Towards the development of a digital twin for subsoil monitoring and stability against overturning of a mobile drilling rig

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Abstract -

Mobile drilling rigs are particularly susceptible to overturning due to the high location of their centre of mass. In some cases, overturning occurs due to a failure in the subsoil. Until now, machine operators are solely responsible for monitoring the machines' stability, and assessment of dangerous conditions is based mainly on experience. This investigation aims to set the grounds for elaborating a digital twin to online monitor the machine's stability to prevent overturning. Stress transmitted to the ground, tracks' settlement, and bearing capacity are calculated from a multibody simulation (MBS) and following existing standards. Furthermore, soil-dependent stability diagrams are generated to describe the stable location of the machine's centre of mass and predict soil failure. Results offer the possibility to function as an online alarm system running parallel to the machine's operation and alerting the operator about dangerous conditions.

Keywords -

Digital Twin (DT); Multibody simulations (MBS); Stability of mobile drilling rigs; Settlement prediction; Monitoring of bearing capacity

1 Introduction

Every year, the overturning of construction machinery causes several accidents worldwide. From 2007 to 2008, there were 38 fatalities and 679 injuries in the UK caused by the overturning of construction machinery, including drilling rigs [1]. Similarly, in the USA, there were 323 fatalities from 1980 to 1992 [2]. In Germany, there were 9 fatalities and 21 serious injuries from 1993 to 2003 [3]. Among the causes of these accidents is ground failure due to poorly prepared working platforms. Satoshi and Tomohito [4] summarize the operations before the accident, equilibrium conditions, and ground properties for a real case study of the overturning of a drilling rig. In this case, a ground penetration of the tracks was observed.

This publication investigates the idea of developing a digital twin to monitor the stability of the subsoil underneath the construction machine's tracks. A multibody simulation (MBS) of the mobile drilling rig is implemented in the Simscape environment of the software Matlab/Simulink. Signals simulating the reading of the internal machine's sensors are used to recreate working conditions. Following standards DIN EN 16228-1, DIN 4019 and DIN4017, the stress distribution, settlement and bearing capacity underneath the machine's tracks are estimated online for the MBS. For these estimations, local information about the soil properties is required. This work presents a mockup dashboard for an online monitoring system of the stability of the subsoil for limiting scenarios.

Additionally, stability diagrams are generated by analyzing the limiting conditions for the failure of the subsoil. Thus, stable areas are determined for the subsoil for all possible locations of the centre of mass. These could be helpful for on-site rapid stability checks or enhance current standards.

The company Liebherr has developed a system following similar industry standards [5]. However, this publication conceptually differs since the calculations of the location of the centre of mass follow an MBS. Furthermore, to the authors' best knowledge, the Liebherr system is based on the assumption of a rigid subsoil.

2 Theoretical framework

This section presents the theoretical tools used in this work. First, the idea of digital twins is briefly addressed. Secondly, the concept of MBS is mentioned, and then a review of the used standards is included.

2.1 Digital twins

In recent years, the fast development of simulation, data acquisition, data communication, and other technologies facilitated the interactions between physical and virtual spaces [6]. The digital twin's framework has emerged from this recent development as the natural consequence to merge simulations and physical space. A digital twin is defined as a comprehensive physical and functional description of a component, product, or system, including helpful information for present and future life cycle phases [7].

The idea of digital twins has been exploited at length in industries like product design, production prognostics, and health management [6]. Given that it is a new emerging trend, there is not a strict framework to define digital twins. However, most authors agree that a digital twin includes three parts: physical product, virtual product, and their connections ([8], [9]). Therefore, digital twins enable manufacturers and users to make accurate predictions and informed rational decisions.

The objective of the digital twin framework proposed in this work is the stress monitoring of the subsoil to avoid working conditions that could cause soil failure. The proposed simulation provides the backbone of an eventual one-to-one simulation with the possibility of intuitively extending it to include detailed machine internal mechanics.

