and field density tests. According to the results of these tests, it can easily be concluded that the ground densified up to maximum 2 m and some mechanical properties of soil increased, even doubled in many cases.

Figure 1. Monitoring and instrumentation tools (courtesy of ANRO Impact Compaction Pty Ltd, source: http://www.anro-compaction.co.za/threesided.html)

The purpose of this study is to evaluate the effect of applying impact roller compaction on decreasing the time of preloading for reducing the closed landfill settlements. In this regard, a numerical model has been developed and analyzed using Plaxis 2D software. The theory of settlement, method and material of modeling are discussed in the following sections.

2 SETTLEMENT ANALYSIS

There are a diversity of concerns related to landfills, including control of the settlement. According to mechanical properties of embedded waste materials in landfills, the settlements are relatively high and can lead to fractures in the structure of landfills such as damages to the cover layer and leachate drainage system (Wu et al. 2017). Moreover, extra settlement increases the potential of instability (Qian et al. 2011, Jang 2013). As a result, settlement control is not only crucial in the landfill body stability, but also it should be limited intended to avoid any damages to the superstructures. There are many investigations associated with the theory and the methods to evaluate the primary and long-term settlements in landfills (Ling et al. 1998, Sowers 1973, Dodt et al. 1987).

2.1. Theory of settlement

Landfill settlement comprises immediate, primary and secondary settlements. Immediate settlement is load-related, resulting from the compression of air voids and the deformation of readily compressible waste “particles”, which occurs very quickly. Primary compression is because of consolidation and occurs when water is expelled and the waste skeleton compresses. Secondary settlement is a long-term phenomenon, related to mechanical creep (including raveling), and biodegradation. In this study, it has been assumed that waste materials are non-putrescible with no biodegradation settlement, thus the settlement due to biodegradation of putrescible materials can be disregarded. The total settlement is the sum of primary and secondary consolidation settlement. Primary settlement can be calculated based on Equation 1:

$$S_p = C_R H_i \log(\frac{P_0 + \Delta P}{P_0}) \quad where\ C_R = \frac{C_c}{1+e_0} \qquad (1)$$

where S_p= primary settlement; H_i= height of landfill layer; C_c= primary compression index; e_0= the initial voids ratio of waste; P_0= existing pressure at midlevel of layer; and ΔP = increase in overburden pressure acting at midlevel of layer.

Secondary (long-term) settlement can be estimated as follows:

$$S_c = C_{\alpha\varepsilon} H_P \log(\frac{t}{t_P}) \quad where\ C_{\alpha\varepsilon} = \frac{C_\alpha}{1+e_P} \qquad (2)$$

where S_c = secondary settlement; H_p= height of landfill after primary compression; C_α= secondary compression index; e_p= void ratio after primary compression; t is the time; t_p= time which is necessary for primary compression. According to Sharma & De (2007), the primary settlement of municipal solid waste normally occurs within the first four months after applying the load. As a result, in this research by placing extra surcharge, the primary settlement occurs and creep settlement is the main concern associated with landfill redevelopment.

2.2. Numerical model

In this study, the settlement of a typical landfill has been estimated, using Plaxis 2D, which is a powerful and user-friendly finite element package, and can be used for two-dimensional deformation in geotechnical engineering related structures.

The geometry of landfill, which has been considered for the numerical modeling in this research is shown in Figure 2. The soil layer descriptions, shown in this section by number labels, have been illustrated in Table 1. In order to determine settlement parameters (C_R and $C_{\alpha\varepsilon}$) in the absence of field and laboratory data, the proposed values based on different studies have been presented in Table 1 and Table 2, respectively.

Table 1. Summary of C_R Published in literatures (Bareither at al. 2011)

Reference	Waste Description	Degradable Organics (%)	C_R
Gabr & Valero (1995)	15-30 years old waste	2	0.156-0.2
Landva et al. (2000)	5 years old waste	47	0.157
Landva et al. (2000)	Prepared waste	9-13	0.184-0.205
Landva et al. (2000)	Mixtures of 2 year and 5 year old waste	13	0.172
Vilar & Carvalho (2004)	15 years old waste	14	0.222-0.325

Table 2. Summary of $C_{\alpha\varepsilon}$ Published in literatures

Reference	Waste Description	Degradable Organics (%)	$C_{\alpha\varepsilon}$
Rao et al. (1977)	15-30 years	2	0.015-0.023
Hyun Il et al. (2011)	10 years old (young)	0.05	0.001
Bareither et al. (2012)	Low degraded (LD) Medium degraded (MD) Highly degraded (HD)	-	0.021-0.03 0.033-0.043 0.029-0.036

As it is obvious from the figure, the section is comprised of an embankment, which is supposed to bear super structure loads. This section shows that waste materials have different height which is averagely 7 m and most part of the embankment is located over the landfill with maximum depth of 14m. In order to evaluate the effect of impact roller compaction, the geotechnical parameters of the 2-m upper layer of landfills have increased. In order to improve landfill materials, extra surcharge up to 1 m applied for about 3 and 6 months and then removed, which is shown in Figure 2 by dash lines.

