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Evaluation of Determinant Parameters for Thickening the Engineered Fills Layers

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Abstract- Roller Compaction is one of the most common methods to modify the soil behaviour for road embankments, railway tracks and earth dams. Using compaction approach for achievement optimized engineered fill, the major factor is thickening of soil lifts, which has always been considered by relevant engineers. It leads to reduce the project costs, timing and finally saving energy. In this study, effective parameters on determining the thickness of engineered embankments are explored and then a 2D numerical modelling is carried out in order to evaluate the effect of these parameters on the lifts thickness. The effects of subgrade conditions and roller energy were evaluated for a single layer embankment with four thicknesses of 150, 300, 450 and 600 mm. Four types of rollers, steel wheel, pneumatic tyred, sheepsfoot and vibratory steel wheel were modelled on the road cross section. According to the obtained results, increasing the subgrade stiffness that cause limited lift displacement, allows for an increase in the lift thickness. Increasing the applied energy can be led to upgrade relative density of the embankment layer. This is due to the increase in the effective depth of stress.

***Keywords*:** Fill lift thickening, roller compaction, soil density, subgrade stiffness, roller energy.

1. Introduction

In many projects such as roads, railway tracks and earth dams, embankments are considered as the main bearing body. So they should have special engineering properties and resistance against the applied loads. Embankments can be divided into two groups of engineered and non-engineered fills. Engineered fill is defined as fill which is selected, placed and compacted to an appropriate specification so that it will exhibit the required engineering behaviour.

Many embankments are consolidated and compacted under their weight. Generally gravelly fills settlement limit to about 2.5%, sandy fills settlement around 5% and settlement of clayey and fine-grained soils may reach about 10%. Settlement amount decreases over time but generally takes between 10 to 20 years. For coarse-grained fills, most displacement occurred in the first two years and after 5 years it will be very low (Eslami, 2011). Since natural soils usually haven't suitable engineering properties, they have to be improved. One of the most common treatment method of the soil behavior, is compaction. The thickness depending on soil type, lift situation, type of roller used and etc., will be different. The current specifications limit lift thickness to 250-300 mm for most soil conditions (Allen et al., 1998).

In recent years, the frequency of large-scale earthworks with high embankments has increased in line with the rising scale of construction projects and efficient implementation of such work is expected to lead to reduced construction costs and other economic effects as a result of early completion. So the determination of the appropriate lift thicknesses used in embankment construction operations has important economic and engineering implications in the design and construction of them, which has always been considered by relevant engineers. For example, small lift thicknesses may cause excessive construction costs while large lift thicknesses may reduce the compaction effectiveness and compromise the integrity of the embankment. On the other hand, according to the development of new rollers, improving the traditional ones, better understanding of soil behavior and etc., it would slow the process of projects.

In spite of promoting the new machines, significant changes haven't occurred in the conventional lift thicknesses. In other words it can be said that using these proposed thicknesses are restrictive and can't exhibit the capabilities of modern rollers.

2. Factors Affecting in Thickening

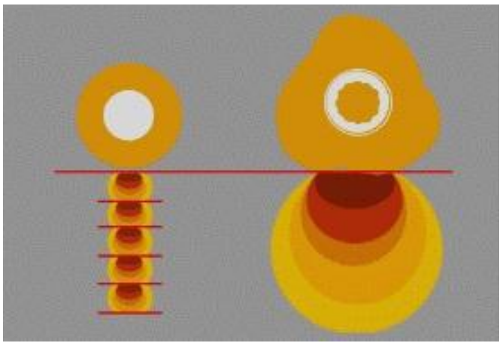
In order to embankment construction, soil layers spread with a defined thickness. Before placing each layer, the previous one must be compacted to the desired relative density. The thickness depending on soil type, lift situation, type of roller used and etc., will be different. Lift thickness for proper roller compaction indirectly affect the amount of pressure required for complete densification. This factor can be a function of soil type. For vibrating compaction of sand layer, pressure as much as 50 to 100 kPa is sufficient. While this is about 400 to 700 kPa for clay layer. Using vibration causes sand particles to move to the denser situation. But it will not happen in clay. So much pressure and shear stress required for compression (Look, 2007).

The current specifications limit lift thickness to 250-300 mm for road and railway track embankments. Because of more sensitivity of earth dams, allowable thickness is less while this can be greater by using coarser aggregates until it can be increased to about 1.5 m in rockfill dams.