2.2 Multibody simulations (MBS)

MBS are crucial for research areas like vehicle dynamics, robotics, biomechanics, etc. Thanks to the recent development in computational dynamics, MBS can run in real-time on digital computers and thus, are of great importance for the elaboration of digital twins. In principle, MBS are numerical simulations including rigid and flexible bodies with dynamics represented by their equations of motion [10].

One of the advantages of using the Matlab Simscape Multibody environment for MBS is the possibility of integrating a wide variety of elements from Simscape and Simulink into the model. This environment for 3D mechanical systems provides a block language including libraries to represent a variety of bodies, joints, constraints, force elements, and sensors [11]. Simscape internally solves the equations of motion for complete dynamical assemblies. Furthermore, Simulink libraries can be integrated to represent control systems, hydraulics, internal friction between elements, etc. Nonetheless, it is crucial to balance the objective of the created model and the complexity level since a higher complexity corresponds to longer simulation times. Thus, the real-time requirement to use it as a digital twin can be compromised.

Additionally, stand-alone applications designed to run in external hardware are supported by C-code generation in Simscape Multibody [11]. Models designed in this environment can be deployed in the internal computers of the mobile drilling rigs and work as digital twins to simulate and monitor the working conditions of the machine in real-time.

2.3 Review of industry standards

This section summarizes the standards used to estimate the stability of the drilling rig against overturning and the estimation of soil failure. These standards are incorporated in the MBS.

Stability calculations

The DIN EN 16228-1 standard [12] bases the stability standpoint of the machine by determining a maximum allowable tilting angle. Figure 1 shows the inclination of a drilling rig about a tilting edge located at the front of the tracks. The maximum allowable tilting angle α_{sr} about a given tilting edge is compared with the actual stability angle α_s. Therefore if $\alpha_s \geq \alpha_{sr}$, the analyzed operating condition is considered as stable. This industry standard proposes an offline calculation of this angle for all possible or expected operating conditions. After that, the smallest of all calculated α_{sr} is defined as the lower bound for α_s. This standard assumes a rigid subsoil for its calculations.

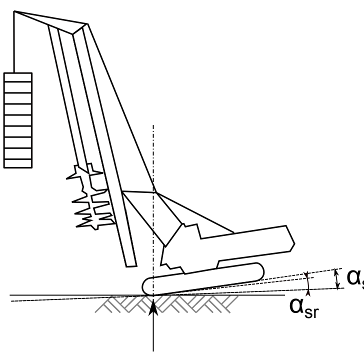


Figure 1: Determination of stability angles according to DIN EN 16228-1 [12]

Stress calculation

Several standards ([12], [13], [14]) describe the pressure transmitted to the subsoil underneath the drilling rig's tracks. These standards simplify the weight and forces acting on the machine using a resulting single-point load. This load represents the total drilling rig's weight, including lifted external weights. Then, the load is divided according to its proximity to each track, and an eccentricity is calculated. Figure 2 shows this simplification.

The stress distribution transmitted to the subsoil is calculated, assuming a trapezoidal distribution. Table 1 summarizes the different cases for different positions of the load along the tracks. Eccentricity e gives the position of the corresponding load acting on each track, and a and b represent the track's length and width correspondingly.

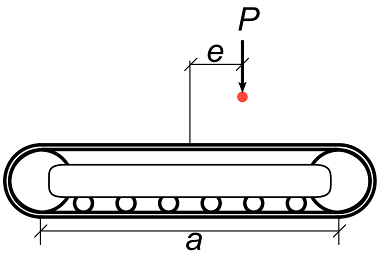
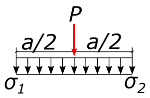
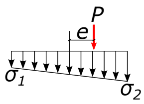
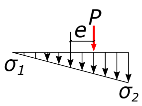
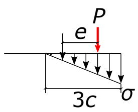


