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HORIZONTAL DRILLING MACHINE

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Abstract. *Installations of sewer pipes are usually manual and very difficult in Brazil, this study's objective is to create a machine to facilitate this work. Initially an analysis of the soil was made, mainly in the region of Maringá, Brazil. The necessary torque to the motor and the stress to the hydraulic actuator were calculated, and the hydraulic system needed to actuate both of them was defined, using the same power unit, to have a more compact machine. It was necessary a system to inject water, in order to reduce the resistance of the soil, but the volume of water couldn't be excessive giving to the soil the characteristic of mud. The idealized system has a bushing that receives the water and, by pressure, in an orifice, drives it from the beginning of the machine to the drilling tip. The structural base was elaborated like the models of tips to different situations found in the underground, like roots and stones. Since the initiation of the study, the mainly objectives were small size, fabrication facility and low price. The objectives were achieved.*

Keywords: *Machine, Drilling, Pipes, Perforator, Ground*

1. INTRODUCTION

The sewerage networks are fundamental to the wellbeing and health of a society, being, even, an index to evaluate the development of a country, as in the case of the HDI (human development index). The form of construction of these networks involves the trenching and opening of manholes, allowing high control of the working process, but bringing serious problems to the society. It is in these cases that the Non Destructive Methods are becoming important. The called Non Destructive Method (NDM) uses special machines that pierce the soil horizontally, between two access points, where the tubes will pass. Such accesses cannot have dimensions in which the equipment and accessories do not fit, as well as the operator, and cannot be so extensive that occupy the width of a building. So, it is not necessary to break down the entire length of the sidewalk or asphalt, under which will pass the installation. This NDM method is extremely helpful in the crossing of heavy traffic roads, once the vehicular traffic will not be injured by the works. The execution of the work by means of this procedure also avoids major replacement of original floors, which is not always satisfactory. This technological progress of civil works to allocate the underground ducts is quite a debated subject in the town hall evaluation about the expansion of network in urban areas already consolidated.

Still about the ducts implementation, the insertion method varies according to the soil characteristic, which is mostly composed of clayey and sandy soil, containing pieces of rocks and roots, requiring the engine to be forced to fulfill its maximum performance. Another problem that still persists is the noise caused by these robust engines, many times specified incorrectly. According to COUTINHO (2007), the uses of NDM have the disadvantages of requiring complete and detailed mapping of others networks in the underground, longer operation planning, skilled labor and constant update of knowledge about the constructing process. However, less space is needed to the execution of the work, generating less impact to the population, more speed, less cost of urban and environmental reconstitution, less movement of the soil, possibility of divert interferences in congested areas and no use of natural resources to decomposition of ditches or manholes.

Currently, directional drilling machines (horizontals) already exists in the market, however are sized high, to drill holes up to one and a half meters, which do not fit in the reality of urban sewer pipes and, furthermore, is expensive. To do so, a study was developed for a smaller drilling machine. In this work, the rotational and linear motion required by the machine is studied, having as objective to define an applicable engine and hydraulic system to the small drilling machine. At the same time, scale a water injection system in the soil drilling, which humidifies the soil, reducing the stress inflicted by it. Initially, started to the study of the various types of existing engines, these include three types for application in these drilling machines: internal combustion, electrical and hydraulic engines.

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2. MATERIALS AND METHODS

Based on a Soil Mechanics analysis about the resistance found in a horizontal perforation, the situation illustrated on the Figure 1 was found:

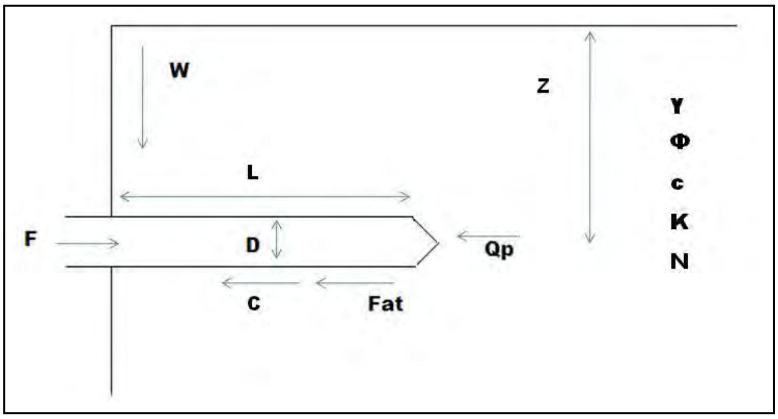

Figure 1. Stress Analysis in a horizontal perforation

Where F is the force requested to perforate the soil, γ is the specific weight, Fat is the friction force between the soil and the axis, Φ is the friction angle, C the cohesion force (cementation), c the specific cementation, Qp is the penetration resistance, K a factor based on the type of soil, W is the weight of the ground on the penetration axis, N is the penetration index and D is the diameter of perforation. All these factors will influence the resistance, ergo, the power needed to the equipment.

