Plants jamming on water-saturated soils during contact with the supporting elements (feet) of walking machines

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Abstract. Walking machines when working on waterlogged soils can be more efficient than wheeled machines. They provide increased ground passability and destroy the soil to a lesser extent. The paper discusses the results of studies of plant jamming by the feet of walking machines. Stamp tests of contact interaction of feet of various shapes with water-saturated soil were carried out. It was found that the greatest damage to the plant is obtained along the perimeter of the foot. This was the case at any depth of the footprint. Plants damaged by the foot, even in the case of small-sized feet, continued to grow after a period of depression. Wheeled and tracked movers, due to slipping and milling effect, are damaging plants to a higher extent. Mathematical modeling of the contact interaction of the foot with weak-bearing soil by the methods of finite element modeling has been carried out. Dimensional contact model for rigid feet of various shapes interacting with elastoplastic soil is formulated. The task was solved under conditions of large deformations of the supporting surface. The regularities of the stress-strain state of the soil in the zone of its contact with the foot under simple normal loading are obtained. Modeling shows that the greatest stresses occur along the perimeter of the foot, and the soil inside the perimeter is less loaded. This explains the nature of the plant jamming. Thus, the walking mode of movement in irrigated agriculture can provide lower plant jamming in comparison with traditional machines. Considering the smaller area of soil compaction and the absence of a continuous track, which is one of the causes of water erosion of the soil, it can be concluded that it is advisable to use small-sized feet.

1. Introduction
At present, over large areas of cultivation as industrial irrigation, sprinkling with the use of wide-coverage sprinkler machines is most widespread. Self-moved carts of sprinkler machines, as a rule, have a wheeled mover. The use of a wheeled mover in irrigated agriculture is one of the reasons for the processes of erosion and soil consolidation, leading to its degradation. The wheel in conditions of water-saturated soils destroys the upper ecologically vulnerable soil layer and leaves a rut. Significant track size reduces the efficiency of land use, and also leads to water losses, which either accumulates in the track, making it difficult to move, or leaves the field along the track, like a canal, destroying and washing away the top fertile soil layer (figure 1).

Walking movers destroys the soil to a lesser extent and have better passability [1-4]. There is also a decrease in the loss of tractive effort for resistance to movement - for walking machines, in contrast to wheeled and tracked, the ground is not an obstacle to movement [5-6]. Another important advantage of the walking mover is the discrete interaction with the ground. When a walking machine is moving, not a track is formed, but a footprint track. The absence of a solid track makes it difficult to drain water from the field and reduces water erosion of the soil.
In the work, in order to develop recommendations for the choice of standard sizes of supporting elements of walking sprinklers, the jamming of plants is investigated during their contact interaction along the feet of a walking mover in conditions of water-saturated soil.

2. Materials and methods
At the VSTU at the Faculty of Automated Systems, Transport and Weapons, several prototypes of walking machines designed to operate on water-saturated and ecologically vulnerable soils have been developed and tested [7]. In particular, self-moved walking supports [8] were developed for the Kuban wide-grip multisection sprinkler (figure 2 a). The walking supports were tested in real-life conditions as part of a circular sprinkler. Tests have shown that on waterlogged soils, the walking mover is superior to the wheeled one on the soil. It was found that the values of the average ground pressure recommended for wheeled vehicles with high cross-country ability can be increased for walking machines. In terms of environmental friendliness, the walking propeller also surpasses the wheeled one. The depth of the track during the tests was only 5–20% of the depth of the wheel track (figure 2 b, c). Moreover, the irrigated crop continued to grow along the track (tests were carried out in the field with planted onions). At the same time, because of the bulky ski-like feet, the area of the soil compaction zone did not decrease, and the track was solid, not discrete. A solid track is one of the causes of water erosion of the soil. This suggests a conclusion about the advisability of using small-sized feet. This will obviously increase the pressure on the ground and the jamming of plants. To assess the crushing of plants with feet with a small supporting surface, theoretical and experimental studies of the interaction of a walking mover with the ground were carried out.