Since equipment has become larger and heavier, is thought to impart greater energy to the subgrade during construction. Also, specialized High Energy Impact Roller (HEIC), as shown in Fig. 1, has been developed by a number of equipment manufacturers. HEIC specific energy inputs range from 10 to 28 kJ/m, with the weight and drop height of the drum modules ranging from 8 to 12 ton and 150 to 230 mm, respectively (Kelly, 2000). Using these specific properties can increase the single-lift thickness significantly.

Fig. 1. Three sided HEIC roller.

As shown in Fig. 2, HEIC rollers due to the large contact area and high contact pressure, have a wider influence zone in compared with other conventional rollers.



conventional rollers HEIC rollers

Fig. 2. Comparison of HEIC and conventional rollers influence zone.

Lift thickening project conducted in Hokkaido island in Japan showed that using the pneumatic tyred-roller, the single lift thickness can be increase from 300 mm to 450 mm for sandy and gravelly soil (with a gravel fraction of less than 60%). Whereas the number of passes limited to 5 to 8 (Adachi et al., 2008b).

The total number of passes required was compared between embankment construction with standard layer thickness and that improved with increased layer thickness. In the most common outcome (58%), one more pass was required in construction with increased layer thickness. If the results in which no difference (i.e., no increase) was seen are included, this rises to 70% (Adachi et al., 2008a).

Comparison between using the standard and increased lift thickness for a 90 cm high embankment, according to Fig. 3 shows the reduction in number of passes to achieve 85% compaction.

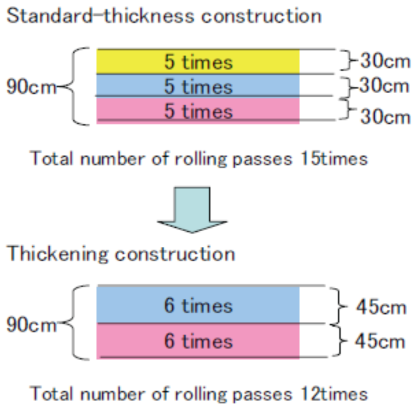


Fig. 3. Comparison of rolling pass totals in construction of a 90 cm high embankment (Adachi et al., 2008b).

According to density management by sand replacement, the layers that satisfy a compaction degree of 85% are as represented by the shaded portions in Fig. 4. The parts above these layers naturally have a compaction degree of 85% or higher. The areas where a compaction degree of 85%is satisfied are located between the surface and a depth of 100 mm (1/3 of the entire thickness) in standard-thickness construction, and between the surface and a depth of 400 mm (8/9 of the entire thickness) in thickening improvement. In other words, thickening improvement requires a higher degree of compaction than standard-thickness construction, and therefore improves the quality of the entire embankment (Adachi et al., 2008b).

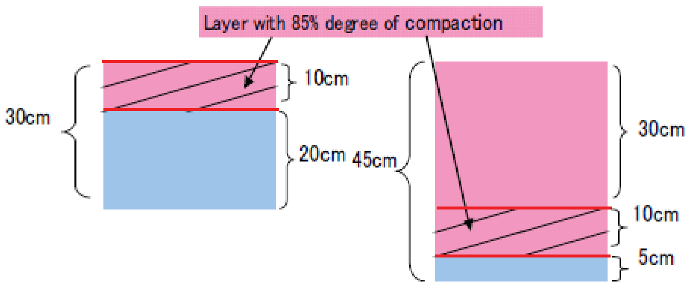


Fig. 4. Depth at which 85% compaction is achieved (Adachi et al., 2008b).

3. Modelling

To evaluate the parameters affecting displacement and density of the embankment layer, a 2D numerical modelling was conducted. The model developed uses a plane strain with elements of 15 nodes for accuracy purposes. The plane strain mode is chosen to simulate the roller in road cross section. The model includes placing a single layer of embankment on the homogenous layer of finite depth (subgrade).

The modelling is based on some assumptions e.g. the material of the embankment and subgrade are at optimum moisture content and underground water level is below the subgrade zone so that no excess pore pressure is exerted on the model as the result of additional loading.

Effect of subgrade conditions and roller energy were evaluated for four lift thicknesses of 150, 300, 450 and 600 mm. Four types of rollers, steel wheel, pneumatic tyred, sheepsfoot and vibratory roller were modelled. While evaluating the effect of each parameter, others are assumed constant. Dynamic analysis was performed only for vibratory steel wheel rollers, while static analysis was chosen for others due to their low speed (Yarbakhti, 2014).

