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PROGRAMME AND METHODOLOGY OF LABORATORY-FIELD RESEARCH ON SOIL AND FIELD CONDITIONS FOR A ROW-CROP TRACTOR WITH A TRANSFORMABLE CHASSIS

Akhmedov Sh., *DSc, senior researcher,*
Department of Cotton harvesting machines,
E-mail: myuzdoc@gmail.com,
Institute of Mechanics and Seismic Stability of Structures
named after M.T. Urazbaev, Uzbekistan Academy of Sciences

Abstract. *Reliable design of a tractor with a transformable chassis requires field data obtained by methods that are reproducible and suited to the machine's purpose. This article presents the programme and methodology of laboratory-field research carried out on cotton fields in five regions of Uzbekistan. The programme addresses three tasks: characterising the surface relief of fields, including slope and the length and height of irregularities; measuring soil moisture, hardness and density; and observing how the soil changes under internal and external influences. Slope was evaluated by combining a digital elevation model processed in ArcGIS Pro 3.2 with RTK-GPS ground control, while irregularities were recorded with a profilometer. Moisture, hardness and density were determined according to GOST 20915-2011 and O'zDst 3090:2016, using a penetrometer and the Kachinsky cylinder in four layers to 40 cm with five replications. To follow soil deformation, we developed an observation device: a glass-fronted chamber in a trench filled with 10 cm soil layers separated by chalk, recorded by camera for 30 days after a machine pass at 8.9 km/h. Daily images were analysed with artificial-intelligence tools and processed statistically. The methodology offers a repeatable basis for obtaining the design inputs for the running system of the tractor.*

Аннотация. *Надёжное проектирование трактора с трансформируемой ходовой системой требует полевых данных, полученных воспроизводимыми методами, которые соответствуют назначению машины. В статье изложены программа и методика лабораторно-полевых исследований, проведённых на хлопковых полях пяти областей Узбекистана. Программа включает три задачи: характеристику рельефа поверхности полей, в том числе уклона, длины и высоты неровностей; определение влажности, твёрдости и плотности почвы; наблюдение за изменением состояния почвы под действием внутренних и внешних факторов. Уклон оценивался сочетанием цифровой модели высот, обработанной в ArcGIS Pro 3.2, и наземной RTK-GPS-съёмки, а неровности фиксировались специально изготовленным профилометром. Влажность, твёрдость и плотность определялись по ГОСТ 20915-2011 и O'zDst 3090:2016 с применением пенетрометра и цилиндра Качинского по четырём слоям до глубины 40 см при пятикратной повторности. Для наблюдения за деформацией почвы разработано устройство наблюдения: камера со стеклянной передней стенкой, установленная в котловане и заполненная слоями почвы по 10 см, разделёнными мелом; изменения регистрировались камерой в течение 30 дней после прохода техники со скоростью 8,9 км/ч. Ежедневные изображения анализировались средствами искусственного интеллекта и затем обрабатывались статистически. Методика даёт целостную воспроизводимую основу для получения исходных данных, необходимых при проектировании ходовой системы трактора. Особое внимание уделено контролю точности измерений и сопоставимости данных между областями. Описанные приёмы могут быть использованы и при исследовании других сельскохозяйственных машин.*

Annotatsiya. *Transformatsiyalanuvchi yurish tizimli traktorni ishonchli loyihalash mashinaning vazifasiga mos keladigan va takrorlanuvchan usullar bilan olingan dala*