Soils that have an elevated void index, ergo, an elevated value to the ratio void volume above solid particles volume, intend to permit the penetration to be done by just compressing the ground sideways to reduced diameters. However, to make this possible, the drill head need to have a geometry that permits the land to leak, otherwise the land will make a built-up edge that affects the penetration.

Considering it, five models of head drills were initially developed and, based on the collected information, have the geometry requested. So the geometry that would have a better resistance was calculated. As a facilitator, the material of the head drill was fixated, just checking the answers to the stress existent.

In order to draw the models and after simulate the geometry, the software CAD SolidWorks was used. In the step of simulation, the reply of the needed stress like penetration force was checked, that is a constant force orthogonal to the surface, and the cementation force, tangent to the side of perforator element. From the simulation was obtained the Von Mises stress, as well as the reply expected of the land of each geometry, making possible the determination of the best geometry to the perforator element.

After dimensioning the drill head, the development of the components that would form the equipment was started. All the calculations were based on the soil analysis and the geometry of the cutting head. The equipment that would have rotary and linear movement to the perforator axis was idealized to this machine, so a motor and a hydraulic actuator were studied before and after the hydraulic system needed and the structure of the machine.

2.1 Hydraulic Actuator

To determine the characteristics of the hydraulic actuator, the types of the existents actuators were checked, and a double action actuator was chosen, in which the fluid pressure is applied to the piston in both directions, so the force is applied in the advance and the return.

Furthermore, the pressure of operation and the requests to the hydraulic system were calculated. The Equation (1) is the base equation to this development.

$$Ff = \pi^2 E J / c^2 \quad (1)$$

Where Ff is the force that the fluid need to overcome, E is the modulus of elasticity of the material, J is the polar moment of inertia and c is the free length of buckling (IRLAN, 2001).

$$C = L / 2 \quad (2)$$

Where L is the length desired to move the perforator axis.

$$J = \pi^2 (dh)^4 / 64 \quad (3)$$

Where dh is the intern minimal diameter, that definition is given by Equation (4).

$$dh = (7{,}22\ Ft\ c^2 / E)^{0{,}25} \quad (4)$$

Where Ft is the total force applied with a safety of security.

Finally, the pressure of operation can be calculated with the Equations (1) to (6), and this pressure will be one of the characteristics of the hydraulic system.

$$P = Ff / A \quad (5)$$

$$A = \pi\ dh^2 / 4 \quad (6)$$

2.2 Motor

Each motor has one specific principle of operation, so the combustion motors, electrical motors and hydraulic motors were studied to choose the best alternative to this machine. Because of the use of a hydraulic actuator, a hydraulic motor that could use the same hydraulic system was chosen.

The calculation of the motor was based on the Equation (7)

$$P = T\ 2\pi\ n / 60000 \quad (7)$$

Where P is the minimal potency, T is the torque generated by the perforation and n the rotary speed.

From the soil mechanic analysis, the torque could be determined by the Equations (8) to (11).

$$T = (C + Fat)\ D / 2 \quad (8)$$

$$C = Al\ .\ c \quad (9)$$

$$Fat = \gamma\ Z\ (\tan \phi\ \pi / 180)\ Al\ 1000 \quad (10)$$

$$Al = \pi\ D^2\ L / 4 \quad (11)$$

The operation principles of the hydraulic motors change with each type. To this equipment a gear motor was selected. This type of motor has a reduced size, can rotate in both directions and has a better tolerance to dirt. It can operate in low and high speed, and the torque is generated by the pressure applied to the surfaces of the cogs.

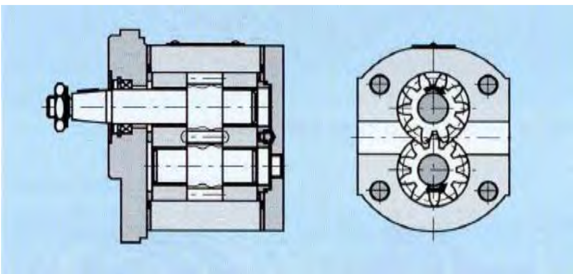

Figure 2. Gear Hydraulic Motor

2.3 Hydraulic System

A hydraulic system is a series of hydraulic equipment supplied by a fluid and linked by hoses and connectors where the fluid circulates in the system transforming hydraulic energy in others forms of energy. In this equipment the transformation is hydraulic energy to mechanic energy, in the hydraulic actuator and in the motor. Furthermore there are other important components like pumps, reservoirs, coolers and etc.