3.1 Materials Actual Parameters

The material parameters for the soil models were chosen to represent a wide range of practical cases. These values are given in Table 1 for fill and subgrade layer. The strength for the lower layer (subgrade) materials used, were ranging from very loose to very dense, while top layer was kept constant.

Table 1. Fill and subgrade material model parameters.

	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	e_o	E_{MC} (MPa)	c (kPa)	φ (°)	ψ (°)	υ
Sandy fill	16.5	19.3	0.77	30	10	36	6	0.35
Clayey fill	16.5	19.3	0.77	30	50	24	0	0.35
Subgrade	18.7	20.6	0.56	60	8	36	6	0.3

In which γ_{unsat} is the unsaturated unit weight, γ_{sat} is the saturated unit weight, e_o is the initial void ration, E_{MC} is the Young's modulus of Mohr-Coulomb Model, c is the cohesion, φ is the angle of internal friction, ψ is the dilation angle and ν is the poisson's ratio of the soil.

In the process of loading-unloading, the settlement amount after unloading will be important. Thus the hardening soil model for embankment and subgrade material is chosen. Assuming the elastic modulus of 60 and 30 MPa, respectively for subgrade and fill materials and using available formulas, stiffness parameters of hardening soil model in the midpoint of each layer can be calculated (Web-3).

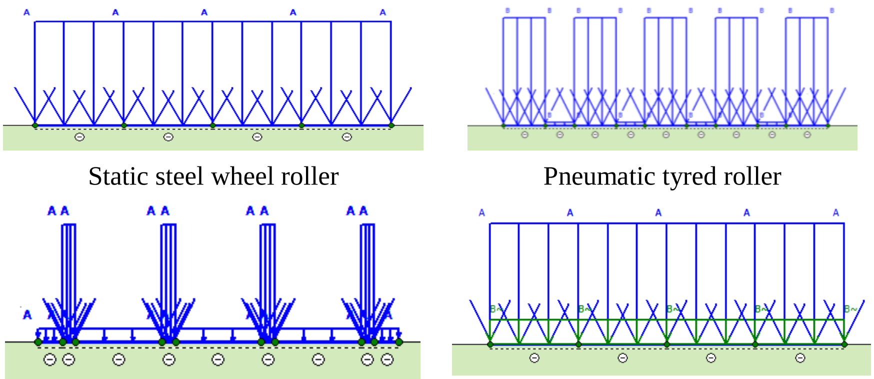
Geotechnical properties of dynamic analysis is similar to Table 1. The only difference is the value of Young's modulus (due to the small ranges of strain) and soil damping parameters (α and β) respectively equal to 0.001 and 0.01.

3.2 Loading Type

Loading system is as uniform load equal to contact pressure of each type of rollers, according to Table 2. It's notable that contact pressure of pneumatic tyred and sheepsfoot roller, respectively are pressure under the tyres and foots (Web-2). Rollers modelling are shown in Fig. 5.

Table 2. Rollers specifications.

	Steel wheel roller	Pneumatic Tyred roller	Sheepsfoot roller
Contact Pressure (kPa)	380	700	1400
Contact Width (m)	2.0	2.1	2.1



Static steel wheel roller Pneumatic tyred roller

Sheepsfoot roller Vibratory steel wheel roller

Fig. 5. Different rollers modelling.

In order to compare the effects of vibration on soil compaction, all the details in static and vibratory steel wheel roller such as contact pressure due to the weight and contact width assumed constant. Just frequency and centrifugal force dynamic were added to dynamic analysis. Since vibratory rollers weigh more, this is a conservative assumption.

Dynamic analysis of vibratory rollers requires two uniform systems of loading. One for modelling the static stress caused by the weight and the other for dynamic modelling caused by centrifugal force generated by the rotation of the two off-centered masses. About vibratory roller, combination of lower frequency and higher amplitude, leading to a greater centrifugal force, is preferred. According to the technical specification of chosen vibratory roller, roller with contact width of 2 meter and frequency of 25 Hz, generate the centrifugal force of 400 kN (Web-1).

4. Results

The effect of the lower layer (subgrade) was evaluated by increasing and decreasing elastic modulus (stiffness). Assuming an initial stiffness equal to *E*, totally 6 different stiffness (*0.5E*, *1E*, *2E*, *3E*, *4E* and *10E*) were considered for subgrade. Results indicated that increasing subgrade stiffness causes less displacement to the extend that if there is a rigid subgrade (subgrade with very high elastic modulus), relative density reduces significantly until loading will not affect the fill compaction.