Figure 2: Simplification of a point load acting on one of the tracks

Table 1: Calculation of ground pressure transmitted to the soil

Diagram	Load position	Stress
	$e = 0$	$\sigma_1 = \sigma_2 = \frac{P}{ba}$
	$e < \frac{a}{6}$	$\sigma_1 = \frac{P}{ba}\left(1 - \frac{6e}{a}\right)$ $\sigma_2 = \frac{P}{ba}\left(1 + \frac{6e}{a}\right)$
	$e = \frac{a}{6}$	$\sigma_1 = 0$ $\sigma_2 = \frac{2P}{ba}$
	$e > \frac{a}{6}$ $c = \frac{a}{2} - e$	$\sigma = \frac{2P}{3cb}$

Settlement prediction

The calculation of the exact settlement of the subsoil is a challenging task due to the heterogeneous nature of soils. Standards work mainly as a reference in magnitude for the expected settlements. The standard used in this work for the settlement prediction is the DIN 4019 [15]. This standard uses the assumption of elastic half-space to determine the deformation behaviour of the soil ([16], [17], [18]). Equation 1 is used to calculate the stress σ_z at depth z caused by a stress σ_0 at the soil surface

$$\sigma_z = \sigma_0 \cdot i_{S,J}\left(\frac{z}{b}, \frac{a}{b}\right) \tag{1}$$

The factor $i_{S,J}$ depends on the shape of the load at the soil's surface. For a rectangular load, the factor i_S is calculated from equation 2.

$$i_S = \frac{1}{2\pi}\left[\arctan\frac{a \cdot b}{z \cdot R_3} + \frac{a \cdot b \cdot z}{R_3}\left(\frac{1}{R_1^2} + \frac{1}{R_2^2}\right)\right] \tag{2}$$

assuming $a > b$ and

$$R_1 = \sqrt{a^2 + z^2}$$
$$R_2 = \sqrt{b^2 + z^2}$$
$$R_3 = \sqrt{a^2 + b^2 + z^2}.$$

where a and b are the length and width of the tracks as shown in Table 1 and Fig 3.

For the case of a triangular load two different factors are calculated. For the case of the smaller side of the triangle i_J is calculated using equation 3 and for the other end, the same expression as in equation 2 is used.

$$i_J = \frac{1}{2\pi}\left[\arctan\left(\frac{b \cdot a}{z \cdot R}\right) + \frac{b \cdot z}{b^2 + z^2} \cdot \frac{R - \sqrt{b^2 + z^2}}{a}\right] \tag{3}$$

where

$$R = \sqrt{a^2 + b^2 + z^2}.$$

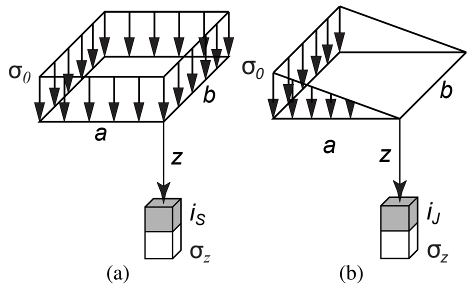


Figure 3: Geometric parameters for a rectangular and triangular load

Finally, the settlement is calculated using equation 4. Superposition is used to calculate the total settlement at the corner points.

$$s = \frac{\sigma_z b}{E_s} \tag{4}$$

Bearing capacity of soil under tracks

The bearing capacity refers to the soil's capability to withstand loads applied on them before developing a shear failure mechanism. This work uses standard DIN 4017 [19] for calculating the bearing capacity of the subsoil underneath the tracks of the drilling rig. Soil failure develops if the vertical load applied to the foundation is larger than the calculated resistance. For the calculations, soil properties are required, such as specific weight, cohesion, friction angle, foundation dimensions, and point load location.

Including the bearing capacity calculation in the digital twin integrates constant monitoring of the stability of the subsoil underneath the drilling rig tracks.