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ma'lumotlarini talab qiladi. Maqolada O'zbekistonning beshta viloyatidagi paxta dalalarida o'tkazilgan laboratoriya-dala tadqiqotlarining dasturi va uslubiyati bayon etilgan. Dastur uchta vazifani qamrab oladi: dalalar sirti releyfini, jumladan qiyalikni hamda notekisliklarning uzunligi va balandligini tavsiflash; tuproq namligi, qattiqligi va zichligini aniqlash; ichki va tashqi omillar ta'sirida tuproq holatining o'zgarishini kuzatish. Qiyalik ArcGIS Pro 3.2 da qayta ishlangan raqamli balandlik modeli va RTK-GPS yer usti o'lchovlarini uyg'unlashtirish orqali baholandi, notekisliklar esa maxsus tayyorlangan profilometr yordamida qayd etildi. Namlik, qattiqlik va zichlik GOST 20915-2011 hamda O'zDSt 3090:2016 bo'yicha penetrometr va Kachinskiy silindri yordamida 40 sm gacha to'rt qatlamda besh karra takrorlashda aniqlandi. Tuproq deformatsiyasini kuzatish uchun kuzatuv qurilmasi ishlab chiqildi: u o'raga o'rnatilgan, oldi shisha bilan jihozlangan va bo'r bilan ajratilgan 10 sm li tuproq qatlamlari bilan to'ldirilgan kameradan iborat bo'lib, texnika 8,9 km/soat tezlikda o'tganidan keyin 30 kun davomida kamera yordamida kuzatildi. Kundalik tasvirlar sun'iy intellekt vositalari bilan tahlil qilinib, keyin statistik qayta ishlandi. Uslubiyat traktor yurish tizimini loyihalash uchun zarur boshlang'ich ma'lumotlarni olishning yaxlit va takrorlanuvchan asosini beradi. O'lchash aniqligini nazorat qilish va viloyatlar o'rtasida ma'lumotlarning taqqoslanuvchanligini ta'minlashga alohida e'tibor berilgan.

Keywords: *transformable chassis; field research methodology; soil moisture; soil hardness; soil density; surface relief; profilometer; GIS.*

Ключевые слова: *трансформируемая ходовая система; методика исследований; влажность почвы; твёрдость почвы; плотность почвы; рельеф поля; профилометр; ГИС.*

Kalit so'zlar: *transformatsiyalanuvchi yurish tizimi; tadqiqot uslubiyati; tuproq namligi; tuproq qattiqligi; tuproq zichligi; dala releyfi; profilometr; GAT.*

Introduction: A machine can only be designed as well as the conditions it will work in are known. For a tractor with a transformable chassis this principle has a particular force, because the design variables are not fixed dimensions but ranges: how far the track should widen, how high the clearance should rise, how much the wheelbase should be changed. Choosing those ranges requires numerical information about the fields on which the tractor will operate, and that information has to be collected in a way that others can repeat and compare.

What has to be known about a field is not obvious in advance. Three groups of data are important for the running system. The first describes the geometry of the surface: its slope, and the length and height of the irregularities over which the machine will travel. These determine stability, vibration and the dynamic loading of the wheels. The second describes the state of the soil, namely its moisture, hardness and density, which together tell us how much load the soil can carry and how susceptible it is to compaction. The third describes how that state changes, either through processes inside the soil, such as the redistribution of moisture, or through external influences, of which the passage of a machine is the most important.

Each of these groups calls for its own method. Some of the quantities can be measured with well-established, standardised procedures. Others, in particular the behaviour of soil layers under load over a period of days, are not covered by a standard instrument, and for them a dedicated method had to be developed. The programme described in this article therefore combines conventional techniques with two tools made specifically for the task: a profilometer for surface irregularities and an observation device for layered soil.

The aim of the article is to describe this programme and methodology in sufficient detail for it to be understood, evaluated and repeated. We explain the logic of the programme, the sites on which it was carried out, the construction and use of the observation device, the geographic-information method for slope, the profilometry of irregularities and the standard procedures for moisture, hardness and density. The article is the second of two. The first describes the soil-

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climatic and agro-technological background that determined where the work was carried out, and we refer to it only where this is needed for context.

Research programme and its logic: The programme of laboratory-field research consisted of three groups of tasks. The first was the study of the surface relief of the fields, which included determining the slope of the fields and the length and height of the irregularities on their surface. The second was the determination of the moisture, hardness and density of the soil of fields under crops. The third was the study of changes in the condition of the soil under the influence of both internal and external factors.

The methods used for the first two groups are generally accepted ones. They are described in the sections where each is applied, together with the standards or instruments on which they rely. The third group was investigated by a method that we developed ourselves, with the aid of an observation device that we also designed. Table 1 summarises the programme and shows which method belongs to which task.

