

Effect of Soil Deformability on Off-Road Vehicle Ride Dynamics

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ABSTRACT

This study analyzes the effect of soil deformation on ride dynamics of off-road vehicles using a quarter-vehicle model integrating different equivalent soil stiffness models. Soil deformation has an effect on the tire sinkage, wheels contact area and the wheels dynamic interaction with the terrain, which affects the overall ride dynamics of the vehicle. Apart from the very simplified equivalent soil stiffness model documented in the literature, a new equivalent soil stiffness model is developed in this study, which encompasses the effect of soil deformability on tire-soil contact area. Two measured ground roughness profiles are then used for vehicle ride dynamics simulation. The analytical and simulation results analyses demonstrated that the variations in tire-soil contact area due to soil deformability and tire sinkage should be modeled for ride dynamics analyses, and soil deformability tends to reduce the vehicle body bounce acceleration and dynamic tire-soil interacting force with a compromise on suspension travel. Parametric studies further demonstrated the potential of optimal tire/suspension settings.

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INTRODUCTION

Ride vibration characteristics of vehicles in on-road conditions have been fairly well understood, and linear vehicle models in conjunction with various suspension models (linear, nonlinear, controlled, etc) have been popularly used for analyzing on-road vehicle ride dynamics and evaluating suspension concepts [1, 2, 3, 14, 15, 16, 17]. It is known that many types of ground vehicles (such as SUVs and construction and agricultural vehicles) are designed to operate on both on- and off-roads [4, 5, 6], which poses a significant challenge on suspension design and tuning. A number of efforts have been attempted in vehicle ride dynamics analyses when operating on off-road [6, 7, 8, 9], assuming either un-deformable or deformable soil. However, significant research efforts are still needed towards provide a generic guidance on off-road vehicle suspension system design and tuning.

When a vehicle travels on a deformable ground surface, the ground deformation interacts dynamically with the tire and vehicle. Vehicle ride vibration characteristics in off-road condition are dependent upon both vehicle parameters as well as terrain conditions, such as vehicle speed, vehicle weight, suspension stiffness and damping properties, tire dimensions

and properties, ground roughness, soil properties, etc. Soil deformation has an effect on the tire sinkage, wheels contact area and the wheels dynamic interaction with the terrain, which then affects the overall ride vibration responses and tractive performance of the vehicle.

This paper aims at investigating the fundamental ride dynamic characteristics of vehicle suspension-tire-terrain systems by using a quarter-vehicle model integrating different equivalent soil stiffness models. These equivalent soil stiffness models include one assuming a constant contact area between the tire and the terrain, and three models considering a varying contact area due to the tire sinkage. Mathematical models for these equivalent soil stiffness properties are derived, and simulation analyses and parametric studies are conducted to compare the effect of soil deformability on off-road vehicle ride dynamics.

QUARTER-VEHICLE RIDE MODEL

Soil deformation can be described by a spring, which has the elastic and plastic ranges as the load increases [7]. For the purpose of the fundamental ride dynamics analyses in this study, the soil deformation is assumed to be an equivalent

soil stiffness that however captures the parameters of the soil property, tire sinkage and tire-soil contact area.

A quarter-vehicle model (Fig. 1) is used, which includes the tire stiffness k_t in series with an equivalent soil stiffness k_{soil} that is in contact with ground. The equations of motion are summarized below:

$$\begin{aligned} m_s \ddot{x}_s &= -k_s(x_s - x_u) - c(\dot{x}_s - \dot{x}_u) \\ m_u \ddot{x}_u &= k_s(x_s - x_u) + c(\dot{x}_s - \dot{x}_u) - \frac{k_t k_{soil}}{k_t + k_{soil}}(x_u - y) \end{aligned} \quad (1)$$

where k_s and c are the spring stiffness and the damping coefficient of the suspension, m_s and m_u are the sprung and unsprung masses, and y is the ground roughness input. The nominal vehicle system parameters are summarized in Table 1, while the equivalent soil stiffness k_{soil} will be mathematically derived using different approaches for different types of soils.