3 MBS of a mobile drilling rig

This section provides a detailed description of the mobile drilling rig's MBS. The environment chosen for the MBS is Simscape Multibody, part of Matlab/Simulink. The reason for choosing this software is the extensive libraries for simulating mechanical characteristics and control, allowing the extension of the proposed work to include more complex behaviour of drilling rigs in the simulation. Furthermore, Simulink provides a simple interface for implementing mathematical functions. Therefore, the calculations for settlement and bearing capacity were implemented using the block language of Simulink in the same model.

Simscape provides a simple solution to deploy stand-alone solutions from the developed model. A stand-alone application can be implemented on different hardware and run parallel to the machines as a digital twin.

3.1 Creation of the parts and assembly

The parts and assemblies in the MBS have intuitive interfaces to define their geometry and inertial properties. The geometry of all parts is parameterized, and the points of their cross-sectional areas are generated using trigonometric functions. Finally, the parts are extruded.

Joints impose primary kinematic constraints and depict each part's interaction with its neighbouring parts. These joints define the degrees of freedom -rotational and translational- between the connected bodies. Additionally, Simscape allows integrating internal mechanics and position or force control.

Figure 4 shows the final model of the drilling rig with three degrees of freedom consisting of the rotation of the uppercarriage (ϕ), the radial movement of the mast (d_M), and the inclination of the mast (α). The overall model's centre of mass (COM) is indicated by point C, and its position is monitored using an inertia sensor provided as a block in Simscape. The COM monitoring allows the calculations of pressure transmitted to the soil and, thus, the inclination and bearing capacity.

Furthermore, an external force (F_M) can be applied at the head of the mast to simulate lifting a load or using an external tool.

3.2 Results and analysis

This section summarizes the results of the MBS and the monitor of different machines' operating conditions. The presented plots are generated from collected data after several simulations. Therefore, they are not generated online. Nonetheless, when exporting the model as a stand-alone application, similar graphs can be generated using, for example, LabView software as an external interface to implement the real-time application.

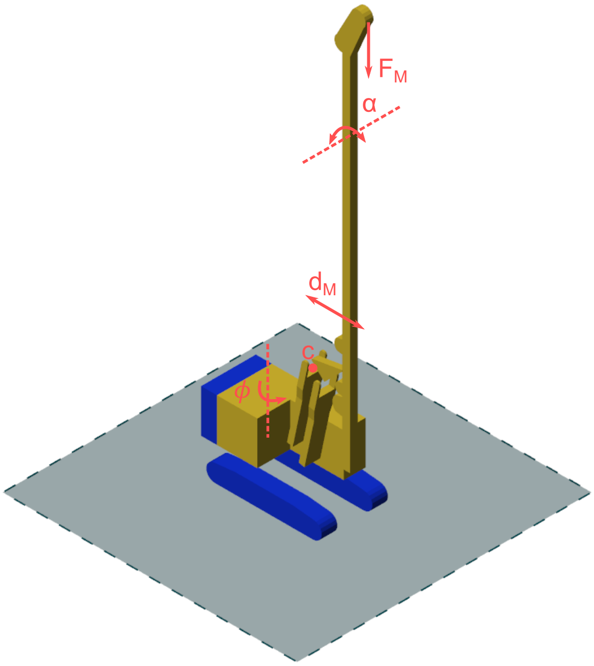


Figure 4: MBS of a mobile drilling rig

The machine dimensions and inertial properties used to obtain the results in this section are summarized in Table 2. The missing dimensions are approximated to a mobile drilling rig of the company Bauer model BG 23 H.

Table 2: Machine's dimensions and inertial properties

Parameter	Value	Units
Total machine's mass	58.97	tons
Tracks' length	5.00	m
Tracks' width	0.80	m
Undercarriage's width	2.58	m

The MBS includes several assumptions and simplifications necessary to keep the model simple enough to deploy a stand-alone online solution and use the methodologies included in the standards. These are summarized as follows.

a) The load on each track acts at the centre of the track's width.
b) The drilling rig tracks are rigid bodies and, thus, treated as a rigid foundation.
c) The soil elastic modulus has a restrained lateral strain.
d) The inclination of the drilling rig is neglected, and thus, the predicted settlement is not feedback to the

model.

e) The subsoil is idealized as horizontal.

f) The machine's force vector does not incline.

