Numerical Study on the Influence of Tire Burial Depth on the Performance of Reinforced subgrade with Waste Tires

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Abstract. Reinforcement with waste tires is an emerging method for enhancing the performance of road subgrades. To investigate the effect of tire burial depth on performance of subgrade, a numerical model was established using FLAC3D to simulate and analyze settlement, soil pressure distribution, and maximum stress within the tires in the subgrade. The subgrade soil was characterized using a nonlinear elasto-plastic constitutive model that incorporates a hyperbolic stress-strain relationship and the Mohr-Coulomb failure criterion. The waste tires were characterized using linearly elastic liner elements. Results indicate that the waste tire reinforcement effectively reduces the subgrade settlement, and this reductioneffect becomes more pronounced as tire burial depth decreases. Tire reinforcement reduces the maximum soil pressure in the subgrade and spreads the soil pressure to a broader area, resulting in a more even distribution of soil pressure. The maximum stress within the tires decreases with increasing burial depth and exhibits a nonlinear relationship. Results provide valuable insights for the design and engineering application of waste tire-reinforced subgrade.

Keywords: Waste tires; Reinforced soil; FLAC3D modeling; Settlement; Soil pressure distribution

1 Introduction

The annual production of waste tires in China exceeds 330 million, occupying land resources and causing environmental pollution [1]. Waste tires possess desirable properties for civil engineering applications, such as high strength, durability, and resistance to corrosion. Utilizing waste tires in road subgrade construction as reinforcement materials can enhance the overall load-bearing capacity of subgrades and avoid solid waste environmental problems.

Recent studies have focused on the reuse of waste tire scraps, obtained through cutting, shredding, and grinding processes, to improve the physical and mechanical properties of soils [2-4]. However, these secondary processing process of waste tires can be complex and may produce environmental pollution. The reuse of whole tires is the most ideal way to consume waste tires.

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The reuse of whole tires is mainly focused on retaining walls. This involves filling the cavity of waste tires with sand or clay to create tire-fill composite units with favorable mechanical properties. These units are subsequently employed as panels in retaining walls [5] or stacked to construct gravity retaining walls [6]. The mechanical bearing mechanism of waste tire reinforced embankment slope is studied, where entire waste tires are used as reinforcement materials to enhance road performance [7]. Retaining walls made from waste tires have been applied in practical engineering projects and have demonstrated good durability [8]. However, the tire reinforcement technology has not been promoted in subgrade engineering despite its excellent performance in scaled model tests [9].

This study presents a numerical study to investigate the behavior of subgrades reinforced with whole waste tires, with a focus on the influence of the burial depth of tire reinforcement, which is a critical parameter that affects the subgrade's performance. Results could provide insights for the wider application of whole waste tire reinforcement in engineering projects.

2 Numerical model

The three-dimensional finite difference program FLAC3D Version 6.0 was used to investigate the response of subgrades reinforced with whole waste tires under static loading. The FLAC3D software offers various material constitutive models, solid elements and structural elements, which is suitable for modeling the waste tire-reinforced subgrade [10].

2.1 Numerical model

A rectangular subgrade model was created with a length of 3 meters, equivalent to the width of a single lane, and a width of 1 meter. The depth of the subgrade soil model was 1.6 meters, which is sufficient for investigating the response of a waste tire-reinforced subgrade under static loading conditions. The subgrade model simulated subgrades reinforced at different depths, as specified in table 1.

Table 1. Simulation cases.

case	reinforcement materials	reinforcement position	buried depth
1	none	/	/
2	waste tires	upper	0.4
3	waste tires	middle	0.7
4	waste tires	lower	1.0

This simulation employed 60 series radial tires as defined in the GB/T 2978-2014 standard. These common waste tires have a diameter of 60 cm, a height of 20 cm, and a thickness of 1 cm. In this paper, "burial depth" refers to the distance from the bottom of the waste tires to the top surface of the subgrade model. Five waste tires were placed in contact with each other, with a spacing of 20 cm from the front and rear surfaces, and they were arranged along the length direction.