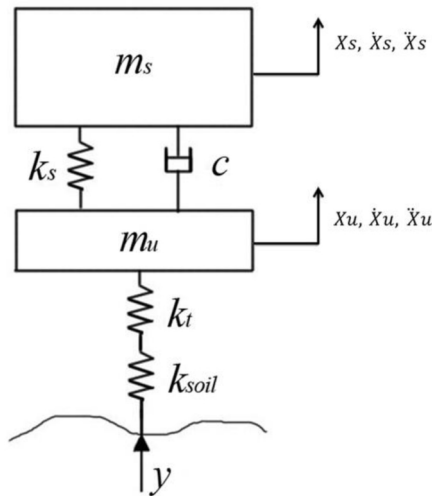


Fig. 1. The quarter-vehicle ride model of an off-road vehicle when traveling on deformable terrain.

Table 1. The nominal vehicle system parameters.

Parameter	Unit	Nominal value
Weight of quarter car (an SUV)	kg	615
Sprung mass (m_s)	kg	546.7
Unsprung mass (m_u)	kg	68.3
Tire diameter (R)	mm	804
Suspension stiffness coefficient (k_s)	kNm ⁻¹	42.2
Tire stiffness (k_t)	kNm ⁻¹	134.6
Suspension damping coefficient (c)	kNsm ⁻¹	2.88

Modeling the Equivalent Soil Stiffness

It has been known that soil property can be represented by [10, 11]:

$$k_{eq} = \left(\frac{k_c}{b} + k_\phi \right) \quad (2)$$

where b is the smaller dimension of the tire-soil contact, k_c is the modulus of deformation due to cohesive properties of soil, k_ϕ is the modulus related to the frictional component of deformation. k_{eq} is the equivalent stiffness with the units Nm⁻³. Multiplying k_{eq} by the tire-soil contact area yields the value of equivalent soil stiffness k_{soil} (Nm⁻¹) [9], such that:

$$k_{soil} = \left(\frac{k_c}{b} + k_\phi \right) \times \text{Contact area} \quad (3)$$

Different soils have different stiffness values k_{eq} resulting from different values of k_c and k_ϕ . The contact area has an influence on the equivalent soil stiffness k_{soil} , as a tire in a softer soil will yield larger contact area than that on hard ground.

Modeling Contact Area

To find the length and width of the contact area, the vertical deformation of the tire has to be found. This can be done by using the simplified formula, without considering dynamic tire load:

$$f = \frac{W}{k_t} \quad (4)$$

where W is the weight of the quarter vehicle and f is the vertical deformation of the tire, as shown in Fig. 2.

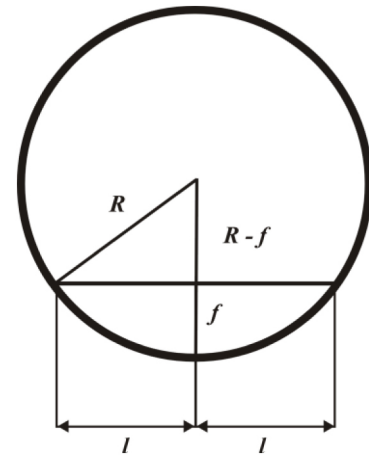


Fig. 2. Tire deflection representation.

Half the length l of the contact area can thus be formulated as:

$$l = \sqrt{R^2 - \left(R - \frac{W}{k_t} \right)^2} \quad (5)$$

Two different modeling approaches for contact area will be considered in this study: (a) constant contact area

considering only vertical deformation of tire; and (b) varying contact area due to the tire sinkage including vertical tire deformation. These are briefly presented below.

Model 1 - Constant Contact Area Considering Only Vertical Deformation of Tire

For the Model 1, constant contact area considering only vertical deflection of tire is formulated, while the change in contact area due to the tire sinkage is neglected [9]. The contact area (CA) is simply the length of the deformed tire $2l$ multiplied by the width of the tire w , such that:

$$CA = 2w \sqrt{R^2 - \left(R - \frac{W}{k_t}\right)^2} \quad (6)$$

Model 2 - Varying Contact Area Due to the Tire Sinkage and Including Vertical Tire Deformation

The contact area of the tire will vary depending on the soil it is operating on. Depending upon the soil properties, the tire will sink to a different depth, which has an effect on the contact area. As only the vertical component of the contact area is considered, this will be equivalent to the cross-section of the tire where it is in contact with the ground surface. This can be represented in Fig. 3.