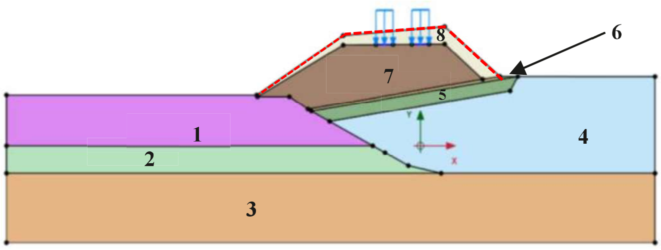


Figure 2. A typical cross section of the proposed landfill

The "Mohr-Coulomb" model has been considered to simulate the behaviour of subgrade soil and embankment, whereas the "Soft Soil Creep" model is employed to exhibit the landfill materials. Since the waste material in this research has been assumed non-putrescible with no biodegradation and no leachate circulation, the SSC (Soft Soil Creep) model is the most appropriate model in Plaxis in order to calculate creep settlement. This model is very common for soft soils such as normally consolidated clays, peats and wastes and this model in PLAXIS computes the secondary compression. The SSC model is and extension of Soft Soil (SS) model based on Cam Clay model which considers Mohr Coulomb failure criterion. In SS model, stress state would fall outside the current cap and the cap expands instantaneously by increasing the load, while in SSC model this expanding requires time (Waterman & Broere, 2004).

Moreover, the super structure load has been considered approximately 100 kPa. The geotechnical and design parameters of different soil and landfill layers are presented in Table 3.

Table 3. Geotechnical and design parameters

Material Type*	Layer No	γ (kN/m^3)	C (kPa)	$\emptyset'$(°)	$C_{\alpha\varepsilon}$	C_R
Alluvium Sand	1	20	0	33	-	-
Medium Strength Rock	2	22	10	30	-	-
High Strength Rock	3	22	200	30	-	-
Landfill (treated)	4	15	0	30	0.0175	0.075
RC Improved Layer	5	15	0	30	0.01	0.05
Cover Layer	6	16	10	25	-	-
Embankment	7	21	5	30	-	-
Upper Fill (Extra surcharge)	8	20	2	33	-	-
Landfill (existing/unimproved)	-	13.6	0	30	0.02	0.15

*γ: unit weight, C: effective cohesion, $\emptyset'$: effective friction angle

3 RESULTS AND DISCUSSIONS

The long-term settlement of the proposed close landfill has been analyzed employing Plaxis 2D. The results of these analyses are shown in Figure 3. As can be seen in this figure, the vertical axis illustrates the additional settlements caused by superstructure load. Referring to Figure 3, it can easily be concluded that by decreasing surcharge time from 6 months to 3 months, landfill settlement increased noticeably after load application for a long period.

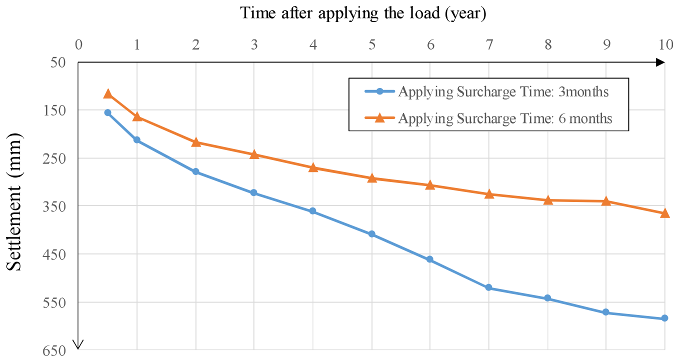
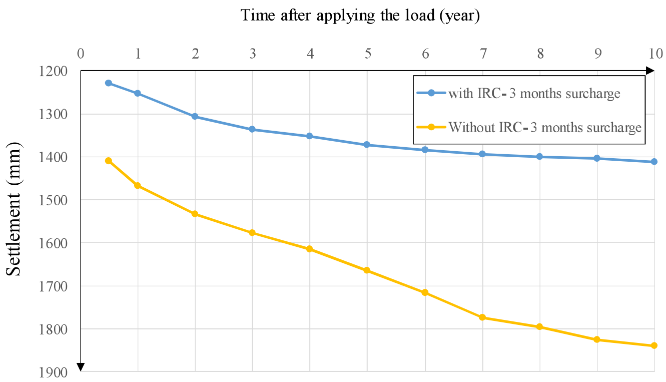
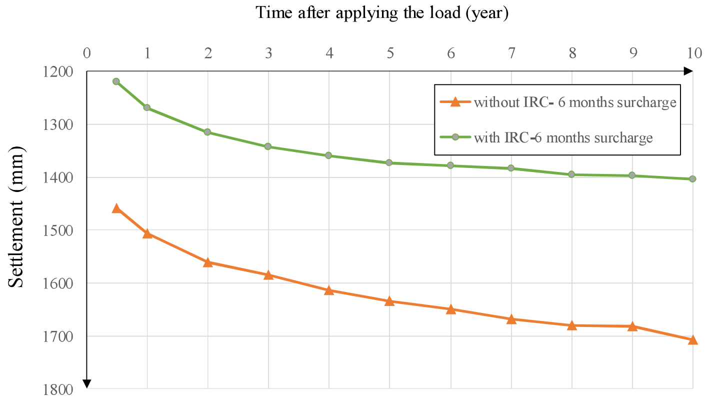


