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REVERSE DESIGN OF EXPERIMENTS THEORY FOR CONTROLLING A WORK SYSTEM FOR IMPROVING GROUND MACHINES

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Abstract

The purpose of this paper is to provide a new mathematical approach to control the black-box parameters related to the reverse design of experiments (DoE). This approach can be applied to the improving ground machines. The aim is to help the machine improve workability, productivity and quality

The (DoE) finds relationships among parameters and is widely applied in science. For example, There are three experimental parameters described in the following table. Those parameters are humidity (W%), temperature (t^0), material strength (σ).

Table 1 Data of X1, X2, and Y

No	X_0	X_1 = W(%)	$X_2 = t^0$	Y = σ, MPa
1	1	6	40	9
2	1	18	40	5.5
3	1	30	40	3
4	1	6	80	7.5
5	1	18	80	4.2
6	1	30	80	2

Based on the available data, by DoE theory, it is possible to build a regression equation as follows:

$$Y = 0,29X1 - 0.0315X2$$

The reverse steps of DoE have not been used. In a programmable control system, the machines encounter problems when they don’t have sensors to identify the working object. Specifically, when the soil properties randomly change (e.g., soil viscosity and composition), the machine working parameters may not adapt to such changes. Mathematics has not been fully applied to this problem. Thus, the author proposes a temporary method: using known mathematical rules on the soil (similar to the regression equation)

The computer can control the system. In nature and reality, many processes are considered black boxes because science cannot explain the explicit rules of the object. Every behavior examining the black box is almost illogical. If the black box is assumed to have a mathematical rule (regression equation), the operator uses an automated computer system to analyze and make a decision to control the machine. The decision may not be optimal, but it has a clear basis. Then, the workers know exactly what they want in the black box.

In previous example, from humidity (X1) and temperature (X2), the strength of the material (Y), the laws can be obtained. Conversely, from the known strength, by reversing DoE theory, it is possible to control the system of two parameters x1, x2 according to the regression equation. This is described in more detail in the following example.

This method has great application potential. In weather forecasting, if there are statistics on temperature, pressure, wind speed...etc. at different locations, DoE can be relied on to establish regression equations (i.e. weather laws are described mathematically). Based on this equation, reverse DoE can know the path of the storm. This mathematical equation can be a theoretical basis for forecasting because it is based on the axiom that "the natural world has laws"

The limitation of the paper is that the theory has not been tested in practice

Keywords: Design, experiments, ground, controller, machine.

Introduction

Economic development requires increasing infrastructure construction. This leads to an increase in the need to renovate the building's foundation. Many methods have been selected for this purpose. However, all options face the barrier that very little ground attribute data has been collected from preconstruction soil surveys. Geological survey sampling at finite points of surface and depth. Data of soil properties (e.g. viscosity, composition) at points between adjacent samples is not collected. The tools work in a continuous environment, so there is a lack of data to control the system. This data is considered a black box.

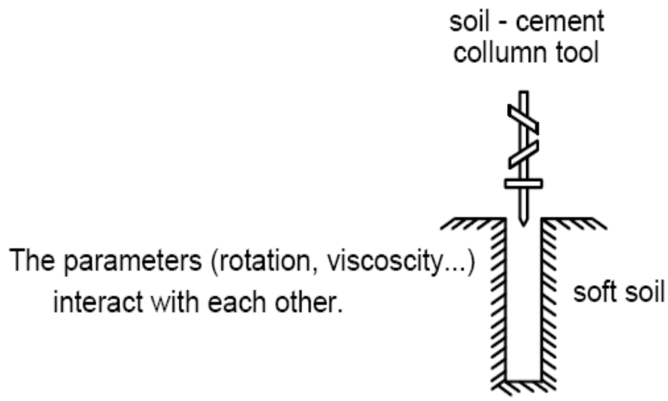

Figure 1. Describe the working of the working set during the initial phase of interaction with the ground

