Stability Analysis of Self-propelled Hydrodynamic Irrigation Machines Used for Food Industry Crops

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ABSTRACT. Some critical limit conditions for the stability of the self-propelled hydrodynamic irrigation machine used for food industry crops, have been studied, and experimental and numerical tests have been carried out for their determination. The strength forces necessary for the machine overturn have been calculated by a computer code realized in **Matlab R2019a**, and the corresponding values are listed as function of the soil slope angle ψ of the weight W and the pipeline strength force., With this aim, different operative conditions for the considered machine have been examined so that the pipeline strength force, under the following conditions:

- water filled pipeline of and empty pipeline;
- dry and wet soil.

By analyzing the data measured in the open field, on a considered machine with a coil diameter of 3 m, the different contributes to the total rewinding strength have been examined during the considered tests. Further, it has been possible to deduce that by changing; only the value of the water pressure, the total value of the rewinding strength force increased by 100 daN, which is clearly due; to the changing pressure which increases the stiffness of the polyethylene pipeline.

Moreover, other very dangerous limit conditions were determined during the rewinding phase of the pipeline on overflooded soil (also due to a rain storm), with a pipeline completely unwound on the soil and sunk into it. In these critical conditions, it has been noted that, to perform the operating phase, it is possible to reach a very high T value, which can cause the machine overturning even for $\psi = 0$ (horizontal case).

Keywords: Irrigating machine · Machine stability · Machine overturn

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1 Introduction

Although the technological development has determined an evolution of the agricultural machineries, in a such way that the comfort conditions for the operators have significanlty improved, there still remain some critical operational conditions for some typologies of machineries that do not succeed to sufficiently guaranteeing the safety of the operators, despite at present there are many safety devices in agricultural machineries that prevent from occasional and dangerous contacts with the parts in movement of the machineries (like e.g. carter, life belts, safety bonnets) [1–3]. In this sector, some collected data on accidents show that on an average, only the tractor is responsible for 10% of the total number of accidents in agriculture and 35% of casualties. In reference to the material agent of accident, the voice "machineries" it represents 17% on the total one of the sector. Among the machineries, the power and self-propelled machine determine about the 60% of the accident events. Indeed the most serious risks to which the operator is exposed are represented by the transversal and/or longitudinal overturns for overloaded of the machineries (i.e. supported equipments, for excessive draught value, for abrupt mouvements, for "excessive" soil slope) (). On these issues different studies, especially specific for the tractor sector (), have been performed in order to reduce the risk of overturn, without considering the particular operational conditions in which they happen, or the interactions between the soil and the propulsion devices [4, 5].

Nevertheless the number of scientific contributions to this topics is still insufficient for the complete evaluation of the many parameters involved, such as mechanical, operational and environmental which are needed to guarantee the safety limit conditions. These limits are often increased by some unpredictable conditions such as the fatigue of drivers under some special environmental and physical agents. The number of studies devoted to the dynamics of the overthrow of the system formed of operative machine - tractor and of some operative machine is also inadequate. In particular a significant study on the irrigating machines, used under very special operational conditions is still lacking [6–9]. In particular, the irrigation machines perform the distribution of water in the form of artificial rain, with a certain intensity according to the main characteristics of the soil and the needs of the crop. Usually the irrigation system consists of: a pumping station, the adduction pipeline and the water distribution system. The pumping station is made by an engine-pump unit that performs the required water pressurization. Sprinklers are placed at the pipelines end. The self-propelled hydrodynamic irrigation machines have a flexible pipeline that can be rolled up on a coil supported by a trolley with rubber wheels, an engine for winding the pipeline and a sprinkler trolley. The latter moves slowly as the drum recovers the pipeline previously unwound on the soil [10–14].

The self-propelled hydrodynamic irrigation machines with coil are located on trolleys generally with three wheels with variable track. A pipeline is applied to these devices which has the dual function of ensuring the flow of water necessary for operation and to pull the sprinkler previously positioned at the end of the pipeline unwound on the soil.

These machines are also equipped with a mechanical rewinding system that ensures the regular rewinding of the spires on the coil.

