# UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

**Colegio de Ciencias e Ingenierías**

# Bearing capacity analysis for a circular indentation

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**Ingeniería Civil**

Trabajo de fin de carrera presentado como requisito para la obtención del título de Ingeniero Civil

Quito, 13 de marzo de 2023

# UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

**Colegio de Ciencias e Ingenierías**

**HOJA DE CALIFICACIÓN DE TRABAJO DE FIN DE CARRERA**

## Bearing capacity analysis for a circular indentation

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## RESUMEN

El análisis de la capacidad portante es un aspecto crucial de la ingeniería geotécnica y se utiliza para determinar la carga máxima que puede soportar un suelo antes de fallar. En el caso de una indentación circular, la capacidad portante está influida por diversos factores, como el diámetro y la profundidad de la indentación, el ángulo de inclinación del suelo y las propiedades del propio suelo.

En este trabajo, se realizará un método experimental para analizar la capacidad portante de una indentación circular con el fin de encontrar una fórmula que relacione la capacidad portante de un suelo con el esfuerzo producido por una rueda en la superficie de un suelo. Esta fórmula podría utilizarse para hallar directamente el esfuerzo generado por las ruedas de un carro en una carretera no pavimentada que tenga el fenómeno washboard.


**Palabras clave:** Washboard, capacidad portante, indentación circular

## ABSTRACT

Bearing capacity analysis is a crucial aspect of geotechnical engineering and is used to determine the maximum load that a soil can support before it fails. In the case of a circular indentation, the bearing capacity is influenced by various factors such as the diameter and depth of the indentation, the angle of inclination of the soil, and the properties of the soil itself.

In this paper, an experimental method will be realized to analyze the bearing capacity of a circular indentation to find a formula that relates the bearing capacity of a soil with the stress produced by a wheel on the surface of a soil. This formula could be used to directly find the stress generated by the wheels of a car on a washboarded road.

**Key words:** Washboard, bearing capacity, circular indentation

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# INTRODUCTION

Road development in Ecuador has been affected since early times due to the geography and topography it faces. The importance of road infrastructure helps define the development of a state in all its orders: social, economic, political, and military, which are interrelated (Arizaga, 1988).

The road network of a country plays a very important role since it allows the connection between provinces, cities, and cantons. The implementation of new road infrastructure in Ecuador arose due to the increase in the number of vehicles, which increased from 320.000 to 2.4 million according to the 2019 records (Riley, 1971).

In Ecuador, the road network has an approximate length of 42.670 km, distributed among the state, provincial, and cantonal networks, and is the responsibility of each corresponding entity. In relation to the country's global road network, Ecuador has approximately 15.000 km of paved roads, with the Sierra region having the longest extension of roads.

Within this framework, paved roads play a crucial role in generating connection and communication between different places in the country. However, the rest of the unpaved roads require a lengthy process of operation and investment to continue extending the country's road network.

On unpaved roads, there is a problem with respect to the usage time due to a phenomenon known as the washboard or corrugated road effect. This issue arises due to the use of variable vehicular loads that transit through the same place in a certain layer of unmodified soil.

*Figure 1: Washboard Road (Dunning, 2022).*

Washboarding is the spontaneous formation of a transverse undulation on a dirt road. Generally, this occurs on heavy traffic unpaved roads in dry weather conditions (South Dakota Local Transportation Assistance Program, 2020). It has been observed that in flat roads, the corrugations arise in the transverse as well as the longitudinal direction. Within this framework, this phenomenon brings an unfavorable condition for users since there is a higher possibility of an accident. This happens due to the wheel's contact with the soil; since there are several waves along the length of the road, the wheel's contact with the area is less, increasing the risk and reducing road safety.

The transverse undulations generated on the roads do not represent a very high value in terms of dimensions, as the soil's deformations are only a few centimeters. However, this represents a strong contact with the car due to the friction and adhesion it has while traveling. The formation of the phenomenon also occurs differently depending on the soil's characteristics and conditions.

