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Assessment of the side thrust for off-road tracked vehicles based on the punching shear theory

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ABSTRACT

The track system is generally applied for heavy off-road vehicles. While moving on the off-road, the track system horizontally transmits an engine torque to the soil-track interface, resulting in slip displacement and an associated soil thrust acting as a traction force. As soil thrust is developed on the bottom and the side of the track system (hereinafter referred to as "bottom thrust" and "side thrust", respectively), it is imperative to evaluate both the bottom thrust and the side thrust to assess the off-road tracked vehicle's performance. Unlike the bottom thrust, however, the mechanisms of the side thrust have not been fully understood. To address this, this study aimed to evaluate the side thrust for off-road tracked vehicles. A new mechanism for the side thrust was theoretically investigated based on the punching shear theory. A series of model track experiments were conducted on a model track system with silty sand. From the experiment results, the shapes of the failure surface were observed, and the side thrust was measured for verification purposes. Particular attention was given to the development of a side thrust prediction model for the heavy off-road tracked vehicles based on the proposed mechanism.

1. Introduction

In infrastructure projects, heavy off-road vehicles such as excavators, trenchers, and bulldozers are widely utilized for executing earthworks. To drive off the pavement, heavy off-road vehicles need to have a low ground contact pressure and to keep their mobility on the ground surface, so as not to lose traction. As the track system, which has a wider ground contact area than the wheel system, can successfully accomplish this, a tracked vehicle is generally suitable for off-road conditions (Yong et al., 1984). Unlike the paved road, unpaved terrain (off-road) cannot sufficiently withstand an engine torque, restricting the tractive forces. When a tracked vehicle travels off road, an engine torque that is transmitted to the track system induces a shearing action on the soil-track interface, causing slippage in the horizontal direction. Consequently, the relative displacement known as "slip displacement" takes place on the soil-track interface, which develops an associated soil thrust acting as a traction force (Wong, 1989).

It should be noted that in the development of the soil thrust, the shearing action on the soil-track interface leads to slip displacement, which limits the off-road tracked vehicle's performance. In particular, for the soft ground condition, excessively large slip displacement may occur for the development of the required soil thrust, which will make the tracked vehicle start to move. As a rule, to reduce the slip displacement at a certain soil thrust level, the outer surface of the track system is designed to protrude with grousers, generating additional soil thrust on the side of the track system with a minimal impact on the mass overheads. With the track system protruded with the grousers, soil thrust is developed on the bottom and side of the track system (hereinafter referred to as "bottom thrust" and "side thrust", respectively). Therefore, to assess the off-road tracked vehicle's performance, it is imperative to evaluate both the bottom thrust and the side thrust of the track system based on the principle of terramechanics.

Since its first introduction by Bekker (1956), the bottom thrust has been clearly identifiable and has been capable of being determined through the integration of the shear stress over the projected soil-track contact area on the bottom, similar to the shear force in the direct shear test of the soil. On the other hand, the side thrust, which becomes more significant with the increase in the grouser height, has not yet been fully understood. Although several researches have tried to investigate the side thrust based on their own established theories, a universal theory accounting for the mechanism of the side thrust has not been clearly established. Bekker (1956) described the side thrust as being generated by the increase in the side stress, which is calculated based on the

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theory of elasticity, assuming the soil mass as a semi-infinite elastic medium. When a tracked vehicle travels on an off-road, however, the soil beneath the track systems is subjected to the compression forces generated by the vertically and horizontally imposed loads, and is brought into the plastic state. Park et al. (2000) demonstrated that the soil on the side of the track systems is brought into a state of active failure by the vehicle's weight, and that the side thrust can be determined based on the Rankine active earth pressure. The vertical stress induced by the weight of a tracked vehicle, however, usually does not exceed the bearing capacity of the ground. This indicates that the soil on the side of track systems is horizontally expanded by the vehicle's weight, but not as active soil failure is taking place. Hence, a higher side thrust value is more probable. Grecenko (2007, 2011) developed a new method termed as "compression-sliding (CS) approach" for the assessment of an off-road tracked vehicle's performance, which regarded the soil thrust as the compression force acting on the soil block beneath the track system. In the CS approach, only the soil cohesion was taken into account for the side thrust evaluation. Considering that the shear strength of the soil is attributed not only to the cohesion but also to the internal friction angle, the shear strength of the soil was not appropriately implemented. As such, none of the previous relevant researches has clarified the mechanisms of the side thrust beneath the track systems despite their significance.