As shown in figure 1, the FLAC3D model represents the subgrade reinforced with tires. The loading area of the model was a 0.6m × 1m rectangle, positioned at the center of the model's top surface, directly above the central tire. The loading process was divided into 17 stages, with each stage applying a load of 50 kPa. The next stage of loading was carried out after convergence in the previous stage, totaling 850 kPa. To make the model's boundary conditions more realistic, the bottom surface of the subgrade model was fixed in the z-direction, the front and rear surfaces were fixed in the y-direction, and the left and right surfaces were fixed in the x-direction. The subgrade model, as well as the loading area, was symmetric along the central axis, making this study a typical plane strain problem.

2.2 Material properties for reinforced subgrade

The subgrade soil was modeled as nonlinear elastoplastic materials with a hyperbolic stress-strain relationship and the Mohr-Coulomb failure criterion. (Duncan et al., 1980). This model can capture the nonlinear behavior of soil and has been successfully employed in numerical studies involving tire reinforced structures[10]. The fundamental physical-mechanical parameters of the subgrade soil are presented in table 2.

Table 2. Soil parameters.

Dr	ρ(kg/m^3)	k	kur	n	rf	kb	c(kPa)	f(°)
70%	1792	370	400	0.55	0.59	75	0	35

The waste tires were modeled using linearly elastic embedded liner element with isotropic behavior. The embedded liner element for the waste tires provides two links at each node on both sides, which allows for simulation of the interaction of waste tires with subgrade soil on both sides. Tensile tests were performed on waste tire strips. The relevant parameters for waste tires are provided in table 3.

Table 3. Material parameters of waste tires.

Element type	Elastic modulus (MPa)	Poisson's ratio	Thickness (mm)	Density (kg/m^3)	Coupling stiffness shear (Pa/m)
Embed liner	700	0.5	10	1250	4.55×107

3 Simulation results and discussions

Numerical simulations were conducted for four different scenarios. The simulation results focused on thewas obtained settlement, soil pressure distribution beneath the reinforcement layer, and maximum stress within the tires.

3.1 Settlement of the loading area

Under the condition of a relative density of 70%, the settlement curves for the loading area of the road subgrade with different tire burial depths are shown in figure 2. All four settlement curves exhibit a similar trend, with settlement increasing as the load increases. Moreover, the rate of settlement increase accelerates with increasing load. For a load of 800 kPa, the settlement of the model without tire reinforcement is 192.7 mm, while the settlement in the subgrade with upper tire-reinforced layer is 123.7 mm, reducing settlement by 35.8% compared to the natural soil subgrade. The subgrade with middle tire-reinforced layer experiences a settlement of 144.1 mm, a 25.2% reduction compared to the natural soil. The subgrade with lower tire-reinforced layer experiences a settlement of 178.9 mm, a 7.2% reduction compared to the natural soil subgrade. These results indicate that waste tire reinforcement effectively reducessubgrade settlement, and this reduction effect is significantly enhanced as the tire burial depth decreases.

When the load is 500 kPa, the settlement in the natural soil subgrade is 89.4 mm, while the subgrade with upper tire-reinforced layer experiences a settlement of 69.5 mm, a 22.2% reduction. With an 850 kPa load, the settlement of natural soil is 216.8 mm, while the subgrade with upper tire-reinforced layer's settlement is 134.5 mm, representing a 37.9% reduction compared to the natural soil subgrade. This indicates that the effectiveness of tire reinforcement in controlling settlement increases with higher loads.

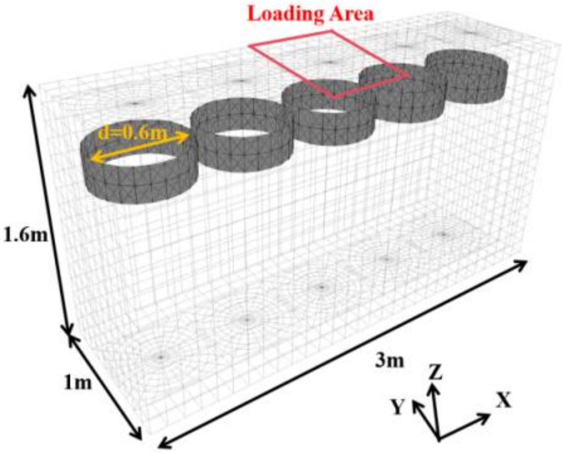

Fig. 1. 3D finite difference mesh for the reinforced subgrade model.