This effect was first studied around 1962 due to the discomfort on the road's surface. Nowadays, it is possible to represent the phenomenon by using steel cylinders to contact a layer of soil and see how the soil interacts with a load. In this way, through this study, it is possible to simulate the vehicle's tire and its contact with the soil to understand how the washboard effect arises through the study of deformations and the behavior of the soil extract used.

## DEVELOPMENT OF THE TOPIC

For the present paper, we started from an experimental test in which sand was placed inside an acrylic container reinforced with steel profiles, to then exert a force on the surface of the sand by means of a hydraulic press. The object that exerted pressure on the sand simulated the tire of an automobile when it is forming the washboarding phenomenon on unpaved roads. The "wheel" was made of two materials: steel and rubber, and of different radius: $35mm$, $28mm$ and $18mm$. The hydraulic press had a loading speed of $10\frac{N}{s}$ and indicated the force it exerted over time, and then, knowing the contact area, obtained the pressure exerted every 5 seconds.

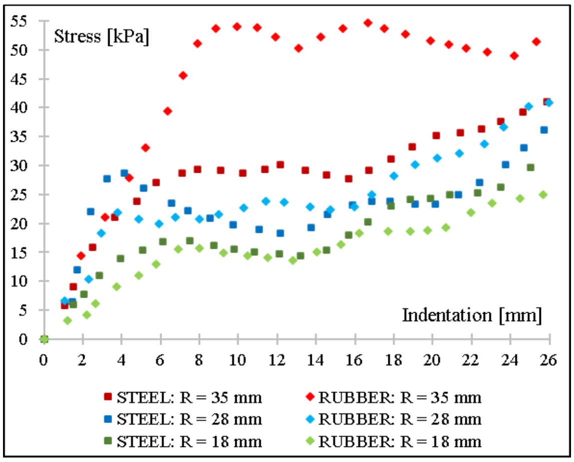


*Figure 2: Experimental stress vs the indentation of each wheel material for each wheel radius.*

For the results shown in Figure 2, an electronic spreadsheet was used to calculate the contact area on the surface of the sand on which the hydraulic press exerted force. The length of the "wheel" was known to be $70mm$ and the PIVLab software was used to know what width of the wheel was being indented every 5 seconds. The force recorded on the hydraulic press panel was divided by the calculated area. This calculated stress will be called "experimental stress". On the other hand, on the x-axis is represented the depth to which the wheel was indenting, this measurement, in the same way, was obtained every 5 seconds until 120 seconds using PIVLab. These data were calculated and recorded for each material (steel and rubber) and for the three wheel radius ($35mm$, $28mm$ and $18mm$).

The graphs in Figure 3, Figure 4 and Figure 5 represent a comparison between the experimentally calculated stress and the maximum stress that the soil would withstand without damage using the soil bearing capacity equation as the wheel was indenting in the sand. Knowing that the equation of the bearing capacity of a soil is:

$$q_u = c'N_c + \gamma D N_q + \frac{1}{2}\gamma B N_\gamma \ \left[{}^{kN}/_{m^2}\right]$$

where:

$c'$ is the cohesion of the soil $[kPa]$

$D$ is the indentation depth $[m]$

$\gamma$ is the unit weight of the soil $\left[{}^{kN}/_{m^3}\right]$

$B$ is the indented width of the wheel $[m]$

$N_c, N_c, N_c$ are the bearing capacity factors

And the bearing capacity factors are calculated using:

$$N_q = e^{\pi \tan\varphi} \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)$$

$$N_\gamma = 2\tan\varphi\left(N_q - 1\right)$$

$$N_c = \cot\varphi\left(N_q - 1\right)$$

where:

$\varphi$ is the angle of internal friction $[rad]$

Since sand is the type of soil used, the cohesion is 0. While the unit weight of the sand and the angle of internal friction were calculated in the laboratory, giving values of $18\frac{kN}{m^3}$ and 40° respectively.

From here, the graphs were separated into steel and rubber to make a comparison between materials, keeping the same radius dimensions for both materials.