Assumptions a), b), and c) are necessary for all standards considered in this work. Assumption d) simplifies the created model since otherwise, the model would need an iterative calculation, and thus the online monitoring would be compromised. Assumptions e) and f) are considered to simplify the estimation of the allowable bearing capacity.

For the scope of this work, an operating condition of a drilling rig is considered stable if the two following conditions are simultaneously avoided:

1. The force vector of the COM points in a direction towards a point outside the machine's drilling rig's body.
2. The allowable bearing capacity is exceeded for the current location of the COM.

Two approaches are presented as an analysis of the results of the simulation. The first approach includes the creation of radial plots where stability areas are drawn for different combinations of soil parameters and the location of the COM. The second approach provides an insight into online monitoring of the estimated transmitted stress, settlement and bearing capacity.

Stability areas depending on COM location and soil characteristics

The MBS model is used to determine stable operating areas. The COM of the drilling rig is shifted by simulating the lifting of a load. The total weight of the load is increased stepwise until one of the two mentioned conditions is reached, and thus, the machine's stability is lost. The weight acts at the top of the mast as the force F_M in Figure 4. This process is repeated for a 360 ° uppercarriage rotation (ϕ) with a step size of 10 ° while keeping the mast's position constant. The load is increased in intervals of 500 kg.

Following this methodology, diagrams for different clays and sands are generated. Tables 3 and 4 summarize the tested soil conditions.

Table 3: Characteristics of different clays

Parameter	Values	Units
Friction angle [φ]	[12, 20, 28, 30]	°
Specific weight [γ']	16.5	kN/m^3
Cohesion [c]	20	kPa
Elasticity [E_s]	40	MPa

Figure 5 includes the stable areas for the clays mentioned in Table 3. The closed trajectories show the stable areas for the COM location and the position of the upper carriage. $\phi = 0$ is assumed as the position shown in 4. The two stability conditions are simultaneously checked for each configuration. The points marked in red indicate the loss of the machine's stability due to the appearance of condition 1, the force vector points outside the body. The failing due to condition one only happens at angles close to 90 ° (or 270 °) for small friction angles, and it is completely avoided for the smallest friction angle $\varphi = 12$ °. Keep in mind that a failure of the subsoil does not necessarily mean that the drilling rig will overturn. However, it is assumed that this situation is dangerous enough to be considered critical.

Table 4: Characteristics of different sands

Parameter	Values	Units
Friction angle [φ]	[25, 32, 41]	°
Specific weight [γ']	18	kN/m^3
Cohesion [c]	0	kPa
Elasticity [E_s]	30	MPa

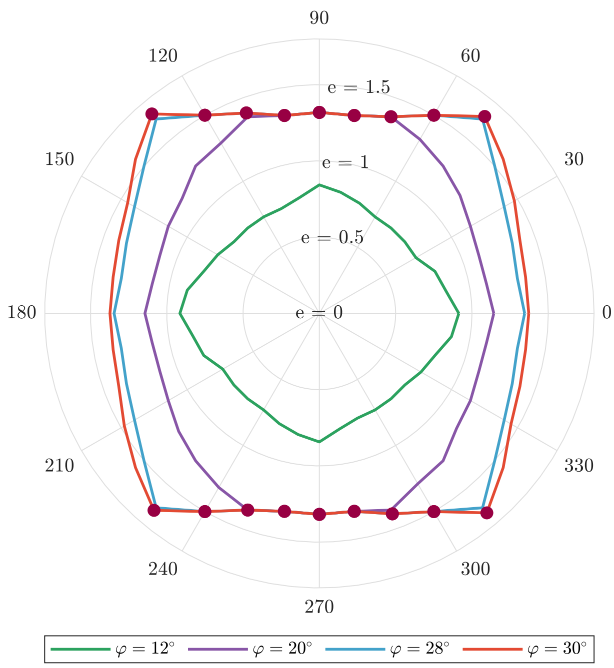


Figure 5: Stable areas for clays with $\gamma' = 16.5$ kN/m^3

Figure 6 includes the stable areas for the sands mentioned in Table 4. Notice that for $\varphi = 25$ °, the stable area draws a perfect circle. This behaviour occurs because, for that specific friction angle, the soil fails for all possible positions of the uppercarriage; therefore, the second condition for unstable behaviour is fulfilled without the need of adding an extra load. The red dots indicate failure due to condition 1 for that combination of parameters.