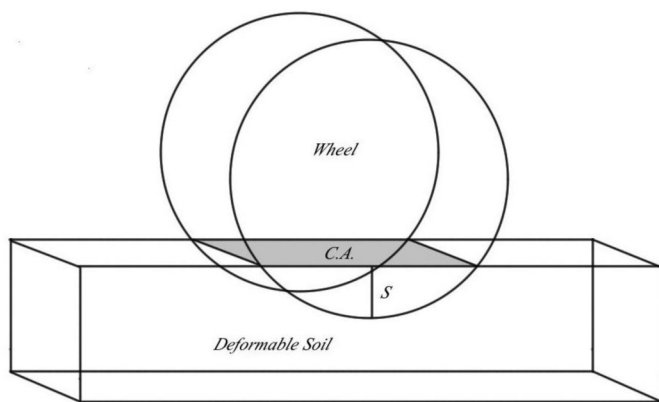


Fig. 3. Tire sinkage in deformable soil.

Five different types of soils are considered in this study. The soils are named after the regions they are from, and are listed along side their properties in Table 2 [11, 12].

As there is no data given about the sinkage in any of the soils used in this investigation, an assumption is to be made on how deep the vehicle will sink in sand. Some assumptions should also be made since the tire slip ratio is also unknown and varies. As the tire slip ratio increases, the tire sinkage generally increases. Three different tire slip ratio situations are assumed in this study, corresponding to three different tire sinkage values: (i) a 10 cm sinkage in sand corresponding to

a low slip ratio (S1); (ii) a 12 cm sinkage in sand corresponds to a moderate slip ratio (S2), and (iii) a 15 cm sinkage in sand corresponds to a relatively high slip ratio (S3).

Table 2. Measured soil properties [11, 12].

Soil	k_c (kN/m ⁿ⁺¹)	k_ϕ (kN/m ⁿ⁺¹)	C (kPa)	ϕ (°)
LETE sand	6.94	505.8	1.3	31.1
Upland sandy loam	74.6	2080	3.3	33.7
Rubicon sandy loam	6.9	752	3.7	29.8
North Gower clayey loam	41.6	2471	6.1	26.6
Grenville loam	0.06	5880	3.1	29.8

Having obtained the value of submersion in sand, the cohesion (C) and the angle of shearing resistance (ϕ) can then be used to find the percentage submersion in the other soils compared to sand. These can then in turn be used to find estimated submersion values for the other soil types presented in Table 2. To find how deep the vehicle will become submerged in the other terrains, the relation can be used [11]:

$$\tau = C + \sigma \tan(\phi) \quad (7)$$

where τ is the shear stress and σ is the normal stress and defined as force over area. The force is the static weight of the vehicle, and the area is the tire-soil contact area (CA in Eq. (6)). Hence σ can be calculated by:

$$\sigma = \frac{W}{CA} \quad (8)$$

A simplified formula for the contact area affected by the sinkage is thus given by:

$$CA = 2w \sqrt{R^2 - \left(R - \left(\frac{W}{k_t} + s\right)\right)^2} \quad (9)$$

where s is the wheel sinkage in the terrain.

Having obtained the value of normal stress on the contact patch, and being given the cohesion and the angle of shearing resistance for each soil, it is possible to find the value of shear stress using Eq. (7). Shear stress has an influence on soil sinkage. The higher the shear stress a soil can resist, the less of a sinkage would be expected to occur. A linear relationship between the shear stress and soil sinkage can be assumed for simplifying the analyses, as shown in Fig. 4.

As the shear stress of the soil increases, the sinkage decreases. A slope of $-1/1000$ can be assumed for facilitating the comparative analyses. Based on these modeling assumptions, Table 3 summarizes the sinkage values for different soils, which suggest a reasonable estimation for