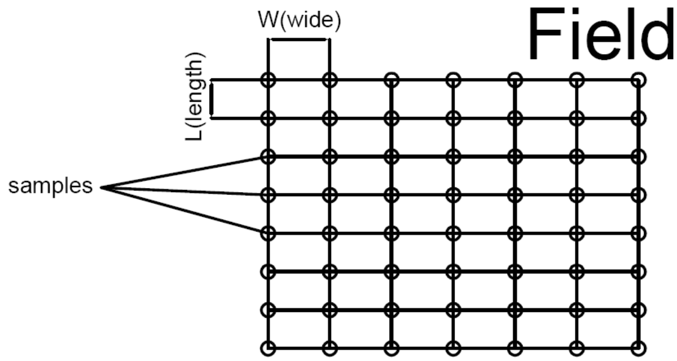

Figure 2. Example of sampling location on the ground

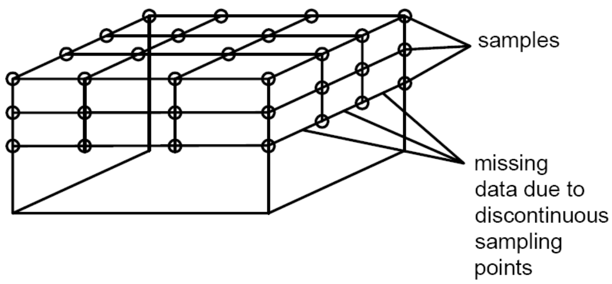

Figure 3. Example of sampling site in soil

The method to handle soils is a challenge. While machines are working, the properties affect the working set, equipment and control system. For example, when making a soil-cement column, there are many influential parameters, including the velocity of penetration, rotation of the working tools, and machine. In addition, the viscosity and soil composition also affect the strength of tool and the system.

These parameters also interact with one another.
Traditionally, with the parameters of soil properties, the proposed actions are drilling into the ground and sampling. The largest problem is that the samples are not taken based on accuracy, fullness and clarity but only based on estimates. Furthermore, the survey results have been interpolated. The samples are spaced as shown in the figure, so estimation and interpolation are unavoidable.

Methods

This paper is based on the DoE, but the difference is that the author proposes to reverse the implementation process to consider and create the proper operation of the drilling machine to create soil cement piles, which will increase the productivity and quality.

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1. Mathematical basis of the reverse DoE applied to making soil-cement.

Traditionally, the DoE theory has long been applied. The theory includes the following steps: information acquisition, mathematical modeling, data processing, algorithm building and result analysis. DoE objects are often processes or phenomena with meager or unclear features and attributes. Researchers do not know the full subject but can make predictions.

Here, the author proposes to apply the reverse DoE. There are many goals to achieve during pile creation. For simplicity, by deriving from the required results of the quality of cement soil piles, based on the available features of the pile-making machine, we can identify the specifications and parameters that must be present with each use of these construction machines. Then, we follow the steps in the reverse order of the DoE.

For simplicity, three parameters are examined: X, Y, and Z. Z is the target parameters. X and Y are the result parameters with known max and min values, but they have an unspecified change rule.

The DoE theory is used to find mathematical models for research subjects. The reverse DoE is used to find the relationship among parameters that were originally unrelated.

With the reverse DoE, the designer applies a mathematical rule on X, Y, and Z such that z = f (x, y). Z is a series of discrete values. Z is applied to the law of distribution (e.g., χ^2 distribution and normal distribution). Parameters X and Y must change based on the value of the Z function. In other words, Z is the black box.

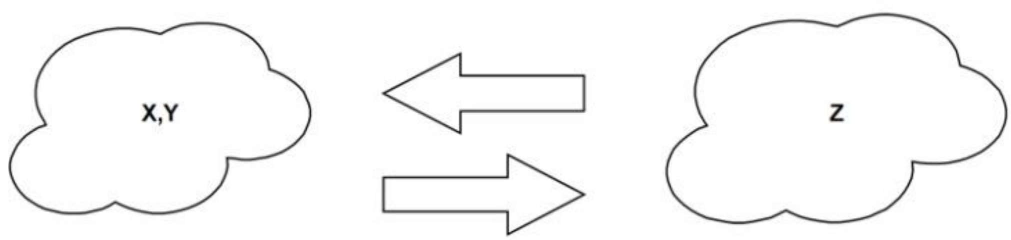

Figure 4. One-to-one corresponding principle.

Mapping: f: Z $\rightarrow$ (X, Y)

The mapping f is bijective function because it is both injective and surjective function.

For each value of X, Y will have a corresponding value of Z, and vice versa. For each value of Z will have a corresponding value of X, Y

Based on this principle, if the Z value is predetermined, then X and Y can be controlled to achieve Z.

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2. Summary steps of the Design of Experiments (DoE).