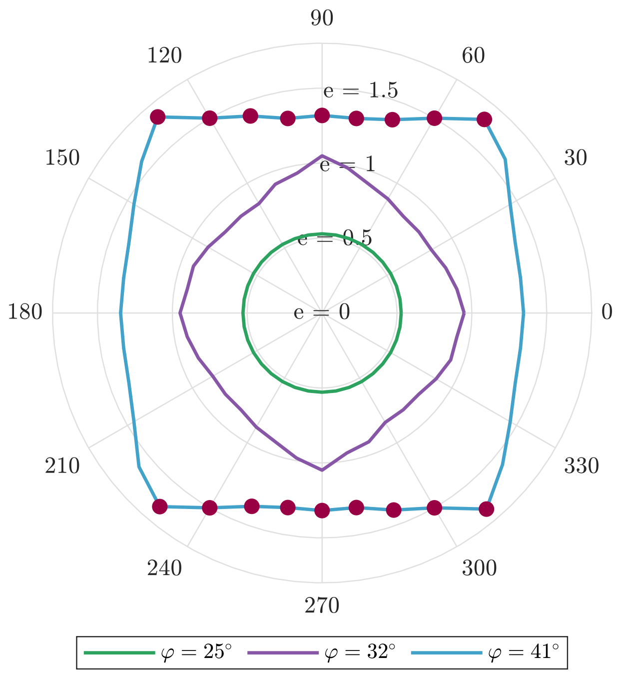


Figure 6: stable areas for sands with $\gamma' = 18$ kN/m^3

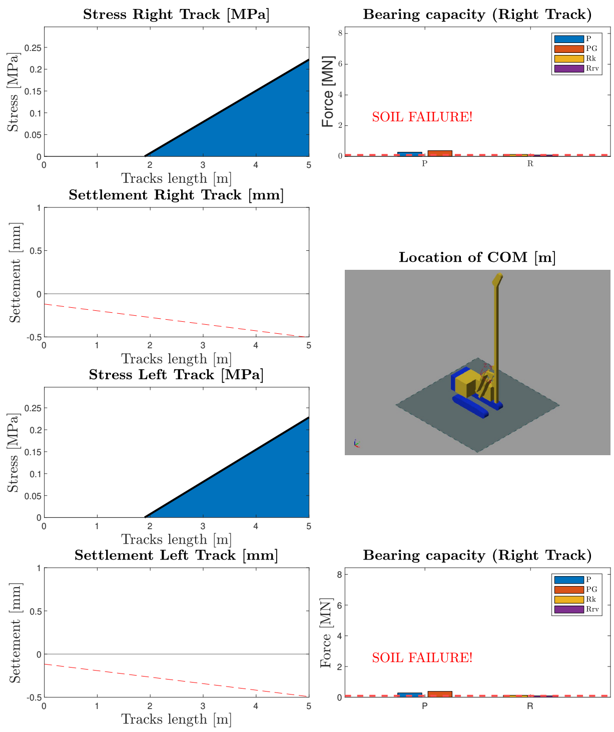


Figure 7: Dashboard for the case of $F_M = 90$ kN, $\phi = 0$, and $d_M = 2.4$

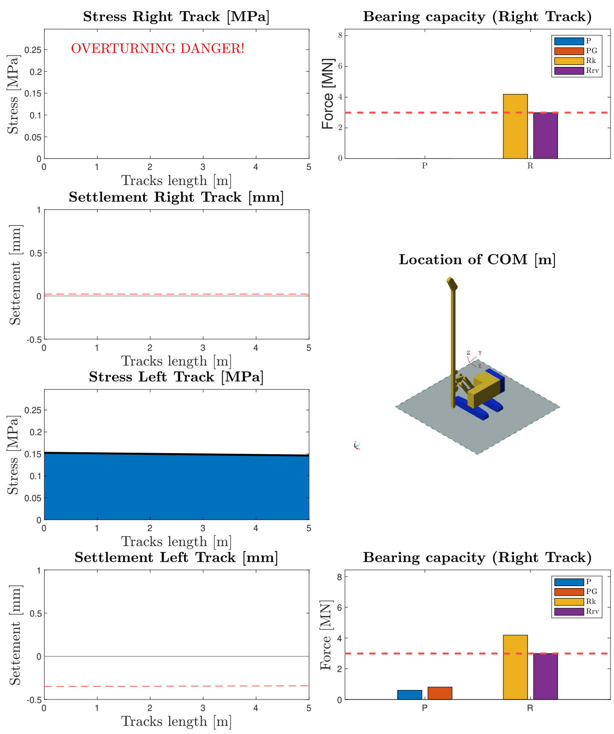


Figure 8: Dashboard for the case of $F_M = 90$ kN, $\phi = 90$, and $d_M = 2.4$

Towards an online machine's stability monitoring

Figure 7 and Figure 8 show examples of what a dashboard for the monitoring of the stability of the mobile drilling rig could look. These plots are again generated offline; however, similar plots will be created after developing the complete stand-alone application. Plots in the dashboard include stress distribution underneath the tracks, the track's settlement and the bearing capacity of the subsoil. If the allowable bearing capacity is surpassed at any point, an alarm is displayed.

Figure 7 displays the warning that the current working condition could cause a soil failure. The warning occurs since the stress distribution is triangular, as seen on the dashboard's left-hand side. Therefore, reducing the contact area between the drilling rig's tracks and soil, concentrating the machine's weight into a smaller contact area and thus, drastically reducing the bearing capacity of the subsoil. In this scenario, stability condition 2 is violated, while condition 1 remains unchanged.

Figure 7 shows another dangerous working condition displayed in the dashboard. In this case, the total stress in the right track is zero, meaning that the force vector acting at the COM is located outside the drilling rig's body, thus causing a rotational moment. This situation could cause the drilling rig's tip over. The pressure on the subsoil underneath the tracks, for this case, remains far from approaching the bearing capacity. This situation violates stability condition 1 while stability criteria 2 remain unchanged.

4 Conclusions and outlook