Figure 3. Settlement versus time by using preloading method

Landfill settlement with or without using IRC method by applying 3 and 6 months surcharge were investigated. The results are presented in Figure 4. According to this figure, there is a considerable decrease (about 300 mm in the first 10 years of applying superstructure load) in landfill settlements, using IRC method in a constant applying surcharge time, such as 3 or 6 months. A comparison between the results, depicted in Figures 4-a and 4-b, indicates that settlements obtained by using IRC method and applying 3 months surcharge is significantly less than the settlements in case of 6 months surcharge, without using IRC, as shown in Figure 5. As a result of employing IRC method, it is possible to decrease the time of applying surcharge in preloading method for landfill site improvement.



a) Preloading time: 3 months



b) Preloading time: 6 months

Figure 4. Settlement versus time with and without using impact roller compaction (IRC) method

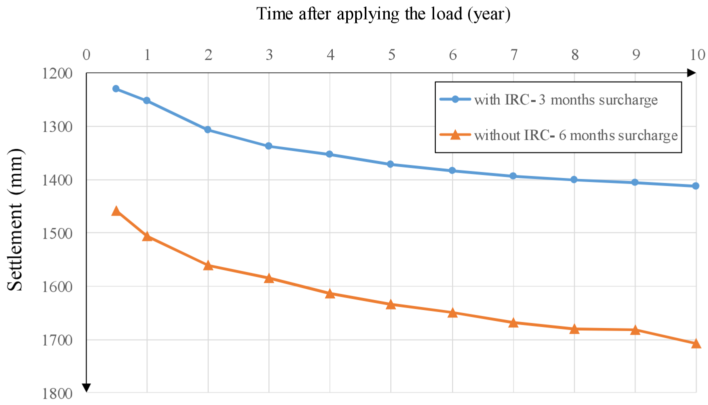


Figure 5. Evaluation of using IRC method in decreasing the landfill settlement

4 CONCLUSION

The impact roller compaction (IRC) method is one of the cost effective and efficient methods for compaction of superficial layers of landfills. This method is a non-intrusive method, which causes the least damage to the liner or cover systems. On the other hand, this method can be used for improvement of layers up to 2 m. Therefore, for deeper improvements it is necessary to use this method with other non-intrusive methods of improvement such as preloading. This research evaluated the effect of using IRC with preloading method in order to control landfill settlements through numerical analysis. According to the results, comparing the settlements obtained from applying only preloading process with those obtained from using a combined method of IRC and preloading, it can be concluded that by applying IRC method and improving 2 m of the upper layer of landfill, the time of preloading can significantly be reduced. Since, improving the upper 2 m of landfill using IRC could be useful for supporting lightly loaded structures with small footing footprints and reducing potential differential settlement due to the bridging layer effect, applying only IRC method is not efficient deep improvement and does not address secondary settlement. However, based on the results obtained from this research and literature, by compacting 2m upper layer, void ratio decreases and the creep settlement parameters improved significantly which can reduce long-term settlement of waste material in preloading method. It should be mentioned that further study is also required to investigate the effect of IRC method in reducing preloading time with putrescible waste material considering decomposition settlement.

Moreover, based on the brief study conducted by the authors about the effect of IRC method in order to decrease the height of surcharge, it seems that IRC method can also be used for reducing the height of surcharge in situations where providing surcharge material is limited. This issue will be investigated in future studies.

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