- 1st: select the change factors and stability factors and output the parameters for the DoE
- 2nd: select the model of recurrence equation
- 3rd: size the min or max varieties of factors
- 4th: select the method of the DoE
- 5th: conduct the experiment
- 6th: calculate the regression coefficient of the mathematical model
- 7th: check
- 8th: analyze the results (plot charts)

3. Suggestion steps of the reverse DoE.

- 1st: suggest the target parameter(s) and result parameters (to control)
- 2nd: apply the rule on the target and result parameters. Consequently, the parameters are connected by a rule (regression equation)
- 3rd: size the min or max varieties of the result factors
- 4th: select the method of the reverse DoE
- 6th: calculate the regression coefficient of the mathematical model
- 5th: plot the 3-dimensional chart
- 6th: analyze the chart and provide suggestions

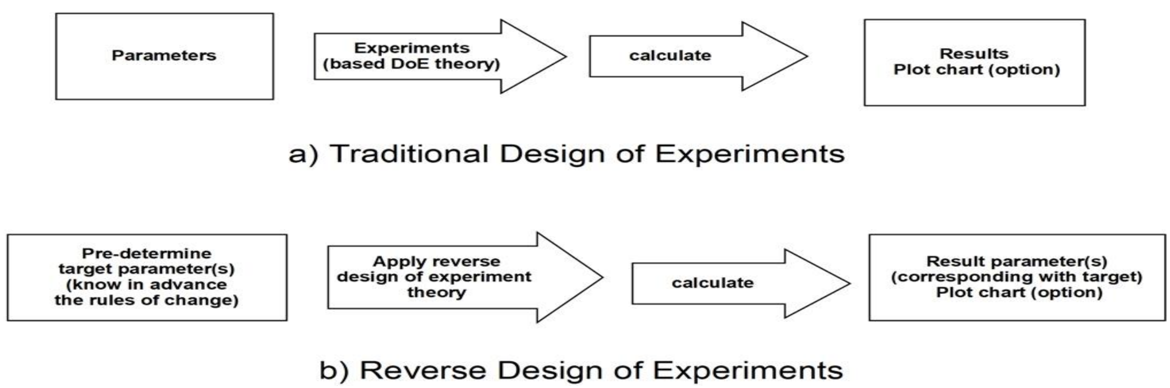

Figure 5. Comparison of the two methods.

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4. Examples.

Soil improvement by soil cement piles is a common method in civil engineering.

The following concepts are necessary because they better clarify the example.

- *Working tool*:

Figure 6. An example of the working tool

The tool is used to make the soil cement piles for the deep-dry mixing method.

- *Productivity* (represented by X, X∈ [6..7] m/min) is as high as possible. However, it relates to other bindings.

- *Quality* (represented by Y, Y ∈ [20..60] rev/m) depends on many factors. According to Larsson. S (p70 [3]), the author defines quality as:

$$T = \sum M \times \{(N_d/V_d) + (N_u/V_u)\}$$

$\sum M$ = number of mixing tool blades

N_d = rotation speed of the mixing tool during penetration (rev/min)

V_d = mixing tool penetration velocity (m/min)

N_u = rotation speed of the mixing tool during retrieval (rev/min)

V_u = mixing tool retrieval velocity (m/min)

- *Stress in tool* (represented by Z, Z ∈ [59000.61000], almost constant, N/cm^2).

An internal force appears in the mixing tool as the main parameter. It tends to increase with depth. During the design, the internal force value is limited. If the generated force exceeds the limit, the tool will be destroyed. By using a computer, the operator can control the stress (internal force) below the limit while maintaining it at the highest possible level.

A smaller depth corresponds to a smaller internal force that the tool can bear.

Moreover, the number of tool revolutions does not change during working.

- *steps of the reverse DoE.*

- ❖ 1st: select X and Y (described above)
- ❖ 2nd: X and Y are the result parameters; Z is the target parameter
- ❖ 3rd: size the min or max X andY (described above)
- ❖ 4th: set the standard normal distribution option for Z (Z values are created by the Microsoft excel software)
- ❖ 5th: calculate the regression coefficient of the mathematical model

Apply the experimental planning of power 2; 2 factors of type B

Table 1 Data of X and Y

MATRIX A					
X0	X	Y	XY	XX	YY
1	6	20	120	36	400
1	7	20	140	49	400
1	6	60	360	36	3600
1	7	60	420	49	3600
1	6	40	240	36	1600
1	7	40	280	49	1600
1	6.5	20	130	42.25	400
1	6.5	60	390	42.25	3600

In this article, there are three random arrays of Z $\in$ [59000...61000] that are selected.

b_i is defined as:

$$b_i = (A^T A)^{-1} * (A^T Z).$$

$Z = b_0 + b_1x + b_2y + b_3xy + b_4x^2 + b_5y^2$

After the calculation, Z is defined as

- Z_1 = 151379.666662693-28478.3*x+103.2375*y-17.375*x*y+2233*x^2-0.22063*y^2), x = 6..7, y = 20..60)
- Z_2 = -37320.667+29755*x+186.2667*y-13.3*x*y-2290*x^2-1.435*y^2), x = 6..7, y = 20..60;
- Z_3 = 204251-45453.33*x+57.7917*y-28*x*y+3618*x^2+1.4925*y^2), x = 6..7, y = 20..60;

❖ 6th: plot the 3-dimensional chart.