There are many types of pumps, with several uses. To this project was selected an External Gear Pump, whose principles are showed on the Figure 3.

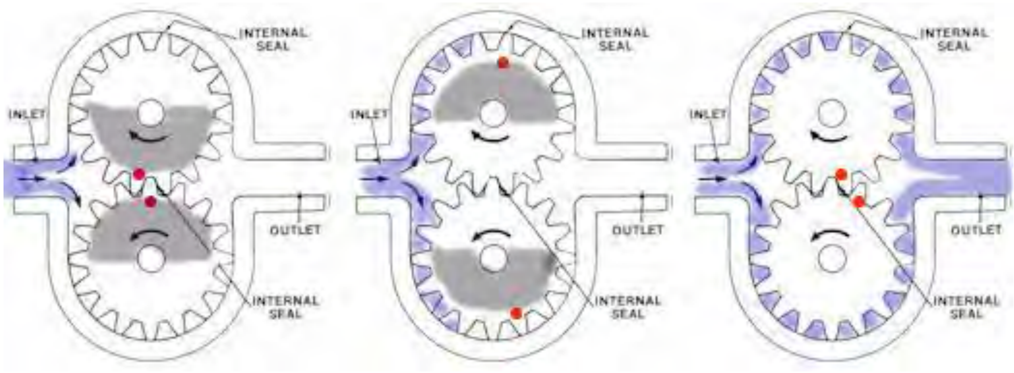

Figure 3. External Gear Pump

The selection of the reservoir is made considering the type of reservoir and the capacity, usually three times the pump output. Figure (4) shows the type of suspended reservoir that was chosen.

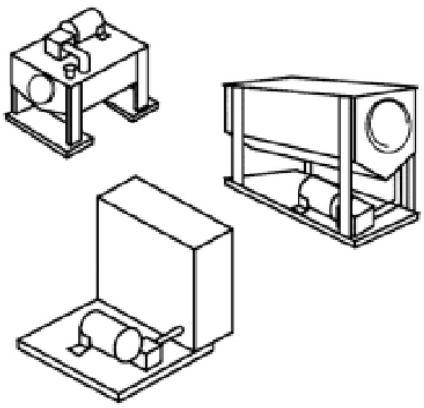

Figure 4. Types of Reservoirs

The other equipment changes according with each system, fabricant and will of the owner of the equipment, so this development was not realized in this project.

2.4 Perforator Axis

To the perforator axis, torsion and flexion analysis were made, establishing maximum and minimum effort parameters and changing materials to verify a maximum length of perforator.

Started with the torque analysis applied to the axis, based on it dimension. The Figure 5 represents these important dimensions.

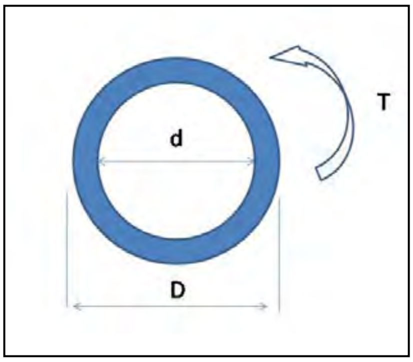

Figure 5. Important dimensions to the torque analysis

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The torque T allocated at the extremity of the drill head, given by the cohesion and friction forces with a polar inertia momentum showed on Equation (12), can find a maximum shear stress indicated on Equation (13).

$$J = \pi/32(D^4 - d^4) \quad (12)$$

$$\tau_{máx} = (T \cdot c)/J \quad (13)$$

Where c is the extreme radius of the axis.

Also is possible to find the maximum deformation, in radians, given by the Equation (14).

$$\emptyset_{máx} = (T \cdot L)/(J \cdot G) \quad (14)$$

Where L is the axis length, G is the rigidity module.

So a scenario was drafted of the flexion analysis on the drill head at Figure (6). With the expected length of the axis, the weight of the drill head and the weight of the axis, both with the defined diameter, we could find the bending moment, and the shear force.