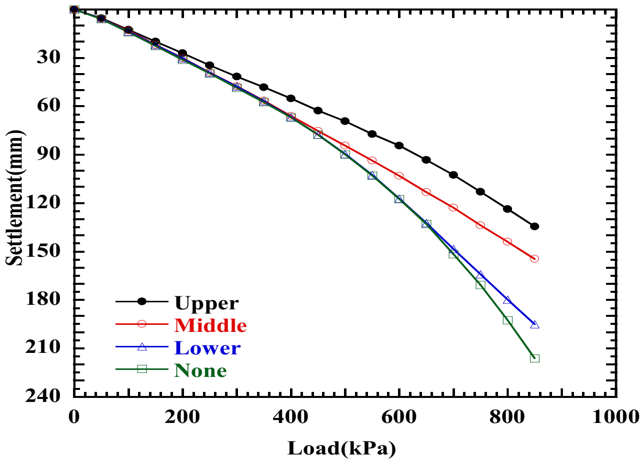

Fig. 2. Settlement of subgrade with different tire burial depths.

3.2 Soil pressure distribution beneath the tire reinforcement layer

To investigate the variation of stress distribution in the horizontal direction within the reinforced subgrade, an analysis was conducted along the central line of the soil layer at a depth of 500 mm. As shown in figure 3, the distribution curves of soil pressure within the subgrade exhibit a similar shape for all scenarios when the load is 650 kPa. The maximum soil pressure in the natural soil subgrade is 577 kPa, whereas the subgrade with upper tire-reinforced layer experiences a maximum soil pressure of 492 kPa, representing a 14.7% reduction compared to the natural soil subgrade. Furthermore, the stress distribution within the subgrade with upper tire-reinforced layer is more uniform. This indicates that the tire reinforcement layer increases the dispersion angle of additional stress, allowing it to spread over a wider area of soil, resulting in a more uniform distribution of soil pressure. The differences in soil pressure distribution between the natural soil subgrade and the middle and lower tire-reinforced subgrades are not significant. This is because the analyzed soil layer is positioned above the tire layers in the latter two cases, where the influence of the tire reinforcement layer on soil pressure distribution is minimal.

In order to investigate the variation of internal stress distribution in the reinforced subgrade in the vertical direction, an analysis was conducted along the center axis of the subgrade, as shown in figure 4. At a load of 650 kPa, both types of subgrades exhibit a similar trend in the variation of soil pressure with depth, which decreases as depth increases. Above the tire-reinforced layer, the soil pressure along the center axis of both types of subgrades is nearly identical. However, after passing through the tire-reinforced layer, the soil pressure for the upper reinforced subgrade is 473.1 kPa, while the soil pressure for the natural soil subgrade is 496.3 kPa. This indicates that the tire-reinforced layer increases the dispersion angle of additional stresses, causing the soil pressure to spread into a larger volume of soil after passing through the tire layer, which is consistent with the conclusion mentioned earlier.

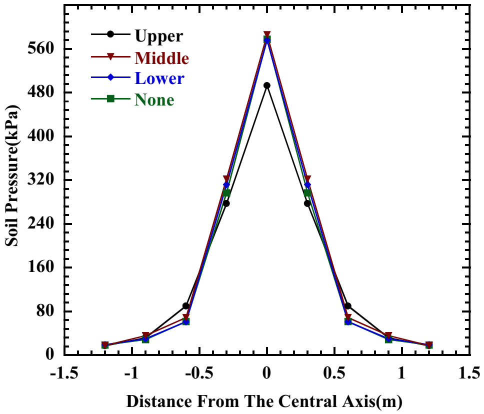

Fig. 3. Stress distribution in the horizontal direction within the reinforced subgrade.