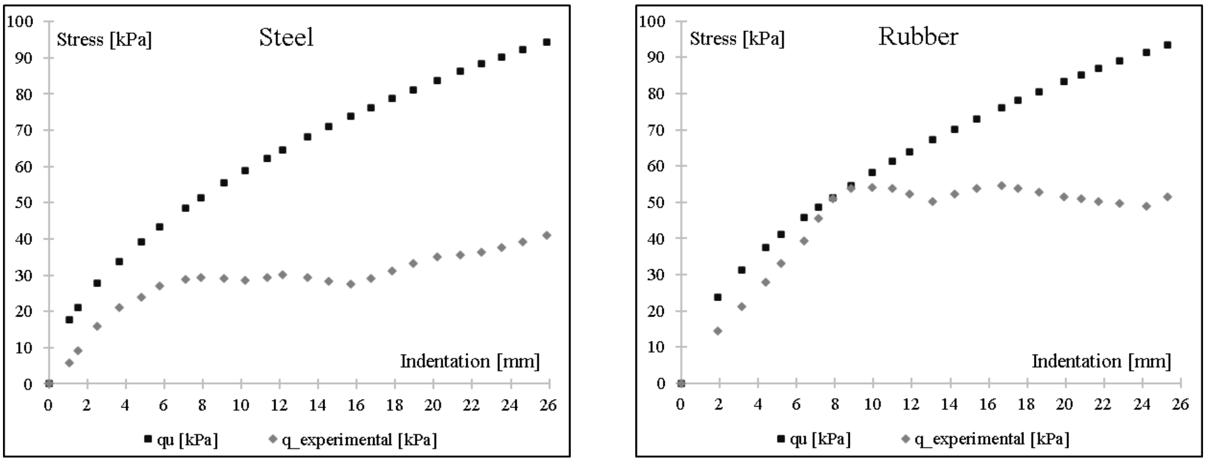


*Figure 3: Bearing capacity and experimental stress of the 35mm wheel in terms of the indentation.*

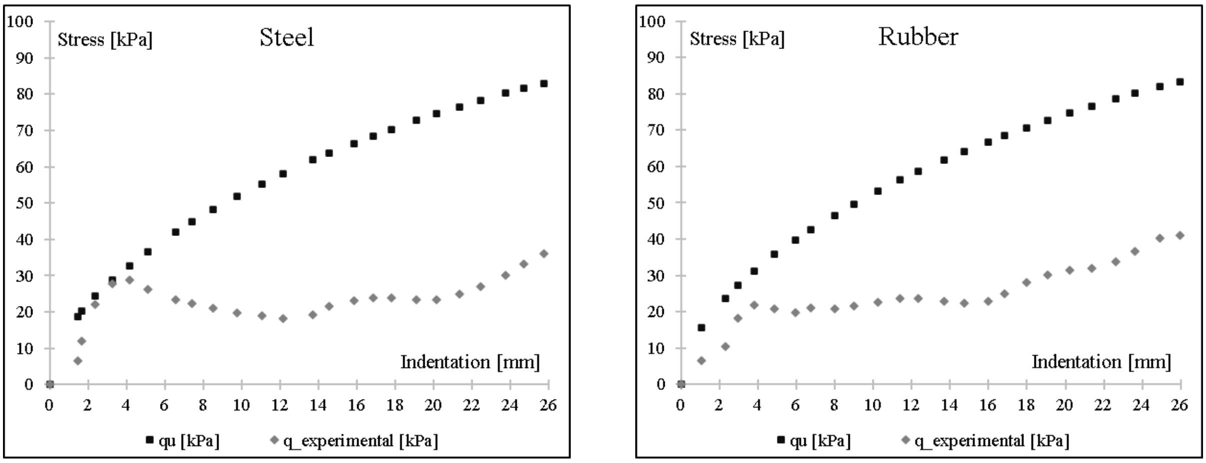


*Figure 4: Bearing capacity and experimental stress of the 28mm wheel in terms of the indentation.*