To perform the set up of this machine, there are fixing bars in the soil, moved by hydraulic or mechanical jacks. In fact, generally, to avoid the overturn of the self-propelled hydrodynamic irrigating machine caused by an excessive draught force, these machines are equipped with some stabilizers, called struts, which are conveniently tilted with respect to the vertical direction. Besides, this machine is equipped with a sensor that points out the machine slope during the operative phase of the machine to avoid its overturning. It should be noted however that despite all safeguard regulations, during the operative phase of the machine, some unexpected critical conditions have happened, that have caused serious damages to the users [15–18]. This is essentially due to the fact that during the operative phase, some critical limit conditions might happen as a consequence of the machine-crop-soil interaction during the operative phase. The main aim of this paper is to study the machine-crop-soil interaction of the irrigating machines and to single out the critical operating limits.

2 Materials and Methods

In this paper we focus on the numerical-experimental study of the overturn dynamics of the self-propelled hydrodynamic irrigating machine. In particular, some critical conditions have been analysed for the operative phases of filling and winding pipeline and for the soil physical state and the soil slope.

The considered machine has a coil with a diameter D = 3 m, with a winding system of semi-rigid pipeline (polyethylene) with a maximum length of about 250 m, at the end of which there is an sprinkler that moves jointly with the pipeline.

The machine has an engine, with 7 kW power which is able to rewind the pipeline with speed values ranging between 10 and 50 m/h, according to the expected water distribution. It can reach the order of about 300 m/h when it is necessary to recover quickly the pipeline by means of a mechanical system operated by the power take-off of a tractor [19–23].

The machine is also equipped with a device that, maintains the rewinding speed of the pipe constant, so that during the rewinding phase of the pipe when r increases, the angular speed decreases.

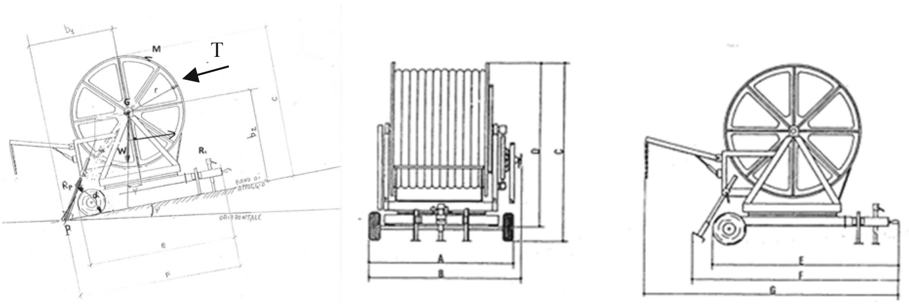
It should be noted that the engine provides high torque values because almost all the mechanical power is transformed into driving torque with minimum angular speed.

For such a machine, the overturn dynamics has been studied, to determine the limit operative condition which depend on the machine-crop-soil interaction. To this purpose, the equilibrium conditions of the considered machine have been examined taking into account its operating conditions.

The machine is equipped with two rods RA and RP so that, if we assume the two reactions RA and RP symmetrical, then they are symmetrically distributed on the two rods and therefore the system can be considered as a two-dimensional system, i.e. without torsion, flat and therefore solvable with the cardinal equations of the static.

In Fig. 1, the considered machine scheme has been reported, with the following notations: M coil winding moment; R = strength force applied to 0.5 of the machine coil radius (r); W = weight, applied in the barycentre G of the machine coil; Rp = rafter reaction; Ra = support reaction; α = angle formed by the support plane with the horizontal plane [24–27].

It has been considered an operative machine with the following characteristic values: $\alpha = 33°$; f a = 0.3; p = 0.6; W1 = 1300 daN with unrolled pipeline on the soil; W2 = 2000 daN with rolled pipeline; ψ ranging between 0 – 30°, and the geometric parameters in Fig. a) Force acting scheme b) Self propelled hydrodynamic irrigating machine schemeb and Table 1 have been reported.



a) Force acting scheme b) Self propelled hydrodynamic irrigating machine scheme

Fig. 1. a) Force acting scheme b) Self propelled hydrodynamic irrigating machine scheme

Table 1. Overall dimensions (mm).