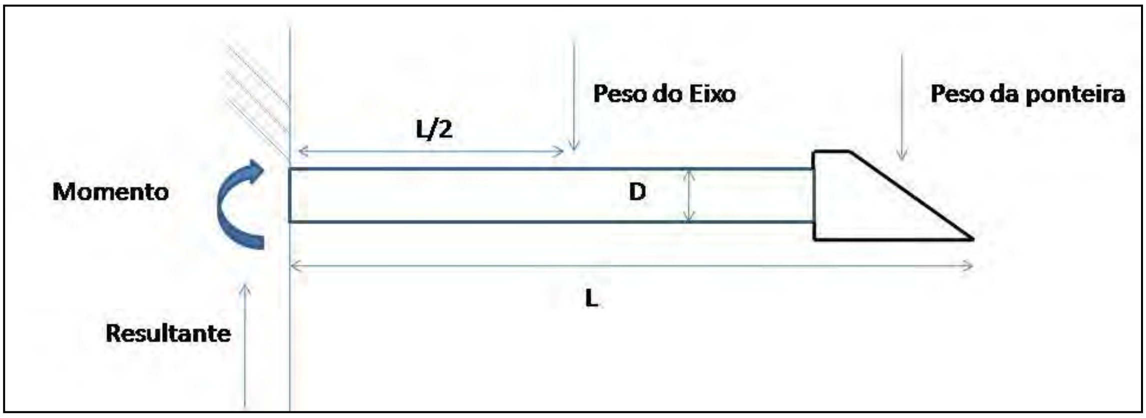

Figure 6. Shear and Momentum Analysis

The analysis was made considering a load concentrated at the extremity (drills head weight) and another load concentrated on the center of the axis (axis weight). So, the diagrams of shear and momentum were found.

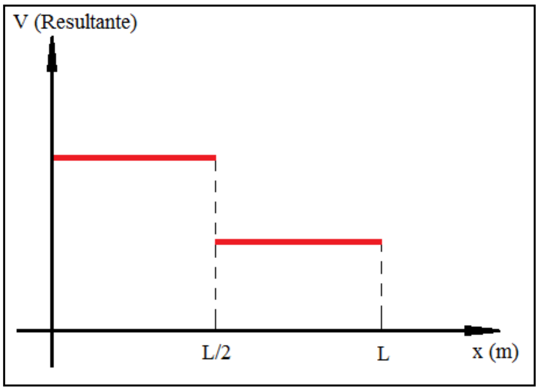

Figure 7. Shear force found

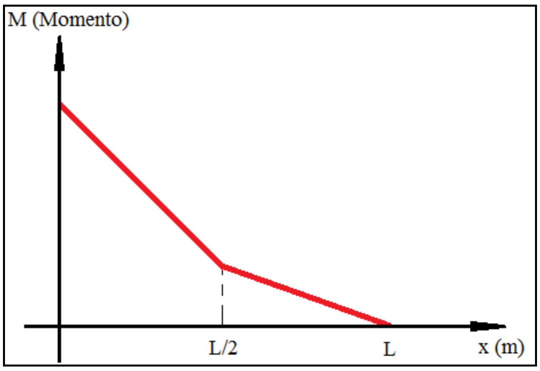

Figure 8. Bending moment found

According with the Figures (7) and (8), it was concluded that the maximum effort is on the fixation extremity.

Considering that the axis will perforate rotating, the effort condition is dynamic, and the tensions are alternated, so the resultant tension is null. Following with the analysis, is needed to find the corrections coefficients to the fatigue resistance analysis, showed on Equation (15).

$$Se=C_{load}\ C_{size}\ C_{surf}\ C_{temp}\ C_{reliab}\ Se' \quad (15)$$

Where Se is the corrected fatigue resistance, Cload is the correction coefficient of the load, Csize of the size, Ctemp of the temperature, Creliab of the reliability, and Se' is the non-corrected fatigue resistance, that is equal to the half of the limit resistance to tensile.

So, to finish this analysis, the safety of security is calculated on Equation (16).

$$N= Se/\sigma_{alternada} \quad (16)$$

The software Microsoft Excel was used to make interactions changing the axis material, in order to find greater length of perforation, with acceptable safety of security. The analysis was made considering a single axis with 0,5 meters of length, but the axis are connected to each other, reaching the length of perforation desired.

2.5 Water Injection System

As seen in the equations above for sizing the motor and actuator, one factor that greatly alters the result of calculated efforts is the index of penetration resistance. This index depends directly on the soil type, condition and humidity.

According to Pinto (2002), the behavior of a soil depends on the relative amount of each of the three phases (solids, water and air). Several relationships are employed to express the proportions between them. At first, the amounts of water and air may vary. The evaporation can decrease the amount of water, replacing it with air, and the compression of the soil may cause the water and air outlet, reducing the number of voids.

Some concepts are important to the understanding of the humidity, which is the ratio between the water weight and the weight of solids, and the Voids Index, ratio between the volume of voids and the volume of solid particles.

The soil of the studied area is clayey. When handling clay, some consistence is noted, unlike the sand, for example, that dislocate easily. For this reason, the state in clay usually is indicated by the resistance it represents. (Pinto, 2002).

Depending on the compressive resistance, the consistence of clay is expressed by the terms shown in Table 1.