Table 1

Research programme and methods

Task	Quantity determined	Method	Instrument or standard
Surface relief	Slope of the field	GIS analysis of a digital elevation model with ground verification	ArcGIS Pro 3.2; Sentinel-2 based DEM, 10 m; Leica GS18 RTK-GPS
Surface relief	Length and height of irregularities	Profiling of the surface	Purpose-built profilometer
Soil state	Moisture	Standard procedure	GOST 20915-2011; O'zDst 3090:2016
Soil state	Hardness	Penetrometric method	Eijkelkamp 06.15.SA penetrometer
Soil state	Density	Cylinder method	Kachinsky cylinder, 100 cm^3
Change of soil state	Deformation of layers under internal and external factors	Observation of marked soil layers in a trench	Observation device, camera, image analysis

The logic that connects the tasks is straightforward. Surface geometry and soil state are measured in the same fields, because they interact: the irregularities of the surface determine the dynamic component of the load, while the state of the soil determines how that load is absorbed. The observation of layer deformation then supplies what neither of the other measurements can, which is a picture of how the soil responds over time once it has been loaded. Figure 1 shows the sequence of the work and how the results feed the final aim of the programme.

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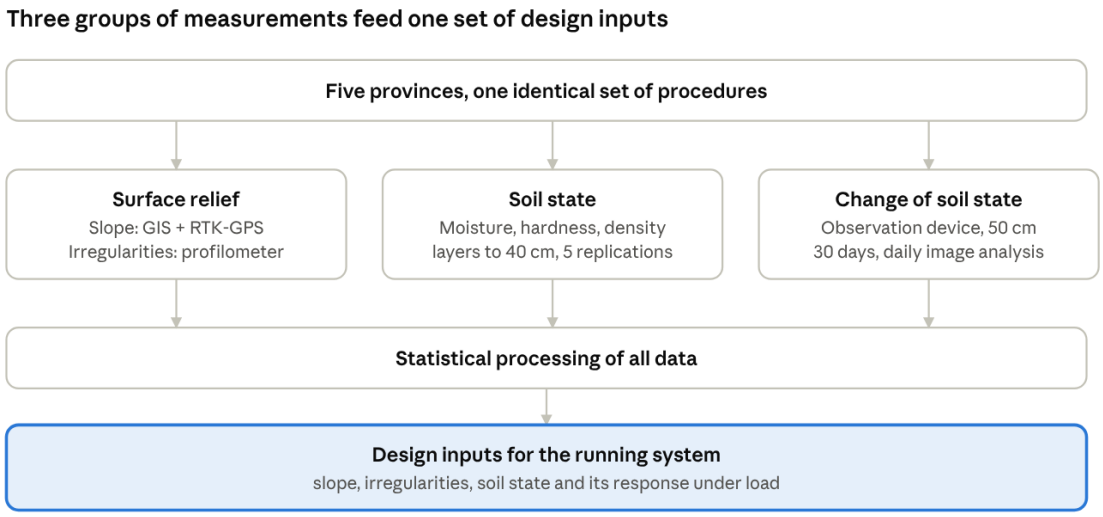

Figure 1. Programme of laboratory-field research

Experimental sites: The work was carried out on farms in five provinces of Uzbekistan: Khorezm, Bukhara, Kashkadarya, Tashkent and Namangan. The farms were chosen on the basis of soil composition, climatic conditions and the area under cotton, with the aim of covering the contrast between saline lowland fields and sloping foothill fields. The reasons for this choice and the characteristics of the agro-technological zones are given in the companion article, and we do not repeat them here.

What matters for the methodology is that the same set of measurements was applied in every province. This was a deliberate decision. Differences in measuring method are one of the most common reasons why results from different places cannot be compared, and by keeping the set of procedures identical we aimed to ensure that any difference observed between provinces reflects the conditions in the fields rather than the way they were measured.

The measurements were made in fields that were being prepared for sowing of agricultural crops, which is the period in which machines enter the field most frequently and in which the state of the soil is most relevant to the choice of running-gear parameters. In each field the surface relief was characterised first, since this determines where it is appropriate to take soil samples and to site the observation device; soil measurements and the layered-soil observation followed.