The author uses MATLAB 2017b to plot 3 diagrams of the Z_1, Z_2, and Z_3 functions

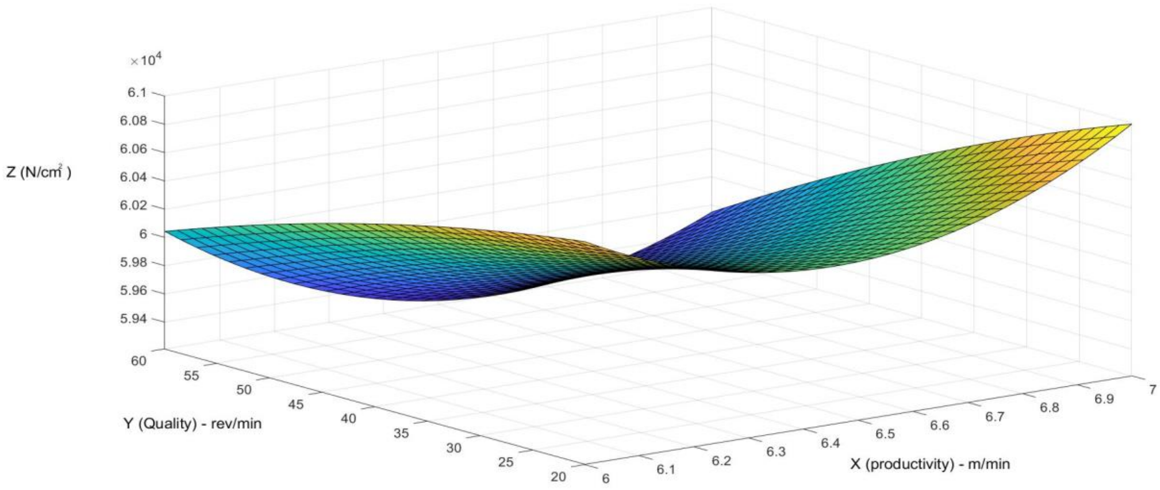

Figure 7. Z_1 function.

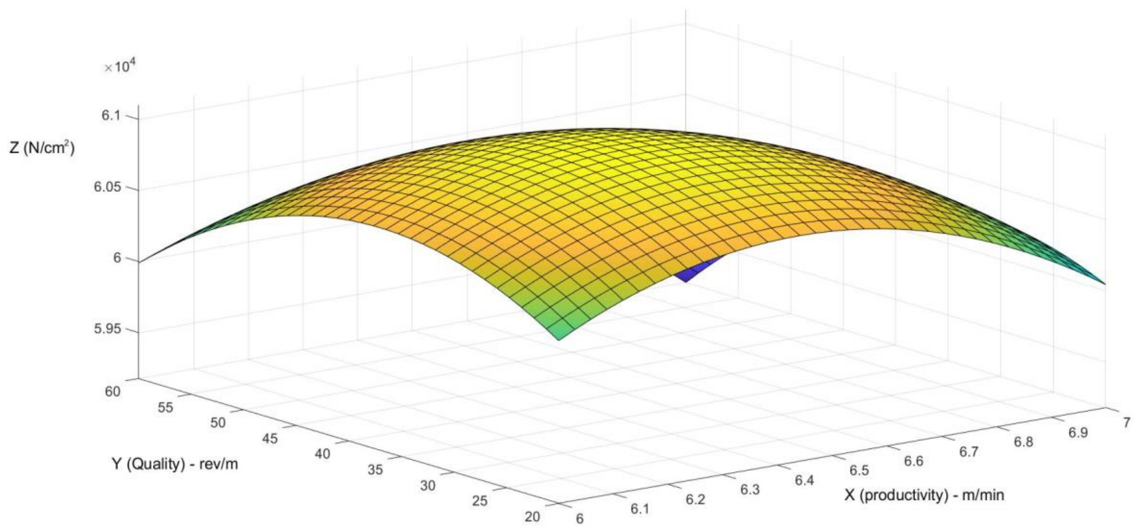

Figure 8. Z_2 function.