A	C	D	E	F	G
2500	3900	3470	4200	4500	6500

Since the coil diameter is D = 3000 mm, therefore r = 1500 mm; then b_2 = C – 1500 mm = 3900–1500 = 2400 mm; b_1 = F/2 = 4500/2 = 2250 mm. M = engine moment, anticlockwise in Fig. 1a, and R the resistant force of the pipeline to be rewind. The strength force has been assumed as applied at ½ of the coil radius. So that, by considering the overturning condition around the point P, when $R_A = 0$; and the equation of moment equilibrium, the values of R computed when $R_A = 0$ we have

$$W\dot{(}b_1 - b_2\, sen\psi) + R(b_2 - 0.5r) + R_A\dot{F} = 0 \tag{1}$$

From where the value of R (strength force of the pipeline) is obtained, which causes the overturning, T_r value. Therefore, it has been necessary to determine the value of R for different possible operating conditions.

3 Analysis of the Overturning Conditions

3.1 Determination of the Pipeline Strength Force Values

In order to study the machine overturning, various operative conditions have been considered, for the evaluation of the resistance of the pipeline to the advancement, and, more precisely, we have focussed on the: Water filled pipeline and empty pipeline; Dry and wet soil; Resistance to the rewinding of the pipeline; Geometric parameters (barycentre position, masses etc.).

a) Sprinkler b) Self-propelled hydro-dynamic irrigating machine

Fig. 2. a) Sprinkler b) Self-propelled hydro-dynamic irrigating machine.

Therefore, some experimental tests have been performed on the considered irrigating machine in order to compare the theoretical results with the experimental ones, The strength force value (R) necessary to rewind the pipeline has been determined, under various operative conditions. The pipeline length was 250 m (Figs. 2ab, 3ab).

Regarding the strength force necessary to rewind the pipeline it should be noted that it is formed by:

1) R1, resistance to pipeline rewinding which depends on the material characteristics, on the diameter of the machine coil (bobina) and the water pressure.
2) R2, frictional resistance of the pipeline on the soil (which is a function of the pipeline length).
3) R3, resistance to advancement of the irrigator (sprinkler) which is located at the pipeline end.

For the evaluation of these three contributions to the total resistance, some experimental tests were carried out, under the following conditions:

1. By means of a force transducer the draught force necessary to roll the pipe on the machine coil has been measured thus enabling to evaluate the winding resistance of the pipe. To this aim some experimental tests have been carried out by wrapping the empty pipe (having an internal diameter of 73 mm, external diameter of 90 mm) on a machine coil with a diameter of 1200 mm. During these tests a constant tangential force of about 90 daN was detected (R1 resistance to pipe winding).
2. Tests have been carried out for the evaluation of the friction coefficient for the polyethylene piping located on a loose and dry soil (density 1.6 g/cm3; umidity = 5%), determining a value of the friction coefficient which generates the force R2 (friction resistance of the pipe on the soil)
3. The resistance to advancement of the sprinkler alone, was experimentally evaluated, about 20 daN (R3)

It should be noted that all experimental tests have been repeated three times, and the maximum error detected between the minimum and maximum values, for each

a) Pipeline rewinding phase b) Experimental test to evaluate the pull force

Fig. 3. a) Pipeline rewinding phase b) Experimental test to evaluate the pull force.

considered test, it was less than 5%, There follows that we have considered the mean values for all performed tests.

Some overturning limit conditions, have been considered by assuming the:

test a) waterless pipeline entirely unwound on the soil; test b) water filled pipeline entirely unwound on the soil; test c) water filled pipeline with pressurized water, p = 8 105 Pa, entirely unwound on the soil.

Furthermore, we have analysed the condition that occurs when the irrigation is performed in full open field, with the machine in steady state and the pipeline completely extended on the soil (250 m of pipes) As a consequence of a sudden unexpected weather events (like e.g. an heavy Summer rain-storm), the operator stops the irrigation, by leaving the water-filled pipeline completely extended on the soil and water filled. There follows that, because of the violent storm the soil might be completely flooded and the water-filled pipeline sinks into it, because of the heavy weight.