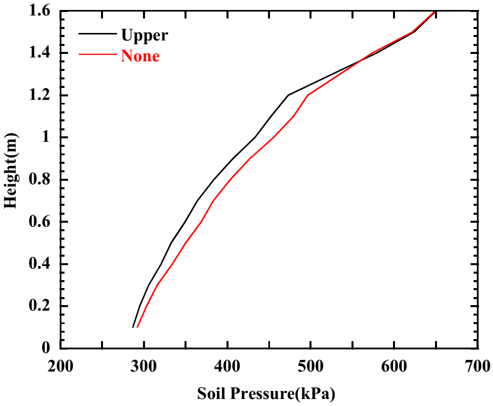

Fig. 4. Stress distribution in the vertical direction within the reinforced subgrade.

3.3 Maximum stress within the tires

The burial depth of the tires significantly alters the soil pressure distribution within the subgrade and also affects the stresses within the tires, as depicted in figure 5. All three stress curves exhibit the same trend: the maximum stress within the tire increases with the increasing load, and the rate of increase of the maximum stress within the tire accelerates as the load increases. Under the same load, the maximum stress on the tire increases as the burial depth decreases. This indicates that shallower burial depths result in a stronger constraint effect of the tires on the soil, leading to more effective enhancement of the overall subgrade strength.

Figure 6 illustrates the relationship between the maximum stress on the tire and the burial depth under a 650 kPa load. As seen from the lines in the graph, the maximum stress within the tire decreases as the burial depth increases, and the rate of increase in maximum stress within the tire slows down as the burial depth increases. This suggests that the maximum stress within the tire is negatively correlated with burial depth and shows a nonlinear trend.

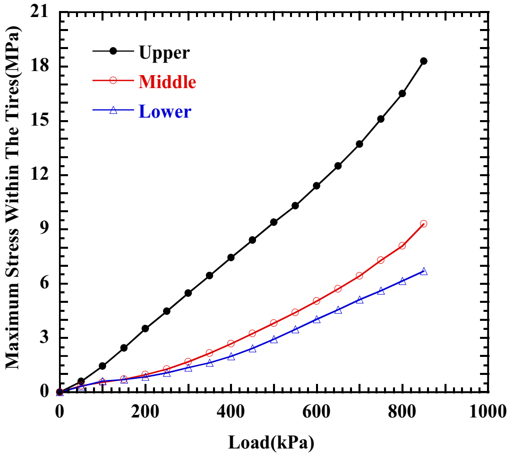

Fig. 5. Maximum stresses within the tires in different subgrade.

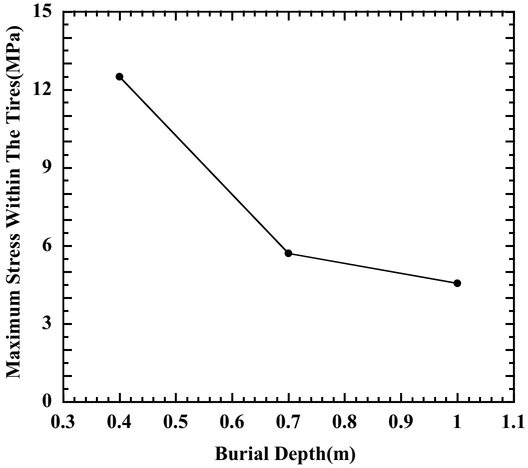

Fig. 6. Maximum stresses within the tires in different burial depth.

4 Conclusion

This paper presents a numerical study to investigate the influence of tire burial depths on the settlement, soil pressure distribution beneath the reinforcement layer, and maximum stress within the tires. The deformation characteristics and mechanical properties of road subgrades reinforced with whole waste tires were revealed, which provides insights for the design and engineering application of waste tire-reinforced road subgrades. The following conclusions are reached:

Reinforcement of waste tires effectively controls subgrade settlement, and the effect of controlling settlement becomes more pronounced as the tire burial depth decreases.

The effectiveness of tire reinforcement in controlling settlement increases with the increase of load.

Tire reinforcement reduces the maximum soil pressure within the subgrade and spreads soil pressure over a larger area, resulting in a more uniform distribution of soil pressure.

The maximum stress within the tires is negatively correlated with burial depth and follows a nonlinear relationship.

The results of this study offer valuable guidance for the design and engineering application of road subgrades reinforced with whole waste tires, contributing to sustainable and environmentally friendly construction practices in the field of civil engineering.

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