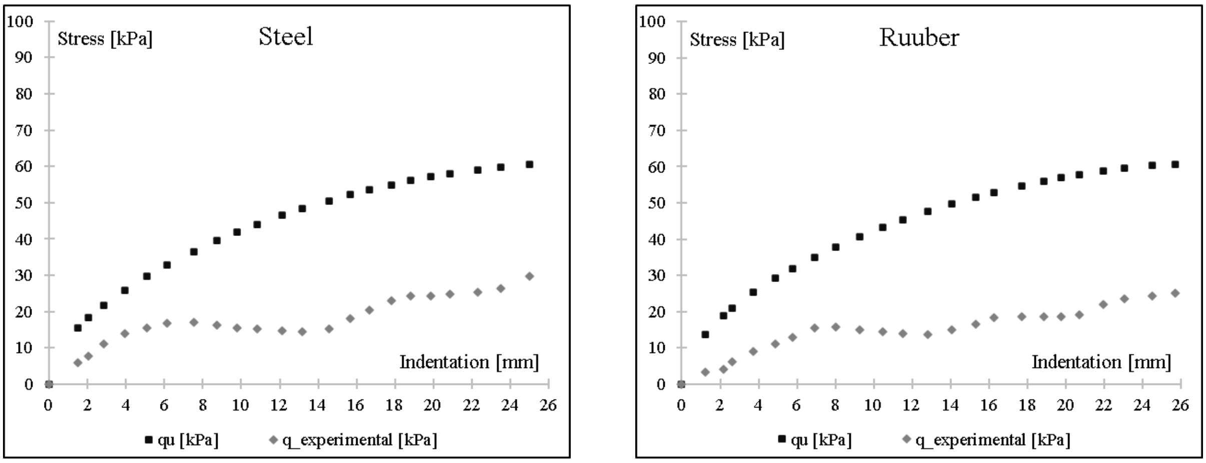


*Figure 5: Bearing capacity and experimental stress of the 18mm wheel in terms of the indentation.*

From the figures, it can be seen that the behavior of the experimental stress is similar when compared to the stresses obtained from the bearing capacity equation, although, as expected, experimentally lower values are obtained since it is a model made to simulate a real-life case in an unpaved road.

From this idea, we started to look for a function that would allow us to bring the experimental results closer to the theoretical ones. The function that allowed us to approximate the values as closely as possible was: $f(Z) = 0.45 + \frac{1}{Z^{\frac{3}{2}}}$, where Z represents the indentation depth.

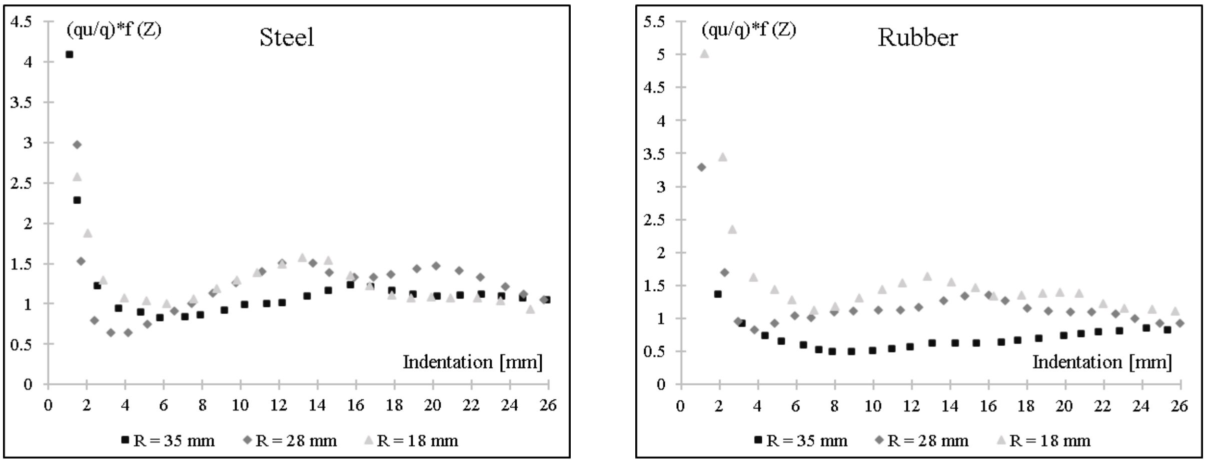

*Figure 6: Ratio between theoretical and experimental stress multiplied by the found function for each wheel radius.*

As can be seen in Figure 6, by multiplying the ratio between the bearing capacity and experimental stress by the function found, values approach 1.