Table 1. Relation between the Consistence Index and the Resistance to Penetration

Consistence	Consistence Index	Resistance [kPa]
Very soft	<<0,5	<25
Soft	<0,5	25 - 50
Normal	0,5 – 0,75	50 – 100
Stiff	0,75 – 0,9	100 – 200
Very Stiff	0,9 – 1,0	200 – 400
Hard	>1,0	>400

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When the clay is reshaped, its state can be expressed by the Voids Index. However, as it is very common that clay is saturated, and, in this case, the Voids Index depends directly on the humidity, the state of clay is usually expressed by the moisture content. But the moisture content, by itself, does not indicate the state of the clay. Is needed to analyze it in relation to the moisture content corresponding to similar behaviors. These contents are the limits of consistency. The Figure (9) shows a diagram in which contains the limits of consistency, according to Atterberg. (Pinto, 2002).

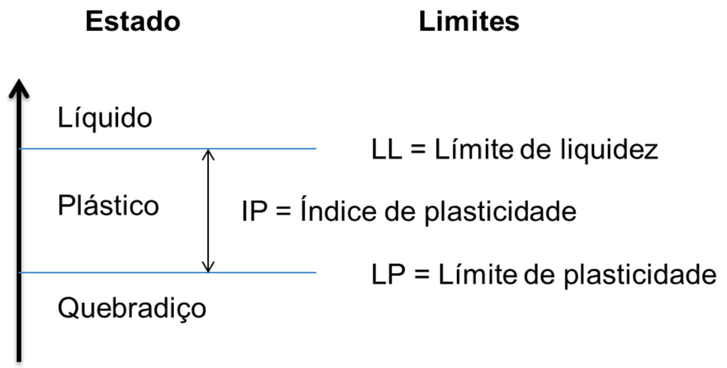

Figure 9 – Atterberg limits of the soils

To indicate the relative position of the moisture to the limits of change of state, Terzaghi proposed the following relationship:

$$IC = LL – w / LL - LP \quad (17)$$

Therefore, this equation can express the consistency index, which will provide the value of penetration resistance, depending on the humidity and, of course, the type of soil.

To know the mass of water required based on moisture, a control volume was stipulated in the region of the tip, as depicted in Figure (10).

$$V = w\, \pi\, D^2\, L /4 \quad (18)$$

$$V = w\, \pi\, (6{,}5 \,.\, 25{,}4 \,.\, 10\text{^-}3)^2 / 4 \quad (19)$$

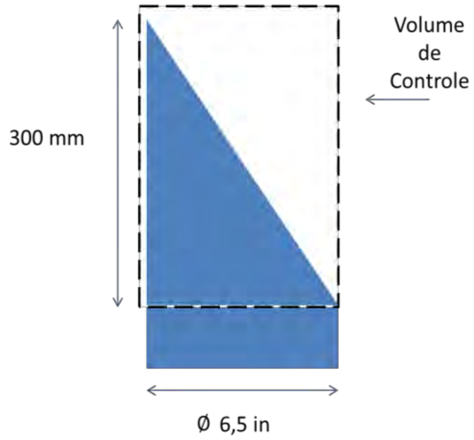

Figure 10 – Adopted control volume to calculate the flow

Taking as an average time for moving this tip in theses 300 millimeters like 1 minute, the required flow to the water injection system becomes:

$$Q = 6{,}4\, w\, [l/min] \quad (20)$$

Verified the advantages of adopting a water injection system and the required flow, it was sized. The main difficulty to overcome is the rotary motion of the cylinder, because the only place where the water would be injected without have

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the effects of the rotation would be in the center of the cylinder. However, in this position is coupled the engine shaft to generate the movement.

It was thought then on systems that do not possess internal hose, but a channel for water displacement. After several idealized systems, two were possibly efficient, and are shown in Figures (12) and (13).

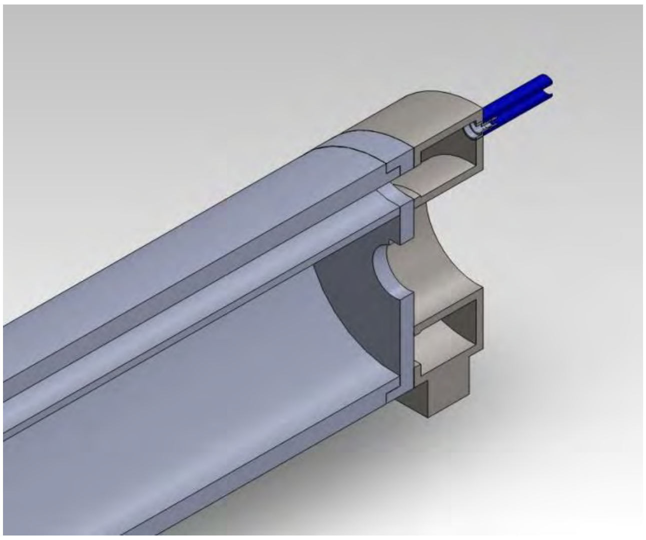

Figure 12 – Water injection system with back support

In this system there is a piece which was called the water tank. This reservoir is responsible for receiving water through a hose, store the water and cause to be sent to the cylinder through the rip present therein. The idea is that as the water pressure inside the reservoir increases due to the insertion constant of water by the hose, the water will seek an escape route, which is the path inside the cylinder and which will lead the water to the tip. The cylinder would rotate through the middle piece that receives the torque of the motor by means of the key, and passes to the cylinder through the thread.