This work introduced the first steps for developing a digital twin to monitor the stability of drilling rigs. The stability monitoring combines existing industry standards and focuses on redefining the concept of stability for drilling rigs to include soil conditions. This work presents an insight into the results of this new stability concept and the perspective of developing a digital twin to online stability monitoring, providing examples of how this system could look for limiting cases. The results of this work seek to include basic information about the soil in the stability assessment of drilling rigs since current standards are based solely on the assumption of a rigid subsoil for their calculations.

Extensive work elaborating on the presented results must still be done to achieve full online stability monitoring and a complete digital twin. Experiments should be conducted to establish communication with the internal sensors on existing drilling rigs since this is crucial for the real-time use of the developed system. Suitable hardware should be selected for this purpose, considering the possible training required for the machine operators to use it and the involved costs.

It should be clear that the stand-alone application works in real-time with current simplifications and assumptions; afterwards, the simplifications should be gradually eliminated to include a more realistic digital twin. Furthermore, numerical calculations using the finite element method (FEM) with state of the art constitutive soil models and field measurements should be carried out to improve the stress estimation underneath the tracks. Preliminary results show that the assumption of the trapezoidal distribution results in an oversimplification. Then, a correction function for the stress should be defined, and a new soil stability criteria should be created.

5 Acknowledgments

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