With this, it has been possible to define a new formula for the stress caused by a wheel on a ground surface based on experimental tests with wheels of two different materials and three different radius.

Then, the formula for the stress caused by a wheel would be represented as:

$$q_{wheel} = q_u \cdot \left(0.45 + \frac{1}{Z^{\frac{3}{2}}}\right)\ [kPa]$$

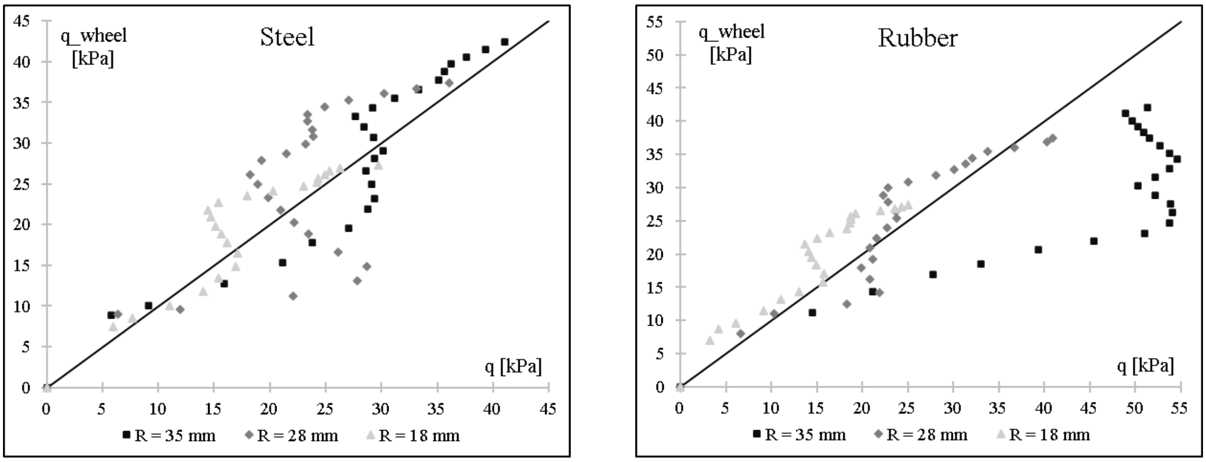


*Figure 7: Correlation between the found formula for wheel stress and the experimental stress for each wheel radius.*

Finally, as shown in Figure 7, there is a tendency towards a linear correlation between the results found experimentally and those calculated with the formula previously defined for a wheel. There is no major dispersion between the data, except in the $35mm$ rubber wheel, making us think that there may have been an error at the time of performing the test in that particular case. For the rest, it leads us to believe that it is a good approximation to know the stress of a wheel using the bearing capacity of the soil.

## CONCLUSIONS

In conclusion, based on an experimental test, it was possible to find a formula that allows to know the stress caused by the tires of a car according to the depth that is generated in the unpaved roads when washboarding is created. It is important to emphasize that the formula is based on the soil bearing capacity equation, so it will be necessary to consider the properties of the soil in which this analysis will be performed. The final results obtained lead us to believe that through the correlation between the bearing capacity of the soil and the stress caused in the contact surface of the test, no major experimental errors were made, but that undoubtedly it could be improved, and more wheel radius could be used or indented in other types of soils to make future comparisons.

Bearing capacity analysis for a circular indentation on a washboard road is a crucial aspect of geotechnical engineering that determines the maximum load that the soil can support before failure occurs. The washboard phenomenon can cause corrugations or ripples in the road surface, which can affect the stability of the soil and reduce its bearing capacity. Overall, this requires careful consideration of various factors and the use of appropriate methods. It is crucial in preventing structural damage, accidents, and costly repairs.

With what has been found, it could be considered feasible to carry out road studies in this way as a first approximation because it does not require major expenses and could benefit to know the necessary measures so that the road does not suffer damages or to see how to readapt it. It is evident that each case is particular in real life, but the exposed in this paper would have the possibility of generating more knowledge on the subject and that more people are interested in having better roads.

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