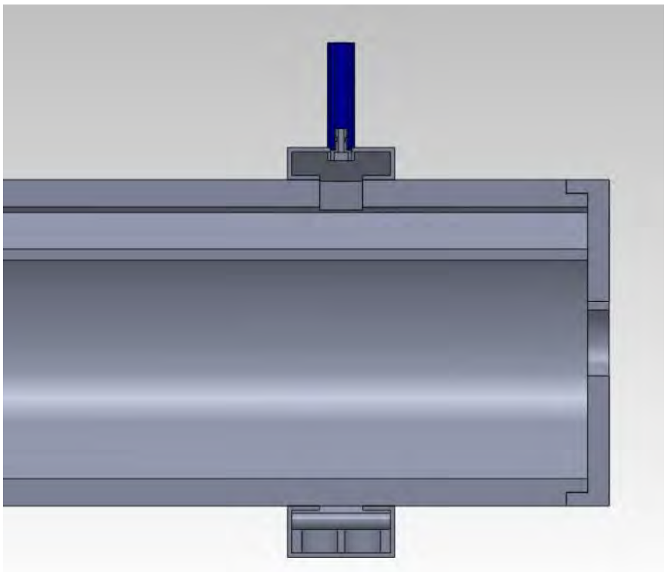

Figure 13 – Water injection system with reservoir bearing

In the system of Figure (13), there is the reservoir support in the form of bearing, to sustain the cylinder and receive the water injection at the same time. The hose is coupled to the upper part of the piece, so the water is inserted into the water tank, and it has two openings for release the water into the cylinder, one in the top, capturing directly the water from the hose, and the other at the rear, so that when the reservoir is full, the water can be released through it.

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3. RESULTS AND CONCLUSIONS

The soil analysis was made considering the region of Maringá, so the type of soil is Clayey Silt. The characteristics of this soil are given on Table 2:

Table 2. Soil characteristics of Maringá

Φ	22º to 28º
γ	15 kN/m³
c	15 kPa
K	250 kN/m²
N	5 (softened) / 10 (hard)

With those data it is possible to find the resistance that the perforator axis will face. Considering the parameters in Table 1, and using a perforator axis with 152,4 millimeters (6 inches) of diameter and a drill perforator measuring 157,8 millimeters (6 ½ inches), and a length of 500 millimeters, the minimum force of penetration was verified, that is approximately 54 kilo newton, considering hard soil. This configuration was the best alternative found in this project, so it was chosen to this machine. This and others configurations were studied in a worksheet changing values and simulating in finite element software: SolidWorks.

Defined the geometry of the axis, the geometry of the drills head was studied. Five models were idealized, changing angles and sizing, regarding the requests of easy fabrication and compactness. All models were simulated on SolidWorks, and the results are showed on Table 3. Is important to check that the conical format has the greater safety of security, but, due to the geometry in this model when in operating, is noted the built-up edge cutting due to the incrustation of mud, so this model cannot be chosen. The defined model is showed on Figure 9.

Table 3. Simulation results of drills head changing geometries

Model	Von Mises Stress (MPa)	Deformation (mm)	Safety of Security
Chamfer 30°	45	0,0114963	4
Chamfer 60°	14,5	0,00446438	6
"V" format 30º	41	0,0102039	5
"V" format 60º	36	0,00934156	6
Conic	14	0,00301577	15

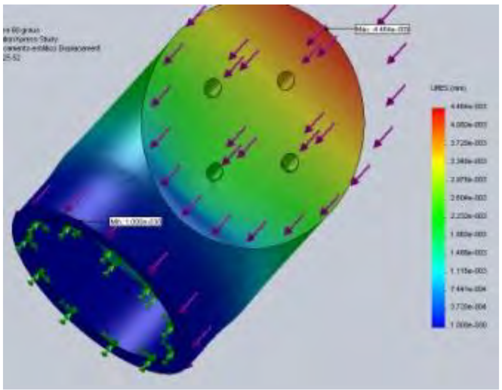

Figure 14. Defined geometry in simulation

To determine the motor torque, there are the Equations (7) to (10), so considering the values of the soil resistance of Φ = 28º, γ = 15 kN/m³ and c = 15 kPa, it is found 1,095 m², 13093,87 N and 16,417, so the torque is approximately 1 kN.m, so the minimum potency to the motor is 6,28 kW.