Observation device and the layered-soil experiment: The most unusual part of the programme is the study of changes in the state of the soil, and it needs the most explanation. Standard measurements of moisture, hardness and density give a picture at one moment and at one point. What a designer of a running system also wants to know is how the soil deforms below the surface when a machine passes, how that deformation develops, and whether it fades or persists. A direct way to see this is to look through a vertical cross-section of the soil, and the observation device was built to make that possible.

The device is a housing set into a specially prepared trench [1, 2]. Its front face is fitted with glass on which a coordinate grid has been drawn, so that the position of any marked feature in the soil can be read against the grid and changes in the thickness of layers can be followed over time. Behind the glass the soil is placed in layers. To a depth of 50 cm it was laid in layers of 10 cm, and between the layers we placed thin separating layers of chalk. The chalk interlayers serve as markers: because they are white and clearly distinguishable from the soil, their displacement and the change in the distance between them directly show how each layer has been compressed or moved. The housing also contains space for a camera, and an antenna stand is mounted on top of the device (Figure 2).

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Figure 2. Schematic of the observation device: housing in a trench, glass front with a coordinate grid, and soil layers separated by chalk. 1 - antenna stand; 2 - device housing; 3 - spaces for placing the camera; 4 - glass with a coordinate grid applied; 5 - chalk; 6 - excavation pit; 7 – alternating layers of soil and chalk

The sequence of work was as follows. First, the trench was excavated and the housing installed. Second, the soil was returned in the prescribed layers with the chalk interlayers. Third, after the device had been set up, a machine was driven over the plot at a speed of 8.9 km/h. Fourth, the camera recorded the state of the layers for 30 days. During this period the images were analysed every day with the help of artificial intelligence, and the values obtained were recorded and later subjected to statistical processing. Table 2 collects the parameters of the experiment.

Table 2

Parameters of the layered-soil observation experiment

Parameter	Value or description
Depth of the layered soil profile	50 cm
Thickness of each soil layer	10 cm
Separating material	Chalk interlayers
Front of the device	Glass with a coordinate grid
Loading	Passage of a machine over the plot at 8.9 km/h
Recording	Camera in the housing
Duration of observation	30 days
Image analysis	Daily, with artificial-intelligence tools
Data processing	Statistical

Several features of this design deserve comment. The choice of 10 cm layers makes the profile fine enough to distinguish the behaviour of the upper, most heavily loaded layers from that of the deeper ones, while remaining coarse enough that the displacement of an interlayer is large relative to the resolution of the grid. The 30-day period covers not only the immediate response to loading but also the subsequent period, during which the soil may partly recover or continue to settle under the action of moisture movement and its own weight. And the daily frequency of recording is a compromise between the need for a continuous record and the volume of data that must be analysed, which is why automated image analysis was adopted.

It is worth being open about what such a device can and cannot do. A cross-section viewed through glass is a two-dimensional representation of what is in reality a three-dimensional process, and the soil next to the glass may behave slightly differently from the soil in the interior, for example because of friction with the glass surface. The loaded layers in the device are also reconstituted rather than undisturbed. For these reasons the observations are best interpreted

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comparatively, between layers, fields and conditions, and not as absolute predictions of deformation in an undisturbed field. As a comparative tool, however, the device provides something that is difficult to obtain in any other way.

Surface slope: GIS analysis with ground verification: Slope was determined by combining geographic-information technology with ground verification. The work was done in ArcGIS Pro 3.2. The input was a digital elevation model (DEM) built on the basis of Sentinel-2 satellite imagery with a resolution of 10 m (ESA, 2022), and the slope was calculated with the Slope tool, which computes for each cell of the model the rate of change of elevation and expresses it as an inclination. Because a model derived from satellite data has its own uncertainty, it was calibrated against a topographic survey carried out with RTK-GPS equipment (Leica GS18, accuracy ±2 cm). Table 3 summarises the components of this method.