After a few days, under dry weather conditions, the pipe would be completely adherent to the soil. The operator, then, will restart the irrigation and performs the rewinding of the pipeline, which is however completely attached to the soil. It is clear that, this condition could be particularly critical and dangerous.

In order to assess the value of the draught force in this condition (test d) a test was performed with a 10 m long pipe which was completely buried. The draught force was evaluated using a force transducer.

3.2 Experimental Tests Data Results

In this section we give the results of the experimental tests in the operating conditions: test a, b, c, d.

Regarding the experimental test a) we have considered 240 m of empty piping with a weight of 432 daN, so that a total draught force of about 240 daN was detected. Taking into account the fact that the resistance detected for the winding of the pipe, R1, was 90 daN, and that the resistance to advancement of the sprinkler, R2, is about 20 daN, we can deduce that the friction resistance due to the pipeline (R1), is equal to 129.6 daN, so that by taking into account that the pipeline weight of 432 daN, it implies that the friction coefficient is equal to 0.3, for the considered soil.

Regarding the experimental test b) we have considered 240 m of filled water pipeline with weight of 1488 daN, so that a total draught force has been detected equal around 550 daN. By taking into account that the pipeline wrapping resistance is 90 daN, and that the sprinkler resistance is around 20 daN, the resulting friction resistance is about 440 daN. Regarding the experimental test c) we have the following situation. Since the pipe contains pressurized water, it has a greater value than the resistance to the winding of the pipeline (R1), therefore considering 240 m of water-filled pipeline with a weight of 1488 kg, with a water pressure of 8 105 Pa, a total draught force of 650 daN was detected, with a friction resistance of the sprinkler (R3) of about 20 daN, so that considering the water filled pipeline, the friction resistance is equal to that of the case (b) and therefore the friction resistance due to the pipeline (R2) is equal to 440 daN, so that the winding resistance of the pipe (R1) is 190 daN.

These values enable us to deduce that in this case, the increasing pressure inside the pipeline implies an increasing value of the pipeline winding resistance of about 100 daN. Thus the tube is more rigid so that the winding resistance increases.

Regarding the experimental test we have a 10 m long pipeline completely buried in the soil, the value of the draught force was about 150 daN. There results, a draught force of 15 daN/m and this implies that for pipeline 300 m long, there is a total draught force of 4500 daN.

3.3 Numerical Simulations

In Tables 2a and 2b the strength force values which are necessary for the machine overturning (Tr) under the conditions W = 1300 and 2000 daN, have been reported, as a function of the considered ψ values. The numerical computations where performed with Matlab 2019a.

Table 2a. Slope angle Values ψ in function of the draught force that provokes the overturn (Tr), with Ra = 0 and with W = 1300 daN Overall dimensions (mm).

ψ (degree)	25	20	15	10	5	0
Tr(daN)	225	411	596	775	948	1114

Table 2b. Slope angle Valuesψ in function of the draught force that provokes the overturn (Tr) with Ra = 0, with W = 2000 daN

ψ (degree)	25	20	15	10	5	0
Tr(daN)	345	632	917	1197	1457	1714

4 Discussion and Comparison Between Numerical Simulation and Experimental Tests Data

Comparing the numerical results with the experimental results, it can be observed that under the condition d the overturning value it dangerously exceeds even in the case of a zero slope soil, while the safety limit is greatly exceeding in the case of an increasing soil slope [28].

Further, it has been noted that the values of the critical inclination angles of the support plane, for T around 700 kg (working conditions), are about 10 degrees, which corresponds to a slope of 17%.

5 Conclusions

Critical limit conditions for the stability of the self-propelled hydrodynamic irrigation machine have been considered and studied. Through experimental tests the values of the pipeline stregth forces have been evaluated in various operating conditions:

By analysing the measured data in the open field, it has been observed that by varying only the value of the water pressure, the total value of the strength force is increased by 100 daN, which increases the rigidity of the polyethylene pipe.

Further, other very dangerous limit conditions have been determined during the rewinding phase of the pipe on a very flooded soil (due to rain), with a pipe completely unwound on the soil and sunk into it. In these critical conditions, we have seen that, to perform the operating phase, it is possible to reach a very high T value, which can cause the machine overturning even for $= 0$ (horizontal case).

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