In the axis analysis it is considered a torque T of 1 kN.m, so there is a maximum shear tension of 6 MPa. With a length of 20 meters (total length desired to perforator with 40 sections), and G equal to 80,8 GPa there is a maximum angle deformation of 0,02 rad. Considering this and the material carbon steel, density of 7800 kg/m³, Elasticity module of 206,8 GPa, Sy of 345 MPa and Sut of 621 MPa, results the alternated and average tensions of 256 MPa and 0 MPa, respectively.

The correction coefficients to the fatigues resistance is given on Table 4.

Table 4. Correction coefficients to the fatigues resistance

Type	Effect	Value
Load	Flection	1
Size	0,3 pol ≤ D ≤10 pol	0,73
Surface	Sut < 100 kpsi eroded	0,3
Temperature	T < 450º C	1
Reliability	99,999	0,659

Calculating Se with the Equation (15) the result was 44,8 MPa. But calculating the safety of security results in 0,18, unacceptable value, so values were changed to the length of perforation and the axis material. The main results are given on Table 5.

Table 5. Relation Material versus length of perforation

Material	Length of Perforation (m)
Carbon Steel 1010 – cold rolled	5
Carbon Steel 1050 – hot rolled	7
Carbon Steel 1095 – quenched and tempered at 400ºC	10
Tool Steel L – 2 quenched and tempered at 400ºC	13
Tool Steel S – 5 quenched and tempered at 400ºC	14

Based on Equations (1) to (6) it is possible to calculate the hydraulic actuator considering an elasticity module of 200 GPa, a free length of buckling of 2 meters, because the soil will sustain the axis and with 2 meters there are 4 cylinders sustained by the actuator, and knowing the perforator effort needed, 54 kN, the minimum diameter to the actuator is 53,34 mm (2,1 in). Considering that this diameter is not usual, an actuator was defined with 82,55 mm (3 ¼ in) getting better resistance and security, and a length of the haste equal to 0,5 meters, so it is possible to perforate one section of the perforator axis each advance of the actuator. The pressure of operating is 78 bar.

The motor and actuator will need a hydraulic pressure to work, so is needed to define the hydraulic system. The Figure (15) shows the basic scheme. This system needs a pump that has an electric motor rotating to 1750 rpm with a pressure of 78 bar (maximum pressure request), so the pump output is 18,43 l/min.

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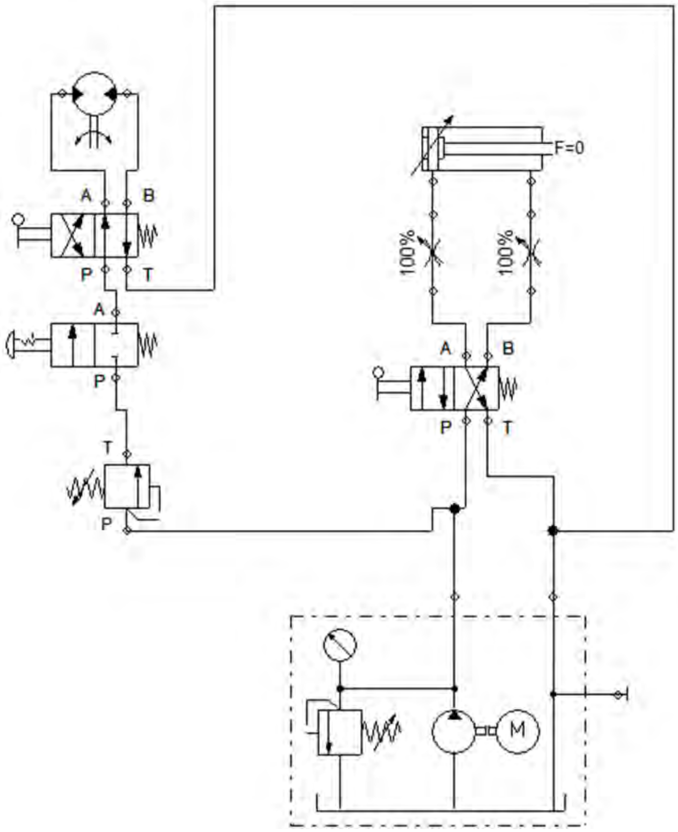

Figure 15. Hydraulic system outlined

The system is compound by one reservoir with 60 liters of capacity from the fabricator PARKER, a hydraulic pump model D11 (PARKER) with capacity of 78 bar of pressure and 18,5 liters per minute, with an electric motor operating 1750 rpm with a potency of 10 CV, model W22 (WEG). A directional valve piloted by lever spring returned to control the actuator, with a valve controlling flow, and to the other way, a pressure reducing valve, a bottom spring returned to turn on and off the motor, and a directional valve piloted by lever spring returned to control the direction of rotation of the motor.