Table 3

Components of the slope determination

Component	Content	Role in the method
Software	ArcGIS Pro 3.2	Processing of the elevation model
Elevation data	DEM based on Sentinel-2 imagery, 10 m resolution (ESA, 2022)	Source of elevation for the fields
Analytical tool	Slope Tool	Quantitative calculation of inclination
Ground survey	RTK-GPS, Leica GS18, ±2 cm	Calibration and verification of the model

The logic of combining the two sources is that each compensates for the weakness of the other. Satellite-based models cover whole fields and, in principle, whole regions with uniform treatment, which makes it practical to characterise many fields in five provinces. Their weakness is the coarse resolution: a 10 m cell averages out everything smaller than itself. The RTK survey has very high point accuracy but can cover only a limited number of points. Using the survey to calibrate the model gives a slope estimate that has the coverage of the first and, at the surveyed points, the reliability of the second.

The resolution of the model also sets the scale at which “slope” should be understood. It describes the general inclination of the field surface, the property that matters for the stability of a machine on a gradient. It does not describe the short irregularities that are felt by the wheels of the tractor as it travels, which are far smaller than the model's cell. For them a different method was needed.

Length and height of surface irregularities: The length and height of irregularities of the field surface were determined by profiling. For this purpose we made a special profilometer (Figure 3). Its distinguishing features, in comparison with the simpler means that are often used, are the speed of measurement, the accuracy with which the profile of the surface is copied, and the

The method follows from the way the instrument works. The profilometer is placed on the surface of the field and reproduces the line of the surface along its working length. The profile that results is a sequence of rises and falls, and from it two characteristics are read: the length of each irregularity, that is, the horizontal distance over which it extends, and its height, the vertical difference between a crest and the adjacent trough. These are exactly the quantities that determine the excitation to which a tractor is subjected as it travels across the field. A long, low undulation causes a slow pitching motion, a short, high one a sharp shock to the wheel and an increase in the dynamic component of its load.

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possibility of observing the profile of the studied surface visually while the measurement is being made.



Figure 3: Photograph of the profilometer

The possibility of visual observation has a practical value that is easy to underestimate. An operator who can see the profile while it is being recorded can immediately recognise a faulty reading, such as one caused by a clod or a plant residue, and repeat the measurement at once. Quick measurement, in turn, makes it possible to take enough profiles in each field to describe its variability, and not just a single section that may be unrepresentative. Accurate copying of the surface guarantees that the heights and lengths read from the profile correspond to the real irregularities and are not distorted by the instrument.

The profile data give us, for each field, the distribution of irregularities by length and height. Combined with the slope from the previous section, this provides a complete description of the geometry of the surface, from the general inclination at the scale of the field to the individual unevenness at the scale of a wheel.

7. Soil moisture, hardness and density: Moisture, hardness and density were determined by standard methods, with the requirements of GOST 20915-2011 and O'zDst 3090:2016 being followed [3,4]. Moisture was determined according to GOST 20915-2011 [3]. Hardness was determined by the penetrometric method, using an Eijkelkamp 06.15.SA penetrometer, and density by the Kachinsky cylinder method with a cylinder volume of 100 cm³. Both were measured to a depth of 40 cm, by layers of 0–10, 10–20, 20–30 and 30–40 cm, with five replications. Table 4 summarises the scheme.

Table 4

Scheme of determination of soil moisture, hardness and density

Property	Method and instrument	Standard	Layers, cm	Replications
Moisture	Standard procedure	GOST 20915-2011	0–10, 10–20, 20–30, 30–40	5
Hardness	Penetrometric method, Eijkelkamp 06.15.SA	GOST 20915-2011; O'zDst 3090:2016	0–10, 10–20, 20–30, 30–40	5
Density	Kachinsky cylinder, 100 cm³	GOST 20915-2011; O'zDst 3090:2016	0–10, 10–20, 20–30, 30–40	5

The depth and the layers were chosen to correspond to the zone in which the running system acts. The upper layers carry the main part of the load of the wheel and are the ones most affected by repeated passes, and the 40 cm depth is sufficient to include the layers in which compaction from tractors commonly develops. Dividing it into four layers of equal thickness allows the vertical distribution of each property to be seen, and the same division is used in the layered-soil

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experiment, whose layers are 10 cm thick, so that results from the two sets of measurements can be compared layer by layer.