In the study of plant jamming with a walking mover, experimental studies were carried out - stamp tests, as well as mathematical modeling of the mechanics of the contact interaction of the foot with the ground. Stamp tests were carried out under the conditions of real objects of irrigation. The stamp device is a rod with a replaceable support part. The replaceable support part of the stamp imitated the foot of a walking mover. In the course of the experiments, the standard size of the stamp and the depth of the imprint were varied. The change in the depth of the imprint was achieved by changing the applied force to the stamp. During the tests, the maximum depth of the footprint was 7-10 cm. After contact with the foot, a visual inspection of the crushed plant was carried out, the degree and nature of its damage was assessed. Visual observation of the damaged plant was carried out for 2–3 weeks.
Stamp tests have shown that the greatest damage to the plant is obtained along the perimeter of the foot (figure 3 a). Moreover, this was the case at any depth of the trace. There was less damage under the central part of the foot - the plants were simply buried together with the top layer of soil located under the stamp. Tests have shown that plants damaged by the foot, as a rule, do not die. After a period of depression, the damaged plants resumed their growth (figure 3b).

Figure 3. Seedlings of carrots after contact interaction with a round foot of a walking mover: immediately after interaction (a); 11 days after interaction (b).

Mathematical modeling of the contact interaction of the foot with the soil was carried out using the ANSYS finite element modeling package designed to solve tasks in the mechanics of a deformable solid, including the tasks of contact interaction. The contact of the foot with the ground in the support phase was considered quasi-static, since the vibrations of the foot on a viscoelastic ground that occur after the change of feet quickly decay [9]. A spatial contact problem was formulated for rigid feet of various shapes interacting with elastoplastic soil, the elastic properties of which were set by Young's modulus and Poisson's coefficient [10-16]. The task was solved under conditions of simple normal loading created by external forces applied to the hinge of the foot, assuming the ideal conjugation of the contacting bodies and the presence of linear friction forces in the contact area. The elastic properties of the ground, the average pressure of the foot on the ground, as well as the shape and size...
of the supporting surface of the foot varied. The task was solved under conditions of large deformations of the supporting surface.

3. Results
The regularities of the stress-strain state of the soil in the zone of its contact with the foot under simple normal loading are obtained. The characteristics of the stress-strain state of the soil under the foot obtained as a result of modeling are in good agreement with the results of stamping tests. Figure 4, for example, shows the von Mises equivalent soil stress distribution under a round foot under normal loading. Soil - wet loam.

![Figure 4. Von Mises equivalent soil stress distributions (MPa) under a round foot (0.4 m diameter) under normal load (q = 0.08 MPa): in vertical section (a) and in top view (b).](image)

Modeling has shown that the greatest stresses occur along the perimeter of the foot, and inside the perimeter, the soil is loaded significantly less. This explains the nature of the plant jamming - it is along the perimeter of the foot that the most significant plant damage occurs. In the central part, the plant simply deepens along with the soil.

4. Discussion
It should be noted that the results obtained describe the mechanics of the contact interaction of the supporting element of a walking machine with the ground to a greater extent at a qualitative level, since the issues of interaction of the supporting elements of walking machines with real ground are currently insufficiently studied. Currently, there are no generally accepted indicators of the impact of movers on the soil [12–14]. The main calculated dependencies used to determine the mechanical characteristics of soils, various criteria for assessing their bearing capacity, compaction effect on the soil, etc., are based mainly on simplified empirical calculation and experimental relationships [12]. The problem of obtaining more reliable information about the traction and coupling properties of
walking machines is associated with the problem of schematizing the physical and mechanical properties of weakly bearing soils.

5. Conclusion
Experimental and theoretical studies have shown that the jamming of plants by the supporting elements of walking machines on saturated soils is relatively small, even in the case of small feet. The wheel mover, due to slipping and milling effect, damages plants much more. Thus, the walking mode of movement in irrigated agriculture can provide lower plant jamming and greater environmental friendliness compared to traditional machines. Considering the smaller area of soil compaction and the absence of a continuous footprint, which is one of the causes of water erosion of the soil, it can be concluded that it is advisable to use small-sized pads.

The results of the work can be in demand in the design of supporting elements of walking machines and robots intended for work in irrigated agriculture.

Acknowledgments
The study was carried out with the financial support of the RFBR and the Administration of the Volgograd region, scientific projects № 19-08-01180, № 19-48-340007.

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