In calculating the void ratio and dry unit weight of soil due to compaction, the equations 1 and 2 are used:

$$\frac{e_o - e_f}{1 + e_o} = \frac{\Delta H}{H_o} \tag{1}$$

$$\gamma_{d_i} = \frac{\gamma_s}{1+e_i} \;,\; \gamma_{d_f} = \frac{\gamma_s}{1+e_f} \quad \xrightarrow{\gamma_s = cte} \quad \gamma_{d_f} = \frac{1+e_i}{1+e_f} \times \gamma_{d_i} \tag{2}$$

Where e_o and e_f are respectively the initial and final void ratio, H_o is the lift thickness, γ_{d_i} and γ_{df} are respectively the initial and final dry unit weight and γ_s is the solid unit weight of the soil.

As an example results of 450 mm lift thickness are given in Table 3. Except for sheepsfoot roller, other results are related to sandy fill.

Table 3. Effect of subgrade stiffness variation on soil compression.

E (Mpa)	Roller	H_o (mm)	ΔH (mm)	e_f	γ_{df} (kN/m^3)	$(\gamma_{df} - \gamma_{di}) / \gamma_{di}$ (%)
0.5E – 10E (E_{MC}=30– 600 MPa)	SWR	450	19.1–16.0	0.69–0.76	15.71–15.08	4.73–0.53
	PTR	450	22.6–21.0	0.68–0.76	15.80–15.08	5.33–0.53
	SR	450	52.0–21.0	0.57–0.75	16.91–15.17	12.73–1.13
	VSWR	450	37.9–32.0	0.62–0.76	16.39–15.08	9.27–0.53

SWR = Steel Wheel Roller
PR = Pneumatic tyred Roller
SR = Sheepsfoot Roller
VSWR = Vibratory Steel Wheel Roller

Effect of subgrade stiffness variation is shown in Fig. 6, as an example for steel wheel roller. As shown in the figure, maximum difference occurs at the surface (top of the fill).

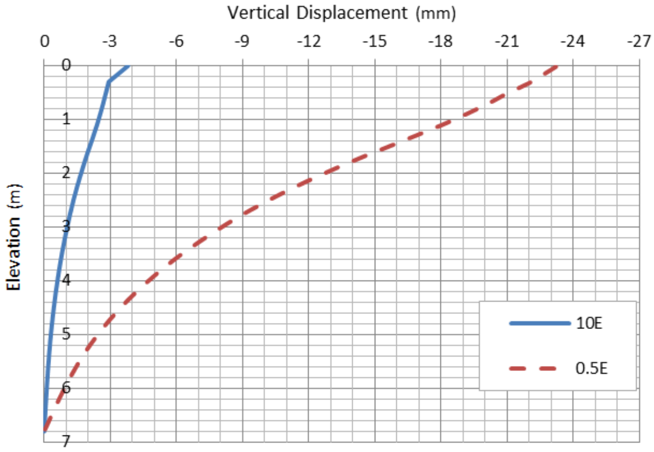


Fig. 6. Effect of subgrade stiffness variation on lift compression – Steel Wheel Roller.

By increasing the applied energy, influence zone of stress will also increase that can cause using thicker embankment layer. Transitional tensions depth, the thickness of the layer of dense can be stressful because of the depth increased. This condition can be reached by increasing the roller drum weight (increase the amount of water or sand inside the drum) or vibration frequency changes of vibratory rollers.

For static rollers, assuming an initial energy equal to *q*, different levels of energy (*q*, *2q*, *3q*) was considered. For vibratory roller, energy changes generate by changing the frequency and finally centrifugal force. According to vibratory roller technical specifications, for the frequency of 25, 30 and 35 Hz, the centrifugal force respectively 400, 300 and 200 kN can be reached. Table 4 shows the effect of roller energy on soil densification.

Table 4. Effect of roller energy variation on soil compression.