To the creation of the structure I beams profile, patterned, and sheet metals with thickness of 12,7 millimeters (1/2 in), both in Steel AISI 1020 were used. The elements were configured thinking about the request angle of perforation. The Figure (16) show the structure dimensioned. All the elements were simulated on SolidWorks.

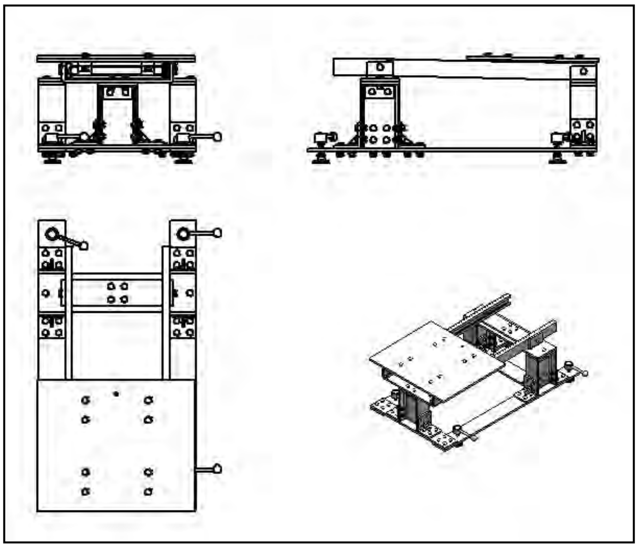

Figure 16. Hydraulic system outlined

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So after all the components had been defined, calculated and simulated, the final machine was defined. The equipment is showed on Figure (17). This equipment has the differential that is to perforate a big length being compact and having a lower price, because of this, this machine is in process of patent.

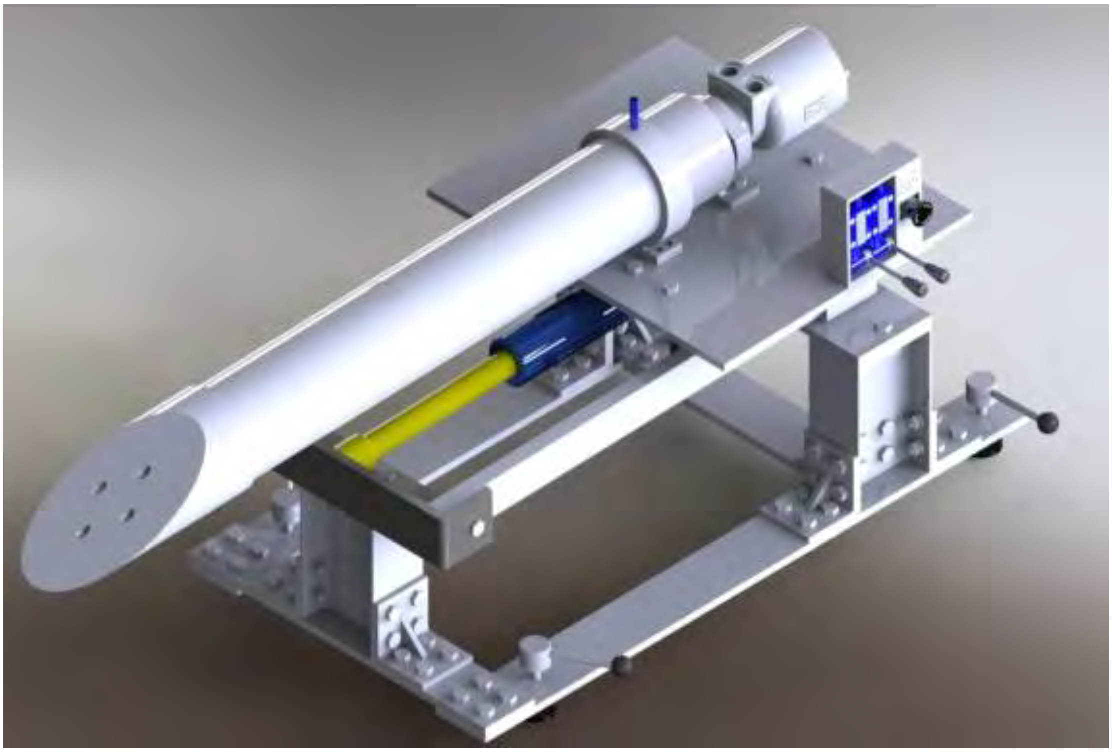

Figure 17. Horizontal Drilling Machine

4. ACKNOWLEDGEMENTS

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