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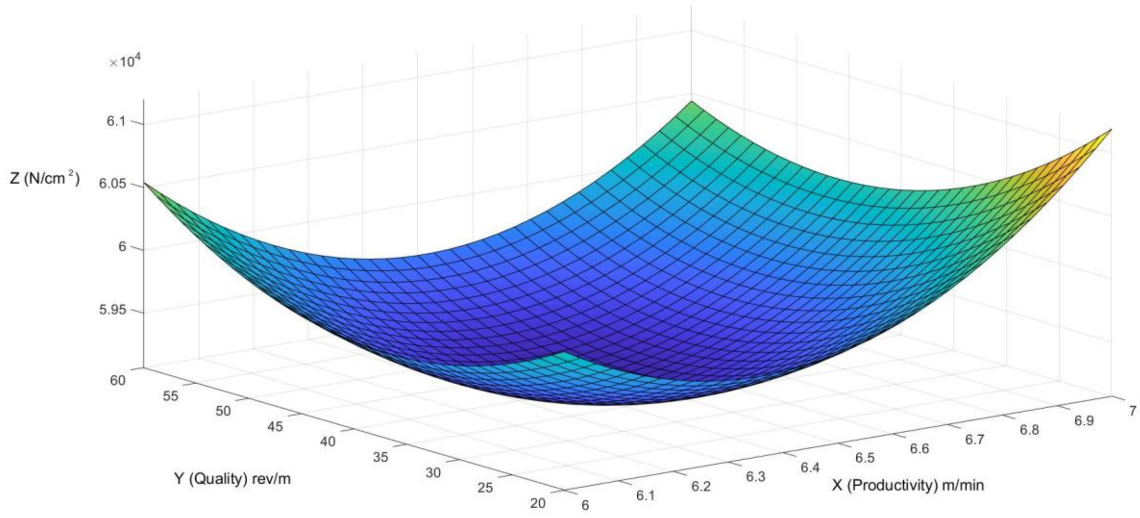

Figure 9. Z_3 function.

- 7th: analyze the chart and provide suggestions.

In the process of creating soil cement poles, the operator may encounter z values at any time. If so, they should follow the curve drawn on the computer.

For example, in Figure 8, when the stress in the working tools reaches 6.05×10^4 N/cm^2, the controller should adjust X to 6 (m/min) and Y to 60 (rev/m).

X and Y are random values. Therefore, if an operator applies a law to them, it is much better for the next stages of work.

Results

The rules will be the basis for the operator to maintain productivity and quality.
In Figure 7,8 and 9, X and Y are the normalized values. Therefore, if a user relies on a computer to provide the X and Y value and relies on critical stress in the tool (which is assumed to be almost constant), they can improve their work efficiency. The system will not abruptly change; for example, Y does not suddenly move from value 60 (rev/m) to value 20 (rev/m). Instead, it moves in a smooth surface.

In reality, data of working tools are continuously collected over time. When data are available, the control values are automatically selected by the computer. The working parameters will follow a previously collected chart.

Interpolation and sampling are going to serve another purpose: building a rule for the Z function (black box) based on the soil properties.

According to the previous examples, Z (stress) is almost constant. In this situation, Z is the easiest rule. In other cases, Z (stress) is more complex and is applied to the stress and other parameters.

Discussion

X and Y are parameters that change without rules. Z is the target parameter, but it has little information to predict. Using the reverse DoE, we apply a rule to Z and force X and Y to follow the value of Z. This method avoids controlling the machine without orientation.

In the given example, with the target, the quality and productivity are rationally supervised.

Inputting the quality and productivity of making soil-cement helps to assess the factors and clarify their interactions.

The advantages of this method are the clarity and logic of the control for the operator. In practice, this method can be applied to forecast weather, such as the path of storms, floods, and droughts. It can also be used for quality control and reliability of complex machines (e.g. airplanes). In the machine building industry, the strength, accuracy, and working modes of the machine are better controlled.

The disadvantages are that the rules of Z are not always easy and ready to apply. The properties of soil vary greatly and are complex. Therefore, applying a rule to it and other parameters requires computer programming knowledge. on the other hand, in some cases, to build a regression equation requires a very large amount of data to ensure accuracy. In the framework of this paper, the author offers a solution based on axioms. A specific (randomly selected) example is given for application. The given results confirm the correctness of this example. More research is needed to confirm in other cases.

In conclusion, if the path is too vague, this method can be one of the solutions.

Data Availability Statement

Some or all data, models, or codes generated or used during the study are available in a repository online in accordance with the funder data retention policies.

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