The five replications are important because soil is a variable medium. Even within a small area, moisture and density can differ noticeably from point to point, and a single determination may be unrepresentative. Repeating the measurement five times in each layer gives a mean value and an indication of scatter, and these allow an observed difference between layers or fields to be distinguished from the ordinary variability of the soil.

The three properties are measured together because they are interdependent. Hardness, in particular, depends strongly on moisture: the same soil may resist a penetrometer much more when dry than when wet. A value of hardness that is not accompanied by a value of moisture is therefore difficult to interpret, and the combination of the three, determined at the same points and at the same time, is much more informative than the sum of the three separate measurements.

Data processing and quality control: All data obtained, both the measured properties and the results of the image analysis in the layered-soil experiment, were subjected to statistical processing. For replicated measurements this means that a mean value and a measure of scatter are calculated for each layer in each field, and that the values for different fields and provinces are compared on this basis.

Several measures contribute to the quality of the data. The first is the use of standards and certified instruments wherever they exist, which reduces the arbitrariness of the procedure. The second is the identical programme in every province, already mentioned. The third is the calibration of the GIS slope model against RTK measurements, which controls the systematic error of the satellite-based data. The fourth is the visual control of the profile during profilometry. The fifth is the daily frequency of recording in the layered-soil experiment, which makes it possible to notice and correct a malfunction early, and not after the period of observation has ended.

The use of artificial intelligence for the daily analysis of images deserves a separate remark. The number of images accumulated over 30 days in several fields is large, and manual measurement of the position of the chalk interlayers in each of them would be slow and subject to the personal judgement of the operator. Automated analysis applies the same rule to every frame, which improves the consistency of the results. It also requires that the algorithm be checked against manual measurements on a sample of images, a step that should be reported together with the results of the experiments.

Discussion: The methodology combines elements of different kinds, and its value lies in their combination. Standardised procedures ensure comparability with other research and with regulatory practice. The GIS approach gives coverage. The profilometer supplies the information about small-scale geometry that satellite data cannot provide. The observation device gives a view of the behaviour of the soil in depth and in time that the other methods do not offer.

There are limitations that we have tried to state openly. The resolution of the elevation model is coarse relative to the irregularities that act on the wheels. The layered-soil device uses reconstituted soil and a glass wall, which can influence the behaviour of the layers. A single machine speed of 8.9 km/h and a single loading condition were used in the experiment, so that the effects of speed, mass and tyre pressure, which are known to be important, are not separated by it. These are reasonable directions for extension of the work, and the device and procedure are well suited to repeating the experiment with different loading conditions.

The methodology can be transferred. Nothing in it is specific to the tractor with a transformable chassis; the same approach can be used for other machines or for other crops in which the interaction of the running system with the soil is of interest, provided that the soil layers and the loading are chosen accordingly.

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Conclusions:

1. The programme of laboratory-field research includes three groups of tasks: the study of the surface relief of fields, the determination of soil moisture, hardness and density, and the observation of changes in the state of the soil under internal and external factors.

2. Slope is determined by a combination of GIS analysis (ArcGIS Pro 3.2, 10 m DEM based on Sentinel-2 imagery, Slope Tool) and RTK-GPS ground verification (Leica GS18, ±2 cm), and the length and height of irregularities by a specially made profilometer that is fast, copies the surface accurately and permits visual observation.

3. Moisture, hardness and density are determined according to GOST 20915-2011 and O'zDst 3090:2016 with a penetrometer and the Kachinsky cylinder, in layers of 0–10, 10–20, 20–30 and 30–40 cm with five replications.

4. The observation device with a glass front and coordinate grid, with 10 cm soil layers separated by chalk to a depth of 50 cm, makes it possible to follow deformation of the soil layers for 30 days after the passage of a machine at 8.9 km/h, with daily image analysis by artificial-intelligence tools.

5. The use of one identical programme in all five provinces provides a repeatable and comparable basis for the design data needed for the running system of a tractor with a transformable chassis.

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