To address this, this study aimed to evaluate the side thrust for off-road tracked vehicles. A new mechanism for the side thrust was theoretically investigated, and a series of model track experiments were conducted on a model track system, with Gwanak soil sampled near the Mt. Gwanak area located in Seoul, South Korea. From the experiment results, the shapes of the failure surface were observed, and the side thrust was estimated for verification purposes. Particular attention was given to the development of a side thrust prediction model that could be utilized to assess the performance of the heavy off-road tracked vehicle based on the proposed mechanism.

2. Proposed mechanism for the side thrust

2.1. Assessment of the soil thrust based on the principle of terramechanics

The soil thrust is exerted by the shearing behaviors of the soil, and its characteristics depend on the shear stress-strain-strength of the soil. As aforementioned, soil thrust inducing a certain slip displacement is mobilized by its running gear (track systems) shearing the soil on the bottom and side of the track systems, which generates bottom and side thrusts, respectively (see Fig. 1). Based on the principle of terramechanics (Bekker, 1956), both thrusts are separately determined through the integration of the shear stress over the soil-track contact area, and the total soil thrust is calculated by adding them (no interaction was assumed). Here, all the soil thrusts were expressed in terms of maximum thrust values mobilized by the shear strength of the soil because the proposed mechanism for the soil thrust in this study was assessed based on the limit equilibrium state.

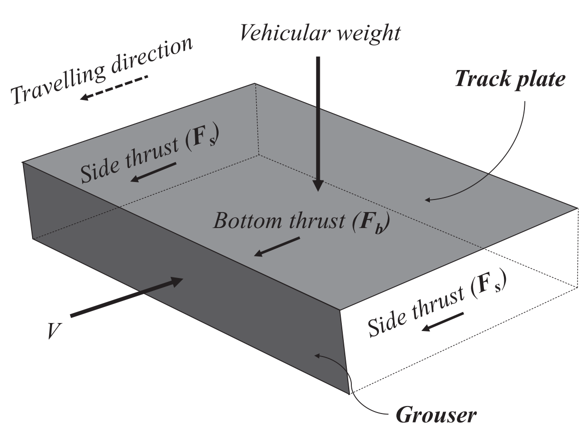

Fig. 1. Schematic diagram of the soil thrust components of a single-track system.

When shear failure takes place on the soil-track interface, the shear strength (τ) of the soil is generated; τ is generally expressed by the Mohr-Coulomb failure criterion (Yong et al., 1984), as shown in Eq. (1).

$$\tau = c + \sigma' tan\phi \tag{1}$$

where c and ϕ are the cohesion and internal friction angle of the soil, and σ' is the normal effective stress.

Assuming a flat terrain surface and a uniform normal effective stress distribution along the soil-track contact area, the maximum bottom thrust (F_b) is expressed by the value obtained after multiplying the shear strength and the shearing area, which is equal to the projected soil-track contact area on the bottom, as shown in Eq. (2). This implies that the mechanism of the bottom thrust is similar to that of the shear behavior in the direct shear test of the soil, determined based on the Mohr-Coulomb failure criterion.

$$F_b = \int \tau_b dA_b = A_b \tau_b = wl(c + \sigma'_b tan\phi) \tag{2}$$

where A_b is the failure surface area on the bottom, τ_b and $\sigma_b{}'$ are the shear strength and normal effective stress on the bottom of the track system, respectively, and w and l are the width and length of the track system.

For an off-road tracked vehicle equipped with protruded grousers, soil shearing takes place not only on the bottom but also on both sides of the track system, generating additional side thrust. Based on the Mohr-Coulomb failure criterion, the maximum side thrust (F_s) can be expressed using the same procedure employed for expressing the maximum bottom thrust, described as follows:

$$F_s = 2\int \tau_s dA_s = 2A_s \tau_s = 2hl(c + \sigma'_s tan\phi) \tag{3}$$

where A_s is the failure surface area on one side, and τ_s and $\sigma_s{}'$ are the shear strength and normal effective stress on the side of the track system, respectively, and h is the attached grouser height.

Consequently, the maximum total soil thrust (F) of an off-road tracked vehicle is defined as the addition of two different soil thrusts, and is calculated by adding Eqs. (2) and (3), as shown in Eq. (4).

$$F = F_b + F_s \tag{4}$$

In this regard, it should be noted that the mechanism for the side thrust has been vague. The failure surface and the shear strength mobilized on the side of the track system (A_s and τ_s in Eq. (3), respectively) have not been clarified, meaning that the effect of the grousers on the off-road tracked vehicle's performance has not been properly identified. To address this, the following section deals with a comprehensive theory for the side thrust. Based on the soil-track interaction theory, the mechanism for the side thrust was newly proposed, and the failure surface and the shear resistance on the side of the track system were theoretically established using the proposed mechanism.

2.2. Mechanism for the side thrust

In the off-road conditions, a tracked vehicle rests on unprepared terrain, and the track systems support the weight of the tracked