Energy	Roller	H_o (mm)	ΔH (mm)	e_f	γ_{df} (kN/m^3)	$(\gamma_{df} - \gamma_{di}) / \gamma_{di}$ (%)
1q – 4q	SWR	450	9.90–42.9	0.73–0.60	15.34–16.59	2.25–10.60
1q – 4q	PTR	450	12.0–47.5	0.72–0.58	15.44–16.80	2.93–12.00
1q – 2q	SR	450	26.8–53.9	0.66–0.56	16.00–17.01	6.67–13.40
1F – 2F	VSWR	450	23.1–26.2	0.68–0.67	15.80–15.90	5.33–6.00

Comparison between stress distribution of static rollers is also shown in Fig. 7. According to the figure, difference in stress distribution is significant by using sheepsfoot roller.

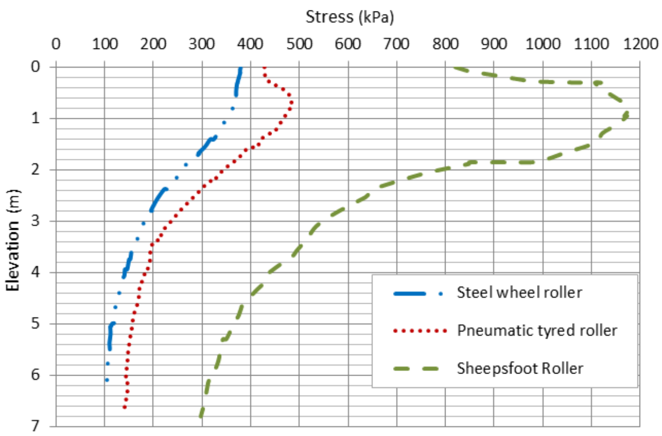


Fig. 7. Stress distribution comparison between static rollers.

As shown in Fig. 8, using vibratory steel wheel roller causes approximately double displacement in comparison to static one.

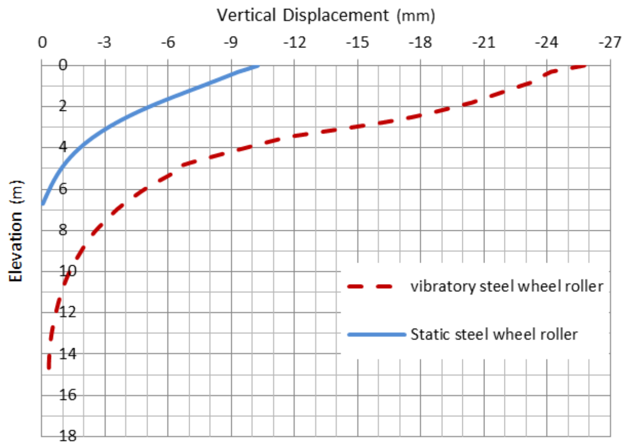


Fig. 8. Compression comparison between static and vibratory steel wheel rollers.

According to the results of only one cycle of loading, if there is a subgrade with suitable stiffness and applying the enough energy using sheepsfoot and vibratory roller, increasing the single-layer thickness of the fill to 450 mm, at least, will be reachable. According to research conducted in island of Hokkaido in Japan, proposed minimum thickness of 450 mm with 20% increase in dry density after each cycle of loading, will not be out of reach. The results of the project showed that by using the pneumatic tyred-roller, a single lift thickness can be increase from 300 mm to 450 mm for sandy and gravelly soil (with a gravel fraction of less than 60%). Whereas the number af passes limited to 5 to 8.

5. Conclusions

Two-dimensional modelling was conducted to evaluate the effect of subgrade condition and roller energy in increasing the embankment lift thickness. The results can be summarized as follows:

- By reducing the subgrade stiffness, lift displacement increases, which is mainly due to the displacement of poor subgarde under loading. If there is a stiff subgrade, total displacement will limit to lift displacement and the possibility of increasing the lift thickness can be provided. Therefore, a combination of treated subgrades due to their higher stiffness will allow for increasing the lift thickness
- Changes in order to increase the applied energy leads to increasing the displacement and finally relative density of the embankment layer due to the higher influence zone of stress. Thus, thicker lift can be affected by compaction energy. According to the results, sheepsfoot rollers, because of their high contact pressure and vibratory rollers, because of their particular mechanism lead to better results with significant differences compared to other rollers.
- In case of using vibratory rollers, combination of lower frequency and higher amplitude, leading to a greater centrifugal force, is preferred. Comparison between vibratory and static smooth wheel roller showed that displacement and density of the lift in case of applying vibration, increases to more than double compared to the static state.
- Finally, with regard to the above and using 3 and 5 sided HEIC rollers, single-lift thickness can increase significantly in comparison to the current allowable thicknesses.

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